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COHERENT CATASTROPHISM

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ABSTRACT

We review the theoretical and observational evidence that, on timescales relevant to mankind, the prime collision hazard is posed by temporally correlated impacts (coherent catastrophism, $\Delta t \sim 10^2$–10^4 yr) rather than random ones (stochastic catastrophism, $\Delta t \sim 10^5$–10^8 yr). The mechanism whereby coherent incursions into and through the terrestrial atmosphere occur is described as being the result of giant cometary bodies arriving in orbits with perihelia in the inner solar system. Hierarchical fragmentation of such large (100 km–plus) bodies — due to thermal stresses near perihelion, collisions in the asteroid belt, or passages through the Jovian Roche radius — results in numerous ~kilometre-sized objects being left in short-period orbits, and appearing in telescopic searches as Apollo-type asteroids. Many more smaller objects, in the 10–100 metre size range and only recently observed, by the *Spacewatch* team, are expected to be in replenished clusters in particular orbits as a result of continuing disintegrations of large, differentiated, cometary objects. Gravitational perturbations by Jupiter bring these clusters around to have a node at 1 AU in a cyclic fashion, leading to impacts at certain times of year every few years during active periods lasting a few centuries, such periods being separated by intervals of a few millennia. Furthermore, fragmentations within the hierarchy result in significant bombardment commensurabilities ($\Delta t \sim 10$–10^2 yr) during active periods occurring at random intervals ($\Delta t \sim 10^2$–10^3 yr).

It appears that the Earth has been subject to such impacts since the break-up of such a comet $\sim 2\times 10^4$ years ago; currently we are not passing through a high-risk epoch, although some phenomena originating in the products of this break-up have been observed in the 20th century. This most recent hierarchical disintegration, associated with four well-known meteor showers and termed the Taurid Complex, is now recognized as resulting in a dozen apparently asteroidal objects — almost 10% of the discovered Apollo population — as well as Comet P/Encke. A substantial asteroidal remnant of the Taurid progenitor may still be present in resonance with Jupiter. The implications of the existence of any asteroidal or meteoroidal cluster due to the progenitor are briefly discussed. We emphasize finally the relative importance of active and inactive comets in the cratering record, pointing out the potentially significant contribution by disintegrating large comets to the population of inactive Earth-crossers.

Preamble

The *global* hazard to civilization from space is by no means only a 20th century problem (Clube 1994). Thus the seminal 1860 British Association debate at Oxford between Wilberforce and Huxley and others concerning the ultimate fate of our species on this planet was as much an issue of short-termism versus long-termism (Ussher *vs.* Darwin) as it was theology versus geology and catastrophism versus uniformitarianism (*e.g.*, Huxley 1931; Gould 1991). Subsequently, with Huxley the victor, the geological line of enquiry turned away from extraterrestrial factors and only shifted back comparatively recently to the role of Earth-crossing bodies and their encounters with our planet, raising questions about sub-km and km-plus near-Earth objects (short-termism *vs.* long-termism again) and hence the primary source of the hazard (comets *vs.* asteroids). Previously, however, the fate of civilization was more a theological matter, the fundamentalism-secularism divide rather than the protestantism-catholicism divide providing the framework after the enlightenment in which the debate over 'divine interferences' and 'second causes' in post-creation terrestrial affairs was to be resolved. Thus the perception at stake was whether comets and their debris (fireballs) were truly matters of millenarian concern or merely divine signals with a less devastating message. From Chinese astronomical records we recognize occasional significant increases in the fireball flux coinciding with revolutionary bouts of millenarianism in Europe (of evident concern to governments) while the implied meteoroid flux enhancements resulting from proximity to their source or its recent fragmentation are apparently associated with the massive cometary-cum-asteroidal sub-Jovian association known in modern times as the Taurid Complex.

The question raised, therefore, is whether the primary hazard from space is the more frequent, of low input threshold, known already in principle to perturb western civilization (at the national level, at least), or the less frequent, of high input threshold, known already in principle to be a global evolutionary force. The conventional threshold is that whereby the smallest (single) input mass produces significant physical damage globally (Morrison 1992; Chapman and Morrison 1994). However, since the human response to the celestial hazard in general is highly non-linear, the conventional threshold results in the critical impactor mass and corresponding inverse frequency being seriously overestimated. Our purpose here is to offer some quantification of the lower bound based on giant comet modelling. The evidence from meteors seems the appropriate starting point for our inquiry.

1. Meteor showers and cometary ejection processes

Anyone watching a meteor shower sees abundant evidence that the influx of extraterrestrial material to our planet is not random in time. A visual observer detects the luminosity produced as a meteoroid originally a centimetre or more in size ablates in the atmosphere, and about 30–50% of all such meteors appear to be members of showers (*i.e.*, orbit the Sun in coherent meteoroid streams) with the rest being quasi-random sporadic meteors which have been thrown out of streams by close approaches to Jupiter (Olsson-Steel 1986). When smaller meteoroids are considered, the luminous meteors being observed either with sensitive photographic or TV systems, or by means of radars which detect echoes from the ionization trains produced in the ablation process, a smaller proportion of the particles are found to be members of showers. Typical meteoroid orbit radars have been used to determine the heliocentric orbits of particles of size around 1 mm, and for such bodies perhaps 20–30% are in streams, although it is not clear where weak streams stop and true, uncorrelated, sporadics begin (for background information see, for example, Cook *et al.* 1972; Cook 1973; Sekanina 1973, 1976; Jones and Sarma 1985; Olsson-Steel 1988). Going down in size to the smallest particles that can be detected via atmospheric ionization trains (particles larger than $\sim$100 μm) an even smaller fraction of all observed meteoroids seem to be in showers (*e.g.*, see Millman and McIntosh 1966; Cook *et al.* 1972; Baggaley *et al.* 1994). The general trend is thus for the larger meteoroids to be in streams and the smaller ones to occur at semi-random times, having been preferentially lost from streams by the combined effects of size-dependent ejection velocities from the parents, radiative effects (Poynting-Robertson, *etc.*: Hughes 1978; Burns *et al.* 1979), collisions with other interplanetary particles (zodiacal dust grains: Grün *et al.* 1985; Olsson-Steel

1986), and planetary perturbations (which are size-independent but nevertheless lead to scattering of orbital elements since the perturbations depend upon the orbital size and eccentricity, which are themselves affected by ejection velocities, *etc.*: see Jones and Hawkes 1986).

Most meteoroid streams are sub-Jovian (see the list of Cook 1973) for the simple reason that any stream having aphelion distance $Q \gtrsim 4$ AU is disrupted, with many of the particles ejected from the solar system on a timescale less than the meteoroid physical lifetimes (Olsson-Steel 1986; Steel 1992a). Exceptions (long-lived streams in Jupiter-crossing orbits) tend to be retrograde (*e.g.*, the Halleyid stream, and the Perseids), their high-velocity Jupiter encounters being ineffective in disrupting them (*e.g.*, Olsson-Steel 1987a). However, the formation of a long-lived meteoroid stream generally requires decoupling from Jupiter (*i.e.*, attainment of $Q \lesssim 4.5$ AU). Although Jupiter may be responsible for producing the long-period to short-period transition, it is likely subsequently to re-direct the short-period object either out of the solar system on a hyperbolic trajectory, or back onto a long-period orbit (see *e.g.*, integrations of Hahn and Bailey 1990; Asher and Steel 1993). The decoupling requires a decelerative event, such as (i) a collision with another small body, presumably in the asteroid belt; (ii) a very close approach to one of the terrestrial planets, causing a significant reduction in Q; or (iii) the non-gravitational force produced by volatile loss from the cometary nucleus being of sufficient strength and duration, and in the correct direction, so as to permit orbital shrinkage within $\sim 10^4$–10^5 yr before a gross accelerative encounter with Jupiter occurs (see *e.g.*, Öpik 1963; Wetherill 1991).

Most meteor showers are observed annually, as the Earth passes the solar longitude at which one of the stream nodes occurs, with roughly equal activity from one year to the next (although conditions in the upper atmosphere can significantly affect the number of meteors detected, particularly with radars). That is, the meteoroids are distributed quite uniformly about the stream without significant concentrations (*e.g.*, see Jones 1982; Williams 1990; McIntosh 1991) and the number passing perihelion (or a node) at any time is constant. This results, for small particles, from the combined effects of large ejection velocities from the parent object (comet or asteroid: *e.g.*, see Hughes 1978) and the radiative forces which effectively reduce the gravitational constant by a small fraction ($\beta \approx 10^{-4}$), dependent upon particle size and optical scattering properties (Burns *et al.* 1979), so that the meteoroids when released into space on free orbits have slightly different orbital periods. Thus the small particles are spread evenly around the orbit within $\sim 10^2$–10^3 years, although there will still be concentrations near the nucleus of an active parent comet. This will be particularly true for the larger particles since the factors causing dispersion around the orbit (ejection velocities, radiative effects) are relatively weaker for such objects. Therefore when the Earth passes close by an active parent a meteor storm may be observed, most especially for the larger particles (brighter meteors), with an especially prominent storm being seen if we pass close *behind* the nucleus. Examples are the Leonid or the October Draconid (Giacobinid) storms (Kresák 1980; Williams *et al.* 1986; McIntosh 1991). Considering just the Leonid stream, a distinct shower is observed every November, but once every 33 years a storm occurs since the parent comet (P/Tempel–Tuttle) has a period close to this, and a node very near 1 AU, so that the Earth passes close by the nucleus on a cyclic basis (Yeomans 1981). Further, some storms are observed once but not again, apparently being related to the recent disintegration of the parent comet with many smaller fragments resulting. An example is the Andromedid storm associated with the break-up of Comet P/Biela in the last century, very high activity being observed in 1872 and 1885 (Porter 1952; Cook 1973; Babadzhanov *et al.* 1991; Hughes 1991). We note, though, that the uniformitarian view gained ascendency in the 19th century precisely because the debris from P/Biela had little apparent effect upon the terrestrial environment (Clube 1988).

