

Centaur as a hazard to civilization

Assessments of the risk posed by near-Earth objects ignore the possibility of a giant comet entering the inner solar system.

Bill Napier, David Asher, Mark Bailey and Duncan Steel examine the likelihood and potential consequences of the appearance of such a centaur.

Do we live in dangerous times? The risks to civilization from impacts by asteroids and comets have been appreciated only in the past few decades. Programmes such as NASA's Spaceguard observations seek to map near-Earth objects (NEOs) as a way to quantify the risk to Earth. But does the current count of NEOs reflect the population over time? We argue that the population is variable and that assessments of the extraterrestrial impact risk based solely on near-Earth asteroid counts underestimate its nature and magnitude for timescales of order 10000 years, i.e. the interval of interest and concern to our civilization. A more variable but significant threat comes from centaurs, giant comets derived from the trans-Neptunian region that reach the inner solar system generally via short-term, dynamically unstable residence periods in the outer planetary region. The disintegration of such giant comets would produce intermittent but prolonged periods of bombardment lasting up to 100000 years. Mass extinction/geological boundary events on Earth show such a pattern, as do levels of dust and meteoroids in the upper atmosphere. Over the past 10000 years, Earth has been experiencing the intermittent arrival of dust, meteoroids and comet fragments from the disintegration of comet 2P/Encke, trapped within the orbit of Jupiter.

The assessments by Chapman & Morrison (1994) and others of the major impact hazard posed to modern civilization are based on the assumption, usually unspoken, that the contemporary NEO population is in a steady state, in terms of the populations at different sizes, being maintained primarily through leakage of

small bodies from the main asteroid belt. The timescale for NEO supply from such a source is tens of millions of years, leading to an expectation that the population of NEOs does not fluctuate substantially over such intervals. Thus crater-counting on planetary surfaces, and the understanding of what such counts imply, is based on an assumption that such craters are produced at a constant rate over geological/astrophysical time; but this core assumption is contraindicated by the terrestrial cratering record (the only craters for which we have individual datings), which shows that these impacts on our own planet have been largely episodic in nature. That is, it seems that the population of NEOs has varied substantially across time. The question arises whether the presently observed NEOs, at all sizes, are characteristic of a long-term average, or whether we are living in dangerous times, at a time of significant enhancement in the NEO population.

Perpetual vigilance

It is clear that no survey of Earth-approaching asteroids lasting just 10–20 years can possibly lead to the identification of over 90% of all Earth-approaching asteroids if there is a significant fraction in larger, intermediate- or long-period (i.e. Jupiter and Saturn-crossing) orbits, because many of these will not come close enough to the Sun during that interval so as to become discoverable. To discover and track all such asteroids would require a survey lasting longer than the maximum orbital periods deemed to be of interest. This links to the problem of long-period or near-parabolic comets: perpetual vigilance is necessary to protect civilization (Marsden & Steel 1994). The claim that the NASA Spaceguard programme has (so far) led to the discovery and orbit determination of 93 or 95% of NEOs larger than 1 km in size is justifiable, so long as one recognizes that the term “NEOs” as used there implies only asteroids in short-period (i.e. cis-jovian) orbits, and not those asteroids in larger orbits – and no comets at all.

The basic model of NEO supply by gravitational perturbations upon main-belt

asteroids predates the discovery of the vast trans-Neptunian and centaur populations, and the finding that centaurs, in chaotic orbits, leak from the outer solar system into the inner planetary region at a significant rate, largely via the Jupiter family of comets. A new, self-consistent picture has emerged in which there is a gradual pass-me-down of substantial objects (50–100 km across and above) into the inner solar system (Horner *et al.* 2004ab, Steel 2014, Napier 2014, 2015).

Napier (2015) discussed how the occasional arrival of a massive centaur will dominate the supply of Earth-crossing debris. The size distribution of centaurs is shallow (Bauer *et al.* 2013), i.e. more of the

mass is in the larger objects. These being comet-like bodies, we may assume they are subject to wholesale fragmentation. This leads to an expectation that when a centaur arrives in an orbit with perihelion within Jupiter's heliocentric distance there will be a temporarily enhanced mass of material in the inner solar system, spread across all sizes from dust at <100 microns to tens of kilometres across. The transition rates into the near-Earth environment indicate that fluctuations in the mass of near-Earth interplanetary material may amount to two orders of magnitude over a timescale 30–100000 yr.

While the terrestrial record of impacts is incomplete and does not support the notion that all mass extinctions arise from asteroid impacts, the idea that impacts can affect our planet's climate and life is now established (see box, “Impacts and extraterrestrial bodies: the story so far”). These new astronomical and terrestrial lines of evidence merit a reappraisal of the celestial hazard faced by contemporary civilization. Here we concentrate on the implications over timescales of order 10000 yr.