However, whilst many meteor showers are observed annually, with broadly consistent activity, this situation does not continue indefinitely since orbital precession takes the node of the stream away from a heliocentric distance of 1 AU on a typical timescale of centuries. For example, the

Geminids were not observed prior to the 19th century, at least for several hundred years (Hunt *et al.* 1985; Jones 1985), and other showers similarly will show epochs of activity for some time followed by a lengthy hiatus before their orbital evolution again allows Earth-intercept (Fox 1986). This also results in different branches of a stream producing showers of differing activities at different times (McIntosh 1991; Steel *et al.* 1991). This cyclic, recurrent, activity of meteor showers, meteor storms, and (we suggest) much larger bodies in complexes, is an essential feature of the orbital evolution under planetary perturbations of such structures; this concept is of central importance to the hypothesis of coherent catastrophism.

It is well-known that comets often break asunder producing large fragments (Sekanina 1982; Bailey *et al.* 1990; Yeomans 1991; or the case of P/Shoemaker-Levy 9: Chapman 1993). 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 remnant core, this is not always the case, as evidenced by the Kreutz group of sungrazing comets (Marsden 1989) and several other well-documented splits (Sekanina 1982; Kresák 1991). The size of the largest particles/bodies that may be lost from the nucleus of a comet under normal-type decay, so as to form a meteoroid stream as described by McIntosh (1991), as opposed to catastrophic splitting into a mass of similar-sized bodies with much smaller debris, is limited by the gas outflow from the nucleus (Whipple 1951; Hughes 1986; but see Hajduk 1991). 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. Apart from cataclysmic disruption, the possibilities are differential erosion amongst natural heterogeneities of the appropriate size in the bulk of cometary material and/or the rocket effect as light volatiles evaporate from newly exposed large fragments. Smaller comets are more likely to produce such fragments in normal-type decay, but with a limited mass-supply. It therefore appears that the disruption of large cometary nuclei is the major source of 10^6–10^{12} g ($\sim$1–100 metre) bodies (*cf.* Kresák 1978a). The terrestrial effects of incoming 10–100 metre objects are of most interest here, although the environmental/climatic perturbations caused by rather smaller objects may also be significant over more extended periods.

After such multiple disruption events it is to be expected that many particles, ranging from millimetres and smaller to $\sim$1 kilometre sizes, will have been released, all in basically similar orbits. The bulk of the larger bodies will remain in orbits of very similar (a, e) such that the secular perturbations are very similar for each, whereas the smaller particles will spread around the original orbit by the action of the various mechanisms mentioned above, becoming more dispersed in the other orbital elements as their initial variations in (a, e) lead to strong differential perturbations (*cf.* Steel *et al.* 1991). Further, if the larger ($\sim$10–100 metre) fragments happen to inhabit a mean-motion resonance with Jupiter, as is often observed to occur both in reality and in numerical integrations, then it is to be expected that a cluster of such objects will orbit the Sun grouped not only in the orbital elements (a, e, i, ω and Ω), but also in the mean anomaly, M. Such clusters, with associated smaller particles, may be evidenced by the cometary trails described by Sykes (1988) and Sykes and Walker (1992); *cf.* Clube and Asher (1990). The presence of these trails with mean anomalies distinct from the apparently associated comet in each case (and in particular P/Encke) is *prima facie* observational evidence for the scenario that we have described above in a series of logical steps based upon well-known phenomena.

The central tenet of coherent catastrophism (Steel 1991) states that as one considers larger particles, of sizes $\sim$10–100 metres but also including some kilometre-sized bodies, cometary disintegrations lead to constrained clusters of such objects which will have repetitive intersections with the Earth when (i) The node is near 1 AU; and (ii) The cluster passes its node when the Earth is nearby. This would mean that impacts by cluster objects would occur at certain times of year, every few years (depending upon the relationship between the cluster's orbital period and that of the Earth), but only when precession had brought a node to 1 AU, and so on timescales of a few kyr. A single massive progenitor, suffering hierarchical disintegration, whereby fragmentations produce large secondary parent objects, which themselves may undergo similar disintegration, can result in multiple meteoroid clusters. We believe that there is at least one such cluster of material currently existing, which over the past 20 kyr has produced episodes of atmospheric detonations with significant consequences for the terrestrial environment, and for mankind.

In Section 2 we discuss the available information on 10–100 metre objects, and in Section 3 we describe the evidence for the presence of the decay products of at least one giant comet in the inner solar system. In Sections 4 and 5 we show how dynamical studies can in principle enable detailed inferences to be drawn about past and future patterns in the terrestrial effects of the complex of material.

2. Near-Earth flux of 10–100 metre objects

Our knowledge of the populations of small bodies in the inner solar system is by no means complete. Until the last few years there have been scarce data pertaining to the population of 1–100 metre objects on Earth-crossing orbits, so that little about their ecology could be investigated in any scientific way. Although smaller bodies than this have been extensively studied by means of meteor phenomena (for particle sizes above ~100 μm) and through zodiacal light observations and spacecraft impact counts (for smaller particles), there are still many unanswered questions. It appears that the present population of interplanetary dust is unusually high (LaViolette 1983, 1985; see also LaViolette 1987, and Clube and Napier 1987) and that much of the present excess may well be cometary in origin since the background meteoritic (*i.e.*, derived from the asteroid belt) flux to Earth is only a few per cent of the meteor flux of predominantly cometary origin (Hughes 1978). Although some of the problems associated with the supply of dust from the asteroid belt (Grün *et al.* 1985) have been resolved by Fulle (1990) and Hajduk (1991), it was suggested many years ago by Whipple (1967) that Comet P/Encke could well be the major source of extant inner solar system dust. A modification of this hypothesis has been advanced in which the extant dust is related to the recent (~2×10^4 yr ago) arrival and subsequent disintegration of an exceptional comet in inner solar system space (Clube 1987, Steel *et al.* 1991). Support for a major cometary contribution to the interplanetary dust population comes *inter alia* from the Štohl meteoroid stream (Štohl 1986) which seems to form an intermediate step between the generation of meteoroids within the Taurid Complex (Section 3.1) and their dispersal into the zodiacal cloud.

As regards meteorite-producing bodies, there is also 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, 1987), with evidence for meteorite streams accumulating (Dorman *et al.* 1978; Oberst and Nakamura 1987, 1991; Dodd 1989; Terentjeva 1990; Halliday *et al.* 1990; Dodd *et al.* 1993). Analysis of Antarctic meteorites indicates that the recent (past 450–750 kyr) influx may not have been uniform (Wetherill 1986; Harvey and Cassidy 1989), arguing for a meteorite source at least partly associated with the break-up of large parent objects from time to time such as we have suggested. It may be in fact that the general 'small body' influence on the Earth during the last million years, typical perhaps of the long-term record as a whole, has essentially been that due to the break-up of very large objects, the mass input due to giant meteorites being comparatively rare and that due to giant comets more common, one of the latter actively undergoing disintegration at the present time.

Although astronomical and terrestrial phenomena observed in the last few millennia are of the greatest significance with regard to the contemporary hazard posed to the human race by extraterrestrial objects, it is pertinent to ask whether the geological record contains any useful pointers to what has happened in the more distant past so that a parallel with the present may be drawn. We mention a few key points only. Regarding the Cretaceous-Tertiary boundary, the association with the Chicxulub crater now seems well established (*e.g.*, Blum *et al.* 1993). Furthermore, it seems that there was at least one growing season between impacts (Shoemaker and Izett 1992), so that multiple impacts apparently occurred, suggestive of the disintegration of a large comet. Indeed straddling the K/T boundary an extended layer of amino acids detected by Zhao and Bada (1989) has been suggested (Zahnle and Grinspoon 1990; Clube and Napier 1990) as having been caused by the deposition of these organics into the terrestrial environment over $\sim 10^5$ yr by cometary dust swept up by the Earth. This is indeed the appropriate timescale for the decay of a sub-Jovian complex of material produced by a giant comet progenitor (Clube and Napier 1990; Steel 1992a). We note moreover various claims that (i) terrestrial crater ages are clustered; (ii) episodes of mass extinctions correlate with crater ages; and (iii) cratering events and/or extinctions occur periodically, every 26–32 Myr, possibly due to comet showers from the Oort Cloud. For background on these topics see, for example, Clube and Napier (1986a, 1994), Bailey *et al.* (1987), Grieve (1987), Hut *et al.* (1987), Stothers (1988), and Weissman (1990). Here we neglect (ii) and (iii) as not of immediate concern (indeed the subject of whether or not comet showers from beyond the planetary region do occur, and if so their effect upon the terrestrial environment, is outside the topic of this paper where we are concerned with the effects of the break-up of single giant comets), but we note regarding (i) that our hypothesis indeed predicts distinct clustering in ages of terrestrial craters, due to multiple impacts by ~km-sized asteroids produced in the break-up of a larger parent comet. Such clusterings would not necessarily occur periodically, and their origin would be distinct from the 'comet shower' hypothesis.

The size range from the population of larger meteoroids (~1 m), observed as fireballs, to the population of smaller Earth-crossing asteroids (~500 m) had been almost entirely unsampled until the *Spacewatch* telescope at Kitt Peak began routine operations in the past few years (Gehrels 1991). Prior to this and until comparatively recently, the general (though not universal) view, erring perhaps on the side of caution, was for 'Tunguska-like' explosions due to bodies in the size range ~50–300 m (say) to occur at the rate of about one every 2000 years (*e.g.*, Brandt and Chapman 1982). Assessments of these small scale impacts, with energies in the range ~ 1–10^3 Mton, were approached in the past by extrapolating from (i) the observed near-Earth asteroid population; (ii) the terrestrial cratering record; (iii) the fireball record; and (iv) the lunar cratering record. All of these approaches amounted more or less to crude guesswork: the first three because of (*inter alia*) the large incompleteness factors and extrapolations involved, and the fourth because the lunar cratering record represents an average flux over an extremely long timespan (~3.5 Gyr) which may not reflect current conditions.

Nevertheless, the first three considerations led Clube and Napier (1982a) to the conclusion that "a few dozen *sporadic* impacts in the tens of megatons, and a few in the 100 to 1000 megaton range, must have occurred in the past 5000 years" (*cf.* Kresák 1978a), while the Shoemaker (1983) lunar cratering data yielded comparable but slightly smaller impact rates. These results were already suggestive, therefore, that impacts in the range ~ 1–10^3 Mton represented a more significant astronomical hazard to civilization than had previously been realized. Indeed it was possible to be more specific. The present fireball frequency appeared to exceed substantially that inferred from the long-term cratering flux and there was a tendency for the fireball meteoroids to be in orbits with semi-major axes and aphelia typical of Taurids (see Dohnanyi 1978). Thus if the fireball flux were ~2 orders of magnitude greater than the corresponding lunar flux, in accordance with a largely cometary source for the zodiacal dust (see above), then it was possible to envisage (Clube and Napier 1986b) greatly increased fluxes of 'Tunguska-like' masses at centennial-to-millennial intervals if (i) the temporarily higher average flux reflected an *intermittent* long-term flux due (predominantly) to the occasional break-up of very large cometary-cum-asteroidal bodies in sub-Jovian space; and (ii) the flux of $\sim$100 m bodies, unlike the 1 m bodies, was not fully sampled, being still largely confined to coherently distributed orbits which (owing to precession) do not currently intersect the Earth. This hypothesis clearly raised the prospect of multiple-Tunguska bombardments of the Earth from time to time, potentially increasing the hazard to civilization to even higher levels than heretofore (Clube and Napier 1990). In view of the extant apocalyptic record not otherwise explained in physical terms (Clube 1994), these arguments based on the average fluxes of bodies that were barely observed, but indicating nevertheless the possibility of the current break-up of a very large comet, clearly gave added significance to the only extensive Earth-crossing meteoroid system so far identified in sub-Jovian space, the Taurid Complex.

The few data now available from *Spacewatch* indicate that in fact the population of $\sim$1–100 m objects at the lower end of the range is indeed about two orders of magnitude higher than previously believed (Rabinowitz 1991, 1992; Ceplecha 1992; Tagliaferri *et al.* 1994). The sampling of phase space is currently too limited to allow firm inferences about the coherence of this flux. Nevertheless, combined with the evidence from the Taurid stream, the preliminary *Spacewatch* data provide evidence for complexes of objects produced in this way and observable in the present epoch.

3. The Taurid Complex

3.1. The Taurid meteor showers and other terrestrial/lunar phenomena

There is a sense in which straightforward visual aspects of meteors mislead (*cf.* Section 1). The luminous efficiency of meteors depends on a high power of the incident velocity and to a very large extent the incoming material is dominated by the least conspicuous low-velocity material from sub-Jovian space. Most of this material is apparently associated with the sporadic background producing both 'helion' and 'antihelion' fluxes at all ecliptic longitudes, consistent with material originating in a common family of orbits which has undergone substantial precession in accordance with its likely age $\sim 10^4$ yr. However, it is also clear that this stream is not uniformly distributed in longitude (Štohl 1986), up to some 50% of the sporadic flux not in fact being truly sporadic, but instead close to a broad stream of meteoric material identifiable with the Taurids.

The Taurid Complex (hereafter TC) of interplanetary objects is presently recognized as consisting of several subordinate night-time (optical and radar) and daytime (radar) meteor showers, Comet P/Encke and possibly other comets, and also several Apollo-type asteroids (Clube and Napier 1984; Štohl and Porubčan 1987, 1990; Steel *et al.* 1991; Asher *et al.* 1993). It has been recognized for some time that the TC and the broad sporadic stream (Štohl 1986) may well be the principal intermediaries associating a major cometary source of the recent past with the zodiacal dust cloud (Whipple 1967).

The TC also appears to contain other large objects which in the present epoch have orbits intersected by the Earth in the last few days of June each year: the largest observed is the $\sim 10^{11}$ g object which entered the atmosphere over the Tunguska region of Siberia in 1908 (Kresák 1978b). There is strong evidence that the TC contains many boulder-sized ($\lesssim 10^6$ g) objects; for example, many lunar impacts were seismologically detected in late June 1975 from a direction consistent with the β Taurid radiant (Dorman *et al.* 1978). Clube and Asher (1990) pointed out that the IRAS-detected trails associated with several short-period comets (including P/Encke), and thought to be comprised largely of millimetre-sized particles and larger (Sykes 1988; Sykes and Walker 1992), 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 1975 lunar events, with the terrestrial ionosphere being disturbed at the same time (Kaufmann *et al.* 1989), presumably by otherwise unobserved large meteoroid ablation effects, is but an example of the passage of the Earth–Moon system through the periphery of such a complex, assuming the latter is spatially confined and replenished by a trail, such as would arise in the case of a resonant source (*cf.* Asher and Clube 1993; and Section 5 herein).

Steel *et al.* (1991) discussed the anomalously young (in terms of space exposure age) chondritic meteorite Farmington, whose 7–25 kyr age provides independent verification of the ~20 kyr period based on dynamical arguments, over which the TC has evolved since the giant comet progenitor entered an inner solar system orbit. Oberst (1989) considered the possible association of Farmington with the daytime β Taurid meteor shower and/or P/Encke, but decided that a link was unlikely on the basis of (i) The lack of swarms within the Taurid stream (although we contradict this in Section 5); and (ii) The results of ablation studies that indicate that such a meteorite arriving at ~30 km/sec would lose ~97% of its mass in passing through the atmosphere. Nevertheless, if Farmington is part of the TC, then the nature of that meteorite — being formed in a non-aqueous environment — may argue for the original cometary body having been highly differentiated (*cf.* Öpik 1966, 1977). This then provides circumstantial evidence for an initial evolutionary phase lasting millennia during which the formation of the TC is dominated by the release of volatiles and dust; and a subsequent evolutionary phase, also lasting millennia, during which the progenitor undergoes intermittent fragmentation producing meteoroids, albeit at a globally slower rate. This scenario seems consistent with contemporary observations of comets, with the active phase we now normally associate with comets being driven by loss of the more volatile constituents carrying away smaller refractory particles (small meteoroids and dust); the later evolutionary stages after substantive de-volatilization are largely unstudied at this stage in our exploration of the inner solar system. Such an evolutionary trend is in accordance with the reduced efficiency of splitting and increased fading which has long been hypothesized (Oort 1950; Oort and Schmidt 1951) for the evolution of typical 'new' comets from the Oort Cloud. It is also in accordance with a period of sustained climatic deterioration on Earth (say ~35,000–10,000 years ago) followed by a period of intermittent climatic deterioration associated with individual fragmentation events, the effects caused by the influx of large impactors which deposit large quantities of dust in the atmosphere, or the more gradual influx of TC-derived dust which is now part of the zodiacal dust cloud (Clube and Napier 1984, 1986a, 1990; Clube 1991; Asher and Clube 1993).

Apart from the dynamical arguments based upon the dispersion of the orbits, the recognition that the broad Taurid meteoroid stream is a dominant fraction of the near-ecliptic sporadic meteoroid population (Štohl 1986) additionally demonstrates the recent origin of the TC, since the meteoroid collisional lifetime for such particles is of order 100 kyr (Grün *et al.* 1985; Olsson-Steel 1986). Thus we believe that the TC-derived zodiacal dust cloud may have been of rather higher density in the past 20 kyr implying that the collisional lifetime of the meteoroids was reduced (*N.B.* the overall collision rate would vary as $\sim S^2$ rather than S, where S is the spatial density, if the TC were itself significantly boosting the zodiacal cloud), while the Poynting-Robertson lifetime for the smaller particles is of the order of 10 kyr. We note that these seemingly short lifetimes are corroborated by cosmic ray exposure ages of particles collected in the stratosphere (Bradley *et al.* 1984; Brownlee 1987).

3.2. The Taurid asteroids

Despite the demonstration long ago that the Taurid meteor showers are exceptional and of great scientific interest (Whipple 1940; Whipple and Hamid 1952; Lovell 1954), the existence of kilometre-sized asteroids in the TC is apparently doubted by some workers in the field of minor solar system bodies. This doubt has never been substantiated in the scientific literature so far as we are aware but to convince skeptics, we clearly require indisputable evidence that the TC not only includes Comet P/Encke and many meteoroids/meteor showers but many less readily observed larger bodies as well (Clube and Napier 1984; Olsson-Steel 1987b; Steel 1992b), with a size distribution implying a very substantial mass. The database of orbits of Earth-approaching asteroids, with the known number of Apollos increasing over the past decade to more than 100, now allows a convincing statistical demonstration. We firstly follow the approach of Asher *et al.* (1993), and then present an alternative analysis by Napier (1993) which leads, however, to the same basic result. An abbreviated form of the following analysis, using an earlier catalogue of asteroid orbits, has been presented by Steel *et al.* (1994).

In selecting plausible TC members from the inventory of Apollo asteroids, we use a variant of the D-criterion of Southworth and Hawkins (1963). Similar stream searches amongst large bodies have been carried out by, for example, Kresák (1982a) and Lindblad (1985) for long-period comets, Lindblad and Southworth (1971) for main-belt asteroids, and Drummond (1991) for Earth-approaching asteroids. Carusi and Valsecchi (1982) have discussed the methods of selecting groupings appropriate in such work, and Kresák (1982b) has indicated how planetary perturbations and other dispersive factors may affect the orbital similarity criterion. As the Taurid meteor showers are widely spread in the argument of perihelion ω and the longitude of the node Ω, the night-time showers persisting from October through to January and even February (Štohl and Porubčan 1990), a criterion using Ω and ω is inappropriate. Instead we define a reduced D-criterion:

$$D^2 = \left(\frac{a_1 - a_2}{3}\right)^2 + (e_1 - e_2)^2 + \left(2 \sin \frac{i_1 - i_2}{2}\right)^2$$

where the relative scaling of a and e is broadly in line with that produced by reasonable dynamical models (see Steel *et al.* 1991). Our experience with integrations and with Brouwer's (1947) secular perturbation theory (Section 4.1) shows that the inclination i of TC orbits can vary by a factor of 3–4 over $\sim 10^3$ yr timescales, with the result that the value of D can be substantially affected depending on what the present-day osculating value of i is. However, we can make our D-criterion meaningful by using Brouwer's theory to adjust i to be the minimum value that ever occurs. This is not necessary in the case of meteoroids because i is constrained to be low by the fact that the particle orbit must intersect the Earth's orbit for a meteor to be produced (see Steel *et al.* 1991). We have also allowed for the corresponding variations in eccentricity e, even though these are much less significant with regard to the D-criterion than the i-variations. Following Steel *et al.* (1991) the reference orbit, based upon observed meteors, is given by a_1=2.1 AU, e_1=0.82 and i_1=4°. We shall impose longitude selection after applying the D-criterion.

With all near-Earth asteroids to 1994 January 31 included in the analysis, Table 1 shows the 40 asteroids with $D < 0.275$. The elements there are current osculating values, not adjusted for long-term perturbations. Appended to the list is P/Encke, the only active comet known in the TC (though tentative evidence for cometary activity associated with 2201 Oljato was given by McFadden *et al.* 1984 and Russell *et al.* 1984). The orbit of 5025 P–L, which is uncertain since it is derived from a short arc, is due to E.L.G. Bowell. Despite 1991 BA being one of the smallest asteroids ever observed at 5–10 m, its orbit is quite accurately known, with a determined to within 2% (Scotti *et al.* 1991); a similar comment applies to 1993 KA_2.

Next we consider whether these asteroids, selected only on the basis of similarity of orbital size, shape and inclination (a, e, i) to the TC, turn out to be aligned with the TC on the basis of their longitude of perihelion ϖ ($= \Omega + \omega$). We assume that ϖ will be uniformly distributed in the absence of a reason (*i.e.*, one or more common progenitors) for groupings. Though this assumption may be invalidated by other factors (such as discovery selection effects) it does appear a reasonable step in order to establish whether any groupings exist for further consideration, and it is more tractable than making assumptions about the a, e and i distributions. It is notable, though, that the high TC value of the eccentricity (e_1=0.82) is more representative of cometary rather than typical Apollo-asteroidal orbits, and the perihelion distance (q_1=0.38 AU) is smaller than usual amongst the discovered Apollo orbits; that is, orbits selected using our D-criterion are

Table 1. Asteroids with orbital elements (a, e, i) similar to the Taurid Complex meteoroids. The probability of TC membership declines steeply beyond about D=0.20.

Aligned with Taurids	Others	a	q	e	i	D	ϖ
	1991 AQ	2.16	0.50	0.77	3	0.05	221.7
	2212 Hephaistos	2.17	0.36	0.83	12	0.06	236.8
1993 KA_2		2.23	0.50	0.77	3	0.06	140.9
1984 KB		2.22	0.52	0.76	5	0.07	146.5
	2101 Adonis	1.88	0.44	0.76	1	0.10	33.0
1991 TB_2		2.40	0.39	0.84	9	0.10	132.8
2201 Oljato		2.18	0.63	0.71	3	0.12	172.8
	1990 SM	2.16	0.49	0.78	12	0.12	243.9
5143 Heracles		1.83	0.42	0.77	9	0.13	177.1
5025 P-L		2.14	0.65	0.70	3	0.13	135.5
4197 1982 TA		2.30	0.52	0.77	12	0.14	129.5
1991 BA		2.24	0.71	0.68	2	0.16	189.6
4341 Poseidon		1.84	0.59	0.68	12	0.16	123.7
	4486 Mithra	2.20	0.74	0.66	3	0.17	251.0
1994 AH_2		2.51	0.73	0.71	10	0.17	189.4
	1990 TG_1	2.48	0.76	0.69	9	0.18	238.4
5731 1988 VP_4		2.26	0.79	0.65	12	0.19	138.4
1991 GO		1.96	0.66	0.66	10	0.19	113.6
4183 Cuno		1.98	0.72	0.64	7	0.19	171.1
1990 HA		2.58	0.79	0.69	4	0.20	133.1
	1983 VA	2.61	0.81	0.69	16	0.21	89.2
	1983 LC	2.63	0.76	0.71	2	0.21	344.5
	1991 EE	2.25	0.84	0.62	10	0.22	283.2
	4179 Toutatis	2.51	0.90	0.64	0	0.23	42.8
	6344 P-L	2.62	0.94	0.64	5	0.25	57.6
1937 UB (Hermes)		1.65	0.62	0.62	6	0.25	126.7
	1993 TZ	2.02	0.88	0.56	4	0.26	74.8
	1991 XA	2.27	0.98	0.57	5	0.26	25.7
	1991 CB_1	1.69	0.68	0.59	15	0.26	303.1
	1991 JX	2.52	1.01	0.60	2	0.26	277.3
	1991 OA	2.51	1.04	0.59	6	0.27	263.8
	1992 NA	2.39	1.05	0.56	10	0.27	357.5
	4015 Wilson-Harrington	2.64	1.00	0.62	3	0.27	1.9
	1993 HD	1.45	0.49	0.66	6	0.27	95.6
	1992 UY_4	2.65	1.01	0.62	3	0.27	346.6
	2608 Seneca	2.49	1.04	0.58	15	0.27	203.5
1989 DA		2.16	0.99	0.54	6	0.27	128.5
	2329 Orthos	2.40	0.82	0.66	24	0.27	315.4
	1991 FB	2.37	1.04	0.56	9	0.27	237.4
	3671 Dionysus	2.19	1.00	0.54	14	0.27	286.1
P/Encke		2.21	0.33	0.85	12	0.04	161

noteworthy in themselves as being atypical of the bulk of Apollo asteroid orbits, so that there is a basis for an alternative mode of analysis (see later).

Inspection of the last column in Table 1 will indicate to the reader that there is a preponderance of asteroids selected, particularly those with smaller D values, which have $100^\circ < \varpi < 200^\circ$. To make this clearer, in Figure 1 we give a polar plot of these values for all $D \leq 0.20$. This distribution certainly does not appear to be random. We next present some statistics to demonstrate that the observed distribution is unlikely to be representative of a random distribution of ϖ.

We wish to answer the following question: if we select asteroids on the basis of having small D, do they show an alignment with the TC that could not be due to chance? In the first instance

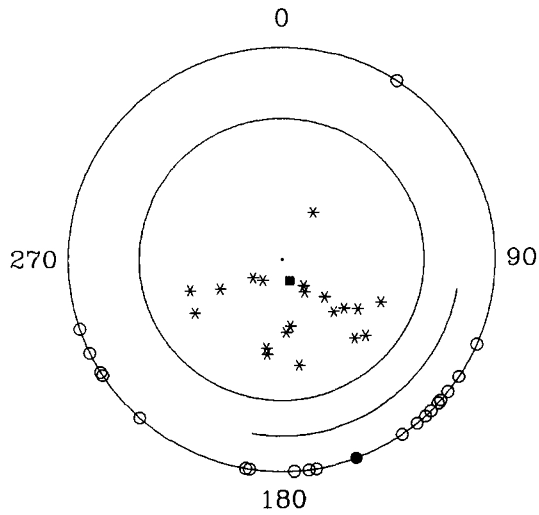

Figure 1. Longitude distribution of asteroids, showing the Taurid Complex alignment. Within the inner circle is a polar plot, the radial coordinate being the value of D from Table 1 and the angular coordinate being the longitude of perihelion ϖ. The 20 asteroids with the lowest D are plotted as stars, and the solid square represents P/Encke. The values of ϖ alone are plotted around the outer circle. The concentration from ϖ = 100° to 190° (ϖ-values of meteoroids that give rise to Taurid meteor showers on Earth) is evident. The other striking feature is the 'Hephaistos group' from ϖ = 222° to 251° (see text).

we do not decide exactly what D-cutoff to use, but check the results for various cutoffs, namely those defined by taking the first 5, 10, 15, 20, 25, 30, 35 or 40 asteroids in Table 1 (see first column of Table 2).

A reasonable range of ϖ to take as corresponding to the TC, based on the core of the Taurid meteoroid stream/meteor showers, is 145°±45°(see Steel *et al.* 1991). The small asteroid/large meteoroid 1991 BA, with ϖ=189.6°, has been independently associated with the Southern ρ-Geminids (Štohl and Porubčan 1992), an outlying stream in the TC. It seems acceptable to allow our range of ϖ to extend up to 190°, in line with the work of Štohl and Porubčan (1990) on Taurid meteors. The numbers of asteroids within the range are shown in the second column of Table 2, and the probabilities that such alignments could arise by chance are shown in the third column. The exact figures depend on the exact longitude range, but whatever range is chosen, provided it corresponds reasonably to the TC, the statistical result is highly significant.

As we did not decide the D-cutoff *a priori*, we cannot immediately select the smallest figure from Table 2 and ignore the others. We could calculate the overall probability that *any* of the individual probabilities in Table 2 would be as low as 0.00003, but rather than be concerned with precise levels of confidence, we observe that the probabilities in order show a continuous decrease to 0.000030 followed by a continuous increase. This strongly suggests that a cutoff in the region of D=0.20, so that about 20 asteroids are considered, best defines the TC asteroids. Thus for a time the significance level improves as more TC objects are included but it worsens as D is increased beyond 0.20 since there is a higher proportion of unrelated objects. Just one or two of the asteroids could be aligned with the TC by chance; individually, those with, *e.g.*, D=0.19 are not quite as likely to be genuine TC members as those with smaller D.

At a very high confidence level, then, we have demonstrated that of the discovered Earth-

Table 2. Probabilities that alignments with the Taurid Complex of asteroids selected on the basis of (a, e, i) similarity to the TC could result from a random distribution in ϖ.

Number of asteroids	Number aligned	Probability
5	2	0.367
10	6	0.0197
15	10	0.0008
20	14	0.00003
25	14	0.0009
30	15	0.0027
35	15	0.0158
40	16	0.0262

crossing asteroids (mainly km-sized) there is a subset aligned with the Taurid meteoroids. We might expect the proportion of asteroids found to be members of the TC to be even higher amongst newly discovered sub-km objects if our hypothesis that the TC is particularly rich in smaller asteroids is correct.

We note also, in the 'Others' column of Table 1, a remarkable alignment of 5 of the first 6 asteroids between ϖ values of 222° and 251° (see Asher *et al.* 1993 for similar statistical analysis to the above). We shall call these 5 the 'Hephaistos group', an interesting discovery in the context of asteroid streams (see below; also Obrubov 1991).

An alternative approach to this analysis, which avoids the subjectivity inherent in the application of the D-criterion but which yields results virtually identical to the above, has also been described (Napier 1993). In this approach, a hypothesis is set up: *significant numbers of asteroids are co-orbiting with P/Encke*, and tested against the null hypothesis: *the numbers of any such co-orbiters do not exceed chance expectancy.* The hypothesis may be regarded as *a priori* since it was formulated largely from physical rather than statistical considerations (Clube and Napier 1982b), at a time when the properties of the asteroidal Earth-crossing population were barely known.

To test the hypothesis, the 118 Earth-crossers known to 1992 March were taken and the distribution of osculating orbital elements used to define a probability distribution in the reduced phase-space (a, e, i, ϖ). The test then consists of comparing the actual numbers of asteroids in the phase space around P/Encke's elements with the numbers expected by chance extraction from this distribution. Beginning with a small element around the comet (in the phase space) and expanding it, one finds that the 4-space encompasses five asteroids when $\sim$0.2 are expected by chance, six when $\sim$0.35 are expected, and so on, until the signal of co-orbiters is lost in the noise of chance associations. In this way it is found that, at a confidence level of $\gtrsim$99.9%, six asteroids are associated with P/Encke, while a further five are associated with the comet at a confidence level of $\gtrsim$99%. Observational selection effects seem quite inadequate to lead to the preferential discovery of objects with orbital elements so closely similar to those of P/Encke.

Overall, therefore, the existence of a stream of asteroids embedded within the Taurid Complex seems to be established at a very high confidence level. Without replenishment, the complex would become unrecognizably dispersed in $\lesssim$30–50,000 years. Thus, in the present state of knowledge of cometary evolution, a sequence of disintegrations of an erstwhile very large comet, yielding short-lived asteroidal bodies *en route* to meteoroid formation, seems the most likely explanation for the association (*cf.* Kresák and Kresákova 1987; Obrubov 1991; Babadzhanov and Obrubov 1992). These asteroids may be little more than dust balls, with physical lifetimes $\sim 10^5$ years, while the presence of P/Encke in the dynamical association, not to mention the Farmington meteorite, would seem to imply a degree of heterogeneity in the originating source: a physical lifetime of order of the dynamical one, for example, can yield a gross overproduction of near-Earth asteroids in Taurid phase space, possibly extending to a gross overproduction of more widely dispersed 1–100 m objects in sub-Jovian space (Dohnanyi 1978; *cf.* Section 2).

A similar exercise based on (a, e, i) alone independently revealed the existence of the triplet (2212 Hephaistos, 1990 SM, 1991 AQ), the other two members of the Hephaistos group also being statistically detected, although with a reduced confidence level. The similarity in (a, e, i) of the P/Encke (or TC) and Hephaistos groups is plausibly due to an ancient splitting of a common progenitor, but the difference of $\sim 100°$ in ϖ may argue against this. Clube and Napier (1984) pointed out that short-period comets perturbed by Jupiter into relatively stable Earth-crossing orbits will preferentially have new orbital elements $a \simeq 2.28$ AU, $e \simeq 0.84$, and very low inclinations, remarkably close to the values of P/Encke and Hephaistos. It is possible therefore that the two groups are the remnants of independent large comets, corresponding to the existence of a prominent 'entry corridor' into the sub-Jovian region (Napier 1984). The numerical simulations of Wetherill (1991) seem to have confirmed this suggestion. He investigated the decoupling of comets from Jupiter, searching in his simulations for particles reaching $Q < 4.35$ AU. Wetherill's results (his Figs. 4 and 5) show a preponderance of final orbits with $a = 2.2$–2.6 AU and $0.7 < e < 0.8$ (*i.e.*, similar to the TC asteroids, P/Encke, and the other bodies in Table 1).

The above discussion has been concerned only with a search for dynamically related objects amongst the discovered Earth-crossing asteroids using as a reference orbit the mean Taurid meteoroid orbit derived from meteor observations (*i.e.*, only one a, e, i). The hypothesis of coherent catastrophism leads to the suggestion that amongst such bodies in (a, e, i, ϖ)-space there may well be several such concentrations, formed as the result of the break-up of other large progenitors in the past. Depending upon the orbital elements of each complex (differential planetary perturbations leading to their dispersal), these complexes may be recognizable for periods up to 10^5–10^6 yr, or for shorter timescales if the aphelia are near Jupiter. As the database on Earth-crossing objects increases over the next few years clearly a rigorous search for such complexes is warranted.

3.3. The size distribution of Taurid members

Asher (1991) estimated a total mass, integrated over individual particles in the range 10^{-6}–10^{6} g (1 μg – 1 tonne), of $\sim 10^{17}$ g for the structured Taurid stream, and $\sim 2\times10^{17}$ g for the broader sporadic stream surrounding it. The calculation followed Štohl (1987) in using a mass function that peaks at 8×10^{-3} g, the differential mass indices being 1.9 and 2.2 respectively below and above that particle mass. This is as expected for meteoroid streams, with the net mass concentrated in intermediate sized particles (Hughes 1978). However, there is no reason why the power law should extend indefinitely; indeed it would predict no km-sized asteroids whereas we now know of the existence of several (Section 3.2). In the discussion that follows, we assume that the Hephaistos group is distinct from the Taurid group, noting that 2212 Hephaistos is several kilometres across and is one of the largest known Apollos.

Comet P/Encke, the largest known object in the TC, is probably over 5 km across (Luu and Jewitt 1990), corresponding to a mass of $\sim 10^{17}$ g, dependent upon the assumed density. As regards the asteroids, the diameters of 1984 KB, Oljato and 1982 TA are each in the range 1–2 km (McFadden *et al.* 1989), and absolute visual magnitudes suggest that five further Taurid objects in Table 1 having $D \leq 0.2$ are also between one and a few km across, with four more being a little smaller (say 0.5 km). Naturally discoveries are more incomplete the smaller the size, but at a reasonable guess there could be $\sim$10–100 times as many Earth-crossing asteroids of these sizes undiscovered (see Helin and Shoemaker 1979; Steel 1992b), so that in km-sized asteroids the TC contains $\sim 10^{17}$ g, and conceivably as much as $\sim 10^{18}$ g, per logarithmic mass interval, demonstrating the importance of this component of the TC both to the complex as a whole, and to the terrestrial impact rate in general.

In the size range just above that where the total mass can be inferred from meteor data, we note that 1991 BA and 1993 KA_2, at just 5–10 m in size, were chance discoveries, passing within the distance of the Moon when the only suitably equipped telescope (the *Spacewatch* camera) happened to be pointing in exactly the right direction (Scotti *et al.* 1991). Given the recent data on objects in this size range (see Section 2), it may be that in the TC the mass function has already started to increase by this point. That is, we would predict that many such small asteroids/large meteoroids will be found as TC members as the database provided by *Spacewatch* and other similar instruments to be built in the next few years becomes more numerous. Furthermore, while it is interesting that the two smallest asteroids found to date by *Spacewatch* are both in the TC, they had to pass very near the Earth to be observed. There may be substantial populations in clusters (Section 1) that are currently not on nearly Earth-intersecting orbits; such objects are presently undetectable.

Masses between 1991 BA and 1993 KA_2, and the other asteroids, are represented by the Tunguska object. The timescale for a single object in the TC to strike the Earth can be calculated theoretically (see Öpik 1976; Steel and Baggaley 1985) and is of order $\sim 10^8$ yr. One Tunguska event per 10^2 yr is consistent with the long-term cratering flux (Shoemaker 1983) and in principle the impactor frequency can yield the overall population, but we note that few such objects penetrate the atmosphere to leave a crater (Chyba *et al.* 1993). For the moment we note the possibility (Section 2) that these Earth impacts concentrate in intense bombardment episodes every few millennia. Thus the peak in the TC mass function may well be at Tunguska sizes, leading to their especial importance.

4. Dynamical studies

4.1. Orbital evolution of the Taurid Complex

Whipple's (1940) work about Jovian perturbations on Taurid orbits yielded an age of ~ 14 kyr for the TC, a timescale of this order being confirmed by subsequent research (Whipple and Hamid 1952; Babadzhanov *et al.* 1990; Steel *et al.* 1991). Thus a central purpose of the dynamics is to determine the difference in the rate of longitude precession for orbits of different sizes so that the observed longitude range of Taurid shower meteors can be interpreted in terms of a timescale over which the TC has been formed. However, in the context of terrestrial catastrophism, we are interested in nodal intersections with the Earth and require more details than overall precession rates.

An analytic theory, if available, is useful for description of ideas, and that of Brouwer (1947) gives fairly simple formulae for the variations of orbital elements with time. In the form presented in Appendix B of Asher and Clube (1993), we have the following equations for semi-major axis, argument of perihelion, longitude of perihelion, inclination and eccentricity respectively:

$$a = \text{constant}$$

$$\omega = \tan^{-1}(R \tan St)$$

$$\varpi = \varpi_0 + Kt$$

$$i = 2\tan^{-1}\sqrt{\frac{\gamma}{A - B\cos 2\omega}}$$

$$e = \sqrt{1 - \left(\frac{H}{\cos i}\right)^2}$$

with ϖ_0, γ, H, A, B, R, S and K being constants for any single particle; ϖ_0, γ and H are chosen to fit initial values and A, B, R, S and K are functions of a, e and (weakly) i. As an example, for P/Encke, in units of degrees and years, A=2.43, B=2.12, R=0.263, S=0.053 and K=0.0068. The derivation assumes that i is low enough compared to e (which holds for Taurids) and that the particle orbit lies wholly within that of Jupiter. Numerical integrations confirm that this theory works well except near strong Jovian resonances.

For calculations of nodal crossings the orbital element to consider is ω. Assuming the terrestrial orbit to be circular, the values that permit intersection with our planet's orbit are given by:

$$\pm\cos\omega = \frac{a(1-e^2)-1}{e}$$

so that a typical Taurid particle can intersect the Earth when $\omega \approx 65°$, 115°, 245° or 295°. Four different branches of the TC — both Northern and Southern branches at both pre-perihelion (night-time) and post-perihelion (daytime) intersections with Earth — are indeed observed as meteor showers (Steel *et al.* 1991; see Babadzhanov and Obrubov 1987 for discussion of the formation of branches in meteoroid streams in general). If the constant R above had a value equal to unity then ω would vary uniformly with time but for the Taurids R is substantially smaller, so that ω changes more quickly through 90° and 270° than 0° and 180° (Figure 2). Thus nodal intersections occur in pairs, with (using the above values for the constants, appropriate to the TC) ω=115° being attained soon after 65°, and 295° soon after 245°. Typically the members of a pair may be spaced by ~200 yr, with a few millennia between pairs. If there is an appreciably sized cometary disintegration fragment that has given rise to a cluster of objects in similar but not identical orbits then encounters with the Earth will tend to occur throughout slightly extended periods centred on the nodal intersections of the main fragment, and the most active bombardment episodes may be expected to last for a few centuries, spaced by a few millennia. The existence of more than one significant cluster of meteoroids or small asteroids would mean that patterns of bombardment episodes would be interwoven in time (*i.e.*, if the TC were not the only current decay structure remaining; perhaps the Hephaistos group described in Section 3.2 could also be producing such episodes).

So far we have assumed that Jupiter is the only gravitational perturbing force, and numerical studies (Jones 1986; Asher *et al.* 1993) show that this assumption is usually justified (though Jupiter's non-zero eccentricity must be allowed for when investigating orbital element trends derived from meteor data: Steel *et al.* 1991). An exception arises when we propose the existence of the Taurid parent object in the 7:2 resonance with Jupiter (Section 5): the Earth and Venus are found, over timescales of a few kyr, to affect significantly the mean anomaly distribution of resonant particles (for further description of this dynamics see Appendix A of Asher and Clube 1993 and references cited there). Whilst this work to date has proceeded by means of numerical integrations, an alternative, statistical study by the authors yet to be completed involves modelling the average frequency of random close approaches (within a few million km) to Venus and the Earth and the energy perturbations produced.

Detailed dynamical simulations can in theory enable a full evolutionary history of the complex to be constructed. Steel *et al.* (1991) analysed meteor data and found that a model involving ejection near perihelion was needed to explain overall trends in orbital elements but that subsequent fragmentation in the region of the asteroid belt (thus splitting of substantial secondary parent bodies from the original parent near perihelion with these secondary parents undergoing more catastrophic fragmentation in the asteroid belt) was required to explain observed scatter in elements. Similar work based on TC asteroid orbits will be possible if the number of discovered objects increases to substantially more than the present dozen (see Asher *et al.* 1993). Even though the chaotic nature of planet-crossing orbits (Milani *et al.* 1989) means that the evolution of any individual Taurid orbit cannot be precisely traced for more than a few kyr, computer simulations can allow statistically significant patterns in elements to be found.

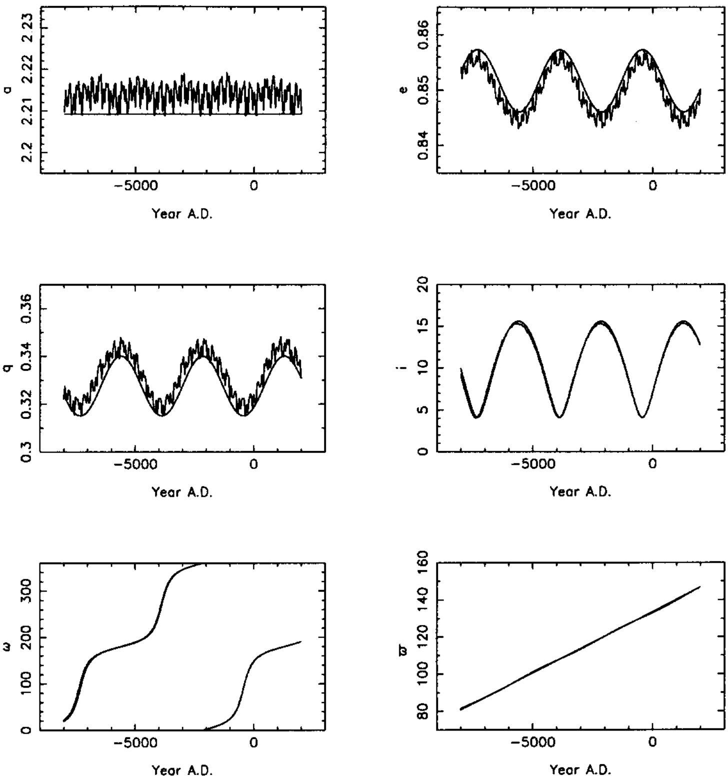

Figure 2. Variations of orbital elements with time of Comet P/Encke; comparison of secular perturbation theory with a numerical integration where the only perturbing force is Jupiter in a circular orbit. The secular theory does not show the smallest-scale variations but reproduces the overall angular precession well. Angular elements are plotted relative to Jupiter, though the differences from an ecliptic reference frame are small.

4.2. Arrival of giant comets in the inner solar system

It is of interest to consider how such structures as the TC might come about. The source objects are visualized as being large differentiated objects which arrive from the outer solar system from time to time and become trapped in Jupiter family orbits. Such orbital evolution is discussed by Bailey *et al.* (1994), and Hahn and Bailey (1990) have previously presented numerical integrations of 2060 Chiron which result in some cases in an inner solar system orbit being attained; they also mentioned the consequences of the plausible break-up of Chiron-like objects whilst on such orbits. Other outer solar system objects of this type which have been found recently include 5145 Pholus and, further from the Sun, 1992 QB_1, 1993 FW, 1993 RO, 1993 RP, 1993 SB, 1993 SC, 1994 ES_2 and 1994 EV_3; all these plus Chiron are in at least the 100–200 km size range. A rather smaller object which may be on an intermediate orbit in this general evolutionary scenario is 5335 Damocles (Hahn and Bailey 1992; Steel *et al.* 1992).

After insertion into a Jupiter family orbit the most likely fate of any such object is that it will be ejected from the solar system by Jupiter on a timescale of 10^4–10^5 yr, so that the total physical decay of an object of cometary nature will not have been completed, if presently accepted ideas on cometary structure are essentially correct. However, some small fraction (Wetherill, 1991, finds about one in 1000, and the action of non-gravitational forces may be expected to increase this probability) will become decoupled from Jupiter and then will have a much longer inner solar system residence time during which complete physical decay may occur. This is the mechanism by which we believe the majority of Earth-crossing asteroids has been supplied, with the TC asteroids being an example of a relatively recent capture/decoupling/disintegration event from an initial giant comet source. In general, of course, if this picture is correct and short-period comets move chaotically from one region of inner solar system space to another, having initially been captured as 'new comets' from the Oort Cloud, then it is to be expected that a large differentiated comet in such an orbit will be in a relatively advanced state of evolution, even to the extent of appearing predominantly 'asteroidal' in nature (like 2060 Chiron) rather than 'cometary'. Broadly speaking though, there are two main routes through Jupiter capture to orbits of low q in which giant comets are likely to undergo rapid evolution producing drastic effects on the Earth. These result in so-called Halley-types (with possible sun-grazers amongst them: *cf.* Bailey *et al.* 1992) and Encke-types, depending on whether we are concerned with isotropically distributed entries from the Oort Cloud as a whole or with those particular entries which happen to be more closely comoving with Jupiter (and which more frequently undergo sequences of small deflections leading to sub-Jovian phase space: *cf.* Everhart 1972). The Halley and Encke types have very different mean periods in general; it follows that, all other factors being equal, the *coherent* catastrophic effects of the former are expected to be considerably less than those of the latter. The more general *relative* effects of Halley-types and Encke-types in Earth-crossing orbits are a complex dynamical-cum-physical problem which is further explored by Bailey *et al.* (1994). Nevertheless it seems very probable that Oort Cloud interactions with our galactic environment are very strongly reflected in the long-term incidence of systems such as the TC (Clube and Napier 1994).

5. Influence upon the terrestrial environment

Referring the reader to other observations discussed by Clube and Napier (1990) and Clube (1994), we note a particular impact event dating from the past millennium. Hartung (1976, 1993) has suggested that a ~1 km object from the TC struck the Moon on 1178 June 18, producing the Corvid meteoroid stream and forming the 20 km diameter Giordano Bruno crater. The hypothesis has been modified by Waddington (1991, and work in preparation), who points out that the Corvid shower was in fact previously active, rendering this particular association unlikely, and (*cf.* Schaefer 1991) that the precise calendrical marker of Gervase's record is mis-translated in Hartung's paper and actually refers to a valid date for the observed lunar event, namely June 19. Quite apart from the importance of this observation in relation to the hypothesis that the TC contains macroscopic bodies which pose a substantial part of the celestial hazard to mankind, assuming this crater is indeed less than a thousand years old, we may be dealing with an observation of immense significance indicating, in accordance with the hypothesis of coherent catastrophism, a cratering flux in recent or contemporary times of quite exceptional magnitude (*cf.* Clube and Napier 1990).

We have presented evidence for the existence of a significant population of potentially Earth-impacting objects in the TC at all masses. An important question is whether we can determine variations, over timescales relevant to civilization, in the expected arrival rate of these objects on Earth. Ideally we want to discover all the most massive clusters of asteroids and meteoroids in the complex, and the most valuable piece of knowledge would be the orbit of the parent object (unlikely to be P/Encke itself), if it has not yet completely disintegrated. In the absence of most of this detailed information, we briefly describe a theory that can explain many observed data, emphasizing that further observational confirmation is required.

Various phenomena, some quite unusual, have been observed this century at times of year that allow a possible association with the TC. If there were no clustering in mean anomaly M within the complex then these events would occur in random years. Table 3 (after Asher and Clube

1993) lists years when there were detections of meteoroids intersecting the Earth–Moon system and years when similar detections were not found despite observations being made. It turns out that the mechanism of a strong resonance with Jupiter can constrain meteoroids in M and that the 7:2 resonance in particular gives a remarkably good fit to the years listed (the 3:1, 4:1, 10:3 and 11:3 resonances do not match all the timings). These measurements are all due to meteoroids of mass above a few grams, below which radiative forces may act to displace particles from the resonance on short timescales. The column ΔM shows the displacement of the centre of the swarm (which is uniquely predicted by dynamical modelling) from the Earth at the time of the Earth's passage through the swarm. Figure 3 is a concise representation of the results of an extensive computational simulation (further description and plots in Asher 1991). It shows the expected distribution in M of a 7:2 resonant swarm; thus particles appear to be concentrated in the central 60°–70° with a gradual decrease over ~10° at each end, in accordance with the observational ΔM values given in Table 3. It is an 'equilibrium distribution' reached within ~10 kyr; the distribution may or may not be similar on shorter timescales, depending on the fragmentation history of the parent.

Table 3. Taurid swarm events since 1930.

Observation (+ reference)	Observation period	Swarm detection time	ΔM
Lightning-like phenomenon on Moon (Giddings 1946)	1931 June 17	1931 June 17	7°
Dutch bright meteors (van Diggelen and de Jager 1955)	1947 – early 1954	1951 Oct 28 – Nov 11	35°
Lunar seismic experiment (Dorman *et al.* 1978)	1969–1977	1975 June 18–26	1°
Finnish bright meteors (Henshaw 1979)	1978 Nov 1, 1979 Nov 3	1978 Nov 1	23°
UV dayglow obscuration (Frank *et al.* 1987)	1981 Nov 1 – 1982 Jan 21	1981 Nov 1–10	–18°
Bright meteors seen in UK, Tenerife (Markham 1988, 1990)	1988 Nov 2, 4, 1989 Oct 27, 31, Nov 3	1988 Nov 2,4	5°

Apparent detections of the presumed Taurid meteoroid swarm at the 7:2 Jovian mean-motion resonance, based on various observational techniques. The 1981 November observation of short-lived obscuration patches in the terrestrial ultraviolet dayglow, understood as being caused by typical disintegrating meteoroids, is unacceptable unless such bodies are concentrated in space. We note that the Tunguska meteoroid (Kresák 1978b) did not coincide with the swarm ($\Delta M \approx 84°$) and so is probably better understood as a single stray object in the Taurid Complex (*i.e.*, a TC member but not in the 7:2 Jovian resonance).

Future observations will help to bolster or disallow this hypothesis, but it is encouraging at present that all these observations may plausibly be fitted by a single meteoroidal swarm in a resonance whose mean period is tantalizingly close to that of the most volatile known member of the TC, namely P/Encke. Thus, if a large heterogeneous source, which is still in the process of disintegrating, is feeding the resonant swarm with its debris, such volatility is plausibly associated with a low-velocity daughter which has been recently released. It is tempting therefore to look for the original parent of the TC within the swarm. In this context the discovery by IRAS of a cometary dust trail along the orbit of P/Encke is relevant and although the trail may be explicable by a model where it is entirely derived from P/Encke (Sykes *et al.* 1986), we consider here the proposition that the trail may be the signature of the as yet unobserved Taurid parent. If we postulate that P/Encke was released from the resonant parent shortly before its discovery in 1786, in association with the last significant enhancement of the Taurid fireball flux recorded by the Chinese (Hasegawa 1992), then it is at the very least a surprising coincidence that P/Encke would have been in an acceptable position relative to the supposedly resonant source of the trail from about 1772 (and at no earlier time that century), while the previous favourable chance for P/Encke's discovery would have been at the 1772 apparation (see Kronk 1984). Although further computer modelling is needed, some work along these lines is described by Asher and Clube (1993), where also tentative orbital elements for the parent are given and patterns in past interactions of TC material with the Earth's atmosphere discussed.

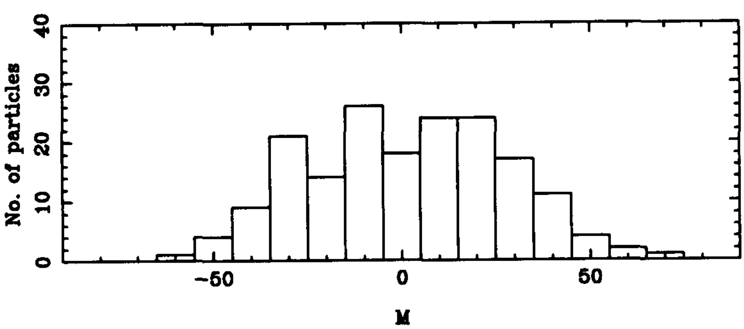

Figure 3. Computer-generated distribution in mean anomaly M of a meteoroidal swarm in the 7:2 Jovian resonance. Sufficient time (>10 kyr) has been given for the perturbations of Earth and Venus to scatter the particles into an 'equilibrium distribution' in the resonance, *i.e.*, all memory of the initial M-distribution is lost.

Of most interest concerning the civilization hazard are timings of possible huge increases in the Taurid meteoroid flux, particularly of Tunguska-sized bodies (*cf.* Section 2). The precession rate of the putative parent object mentioned above would lead to the last extended epoch of nodal intersection being around AD ~400–600 and the next around AD 3000. Events recorded during the AD 400–600 period that could reflect such changes in the astronomical environment are discussed by Asher and Clube (1993) and Clube (1994). Hasegawa (1992, 1993) has investigated Chinese records of bright meteors and fireballs over the past nineteen centuries, finding the most significant maxima in the 11th and 15th centuries, with peaks in October–November which he linked to the TC (see also Astapovič and Terentjeva 1968). This is in accordance with our model, such enhancements finding plausible explanations as corresponding to nodal intersection epochs of significant (perhaps secondary) parent objects in the TC.

Whilst we have emphasized the expectation of repeated intersections by the Earth of coherently moving debris close to its orbital node on the grounds that these are probably significant for correlated encounters with large (Tunguska-like) meteoroids, corollaries of this effect are the similar sequences of intersections that arise with more widely dispersed meteoroid concentrations further from the orbital node. The correlated encounters with fairly extreme meteor showers may also give rise to low-level atmospheric detonations, which could sometimes pose a significant *local* threat. The variety of coherent catastrophic effects thus amounts in principle to a continuum and it may be difficult in practice to avoid confusion between predictable and unpredictable threats. This is conceivably of importance when seeking to explain the historical record or to anticipate future events. Nevertheless, although the exact epochs of increased bombardment of the Earth cannot yet be determined with certainty, it is an inevitable consequence of dynamical processes that if a meteoroid cluster of the sort described is present in the inner solar system then mankind cannot be safe on timescales of at most a few millennia.

Finally, we comment on the role of active versus inactive comets in terrestrial catastrophism (Napier and Clube 1979). The disintegration of a giant, active comet in the near-Earth environment may yield prolonged climatic trauma through the injection of meteoric dust into the stratosphere; the timescale is similar to that involved in the multiple impact hazard. These effects are discussed elsewhere (Bailey *et al.* 1994). The theory of coherent catastrophism, however, relates mostly to inactive cometary (and hence asteroidal) material. We set the theory therefore in the context of a specific understanding of the origin of short-period comets. For this reason, where it is commonly assumed at present that these (short-period comets) mostly originate in the Kuiper Belt, we note here the known tendency towards increased resilience and reduced volatility amongst split objects from the Oort Cloud deflected towards the inner solar system (Oort 1950), characteristic also of differentiated large bodies. Such characteristics are clearly consistent with a short-period comet population which includes an overabundance of ordinary comets (relative to the predicted rate of capture from the Oort Cloud) alongside Chiron-like bodies. It follows therefore that we do indeed expect the short-period active comets in sub-Jovian space to be accompanied by inactive bodies as well, additional to the asteroids deflected from the asteroid belt. In other words, the TC which we observe is a straightforward adjunct of the Oort Cloud which we observe, without the involvement of a Kuiper Belt. The relative contributions of the two sources of asteroids to the Earth-crossing population clearly depend however on their physical properties/lifetimes, which remain matters for further empirical and theoretical study (see Bailey *et al.* 1994 for additional comments).

6. Conclusions

A commonly held view is that the predominant danger posed to mankind by extraterrestrial objects incoming at hypersonic speeds is due to the occasional arrival of kilometre-plus asteroids and comets, these cataclysmic events occurring randomly in time (Morrison 1992). This we term *stochastic catastrophism*, which says that it is only these large impactors, above the threshold causing global effects, that are significant to mankind as a whole (as opposed to smaller objects causing only local damage). Such mega-impacts occur on timescales of $\sim 10^5$ yr, with evidence for past such events coming from observations such as the populations and orbits of these objects in space, large impact craters on the Earth, Moon, and other terrestrial planets, mass faunal extinctions in the palaeontological record, and so on.

Here we promulgate a contrasting idea (Clube and Napier 1990), which is supported by astronomical and other physical observations in the present era, and indeed the historical record. Under this hypothesis — *coherent catastrophism* — the global hazard on shorter timescales ($< 10^5$ yr) is dominated by smaller objects in the size range ~50–300 metres which arrive not randomly in time but rather in epochs of high activity. These epochs, lasting a few centuries every few millennia, are the result of precession of the orbit(s) of complex(es) of such bodies being brought around to have a node near 1 AU on the latter timescale. In those epochs impacts occur at the same times of year for extended periods, though with the annual impact rate varying because of the concentration of many large meteoroids in mean anomaly in the complex's orbit by their recent low-velocity ejection and/or by a mean-motion resonance with Jupiter. The dominant contemporary complex is that associated with the four Taurid meteor showers and Comet P/Encke, having been produced in the hierarchical disintegration of a giant comet which arrived in the inner solar system $\sim 2\times10^4$ yr ago. The objects which we believe dominate the extraterrestrial threat to mankind have been largely unobserved until now, although the operation of the *Spacewatch* telescope has led to the recognition that the present population of ~10–100 metre asteroids is indeed two orders of magnitude greater than its long-term average (Section 2). Whilst the discovered population of such small bodies, the significance of which may yet be related to the central coherence of low-velocity debris from the progenitor, is still not numerous, we note that two of the smallest such objects (1991 BA and 1993 KA_2) are apparently members of the Taurid Complex. We predict that future *Spacewatch* discoveries (this being the only search program currently capable of detecting these smaller objects) will demonstrate a preponderance of objects in Taurid-type orbits; should the *Spaceguard Survey* (Morrison 1992) go ahead then our hypothesis will be verifiable quite rapidly. Already when we consider all known (mostly >0.5 km) Earth-crossing asteroids we find that at a very high confidence level there are two alignments of high-e, low-q, low-i orbits, one with the orientation of the Taurid meteors and P/Encke, and the other finding its archetype in 2212 Hephaistos; these two groups may or may not be genetically linked. There are at least 10 asteroids in the Taurid Complex asteroid group, which is almost 10% of the known Earth-crossers, indicating the order of their contribution during the last 10^4–10^5 yr to the impact rate by ~1 km objects; the fractional contribution is much higher for 50–300 metre impactors according to our model.

Coherent catastrophism, then, says that our major problem is not the once-per-10^5 year large impact with global effects, but rather the multiple-Tunguskas (and larger) which occur in clusters every 1–2 $\times$ 10^3 years at such time as the orbital evolution of the Taurid Complex (and other similar structures) results in a temporary (century or two) nodal intersection with the orbit of the Earth. Whilst global catastrophes of the scale of a kilometre-plus impact do not occur on these shorter timescales, nevertheless such persistent storms of smaller impactors produce deleterious effects which could lead to the collapse of civilization, as they have already done in historical times (Clube 1994).

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Note added in proof

Apart from P/Encke, the only known comet with an orbital period of less than five years is 1766 II Helfenzrieder. Its period is very uncertain, since it was observed only over a 25 day arc, and the nominal value of 4.35 years may be in error by perhaps a year (Marsden and Williams 1993: p.12 and p.54).

After sending this paper to the printers, we noticed that the tabulated elements of Comet Helfenzrieder ($q = 0.406$ AU, $e = 0.848$, $i = 8°$, $\varpi = 255°$) would put it on the periphery of the Hephaistos group of asteroids discussed herein. Its semi-major axis is likely higher than the norm for that group, so that its longitude of perihelion would be expected to be larger, due to swifter precession.

The observation of this apparently-cometary object on one apparition only, over two centuries ago, adds weight to our suggestion that the two complexes (Taurid/Encke family plus Hephaistos/Helfenzrieder group) are derived from massive cometary disintegrations with subsequent comet-like activity being spasmodic.

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