The centaur flux

(5145) Pholus, the second-discovered centaur after (2060) Chiron, and (15760) 1992 QB₁, the second trans-Neptunian object (TNO) after Pluto, were both discovered as recently as 1992. Discovery rates have increased such that known centaurs now number in the hundreds and

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Impacts and extraterrestrial bodies: the story so far

The idea that the geological and biological evolution of the Earth proceeds in isolation from its surroundings, developed by Darwin, Hutton, Lyell and others, was the default position in the Earth sciences until the 1970s. This perspective began to change when terrestrial craters such as Odessa (Texas), Barringer (Arizona) and Henbury (Australia) were associated with iron meteorites; when spacecraft missions in the 1960s indicated that planetary surfaces are generally pockmarked with craters as predicted by Öpik (1951); when returned Apollo samples were shown to display evidence of shock metamorphism, demonstrating the well-known lunar craters to be of impact (rather than volcanic) origin; and when wide-field telescopic surveys unveiled a significant population of small (~1 km) near-Earth asteroids (Helin & Shoemaker 1979). Impact cratering is now considered a common and continuing geologic process.

Napier & Clube (1979) indicated that impact rates were high enough to be associated with the mass extinctions seen in the geological record and they proposed possible extinction agencies: collapse of food chains as a result of impact-generated fine dust in the upper atmosphere blocking out sunlight; ozone-layer destruction; straightforward blast; and others. The concept of food-chain collapse caused by dust was not new: Hoyle & Wickramasinghe (1978) had suggested that such dusting might be caused by an encounter with the coma of a comet. Earlier suggestions of links between asteroid impacts and geological boundary (i.e. mass extinction) events include Nünninger (1942) (see Steel 1995).

The discovery of iridium – an element common in meteorites but sparse in the Earth's crust – at the Cretaceous–Palaeogene boundary (Smit & Hertogen 1980, Alvarez *et al.* 1980) cemented the idea that the great mass extinctions of the biological record could originate in highly energetic asteroid impacts. Early enthusiasm for a simple link – giant asteroid impacts = mass extinctions – has not generally been supported by palaeontological evidence. Some of the major extinctions may be associated with relatively small craters, perhaps incapable of explaining the biological devastation recorded in the strata. Conversely, several large craters, such as the

90 km diameter Popigai crater, are associated with regional, not global, effects. The evidence of iridium excess, shocked quartz and the like at extinction boundaries has either been ambiguous or absent (MacLeod 2013). Further, some of the mass extinctions, such as that in the Late Devonian, 365 Myr ago, appear to have occurred in steps (McGhee 1996), while others coincide in time with massive volcanic/flood basalt activity (see table 1).

The fact that the main asteroid belt between Mars and Jupiter fails by an order of magnitude to supply the required transient population of large near-Earth objects (NEOs), or to account for the number of large impact craters (Menichella *et al.* 1996, Minton & Malhotra 2010) is another complication.

This perspective raises the question of whether, and to what extent, cosmic impacts in the present epoch (the Holocene) might have deleterious effects limited to restricted areas, as with the 1908 Tunguska impact or the 2013 Chelyabinsk event, or globally. Chapman & Morrison (1994) considered that the arrival of a ~2 km asteroid would result in the death of a large fraction of the human population, and that there is a probability of about 1% of such an event in the next 10 000 yr. The combination of small probability and large consequences (for substantial NEOs) has led to systematic searches for large near-Earth asteroids (>1 km) in cis-jovian orbits and their discovery appears to be above 93% complete (cf. Harris & D'Abramo 2015), although attention has now been shifted to smaller NEOs around 50 m across.

There are emerging claims from some Earth scientists that the terrestrial disturbance of ~12 800 BP, the sudden onset of 1300 years of cooling, a global collapse of large animal populations and other terrestrial phenomena (e.g. Wittke *et al.* 2013, Kinzie *et al.* 2014, Kennett *et al.* 2015) had a cosmic or even cometary origin, although this remains controversial. A similar claim has also been made for the simultaneous collapse of civilizations, global cooling and drought, at near 2350 BC (Courty *et al.* 2008). With current collision rates, the largest asteroid impact energy expected during the Neolithic is 300–600 megatons, which is incapable of causing the global upsets that appear to have taken place.

known TNOs over a thousand. Although formally classed as being “minor planets” (i.e. asteroids), centaurs are cometary bodies, composed of volatile ices as well as silicates, which cross or approach the orbits of one or more giant planets and are therefore dynamically unstable. The exact definition of what entails a “centaur” varies between researchers: Emel'yanenko *et al.*

(2013) use $5 < q < 28$ and $a < 1000$ au, where q is perihelion distance and a semimajor axis (see Steel 2014). Centaurs comprise a transitional population deriving from cometary reservoirs beyond Neptune. Some reach Earth-crossing orbits (Hahn & Bailey 1990, Asher & Steel 1993), even though only a minor fraction of the objects that begin such an inward passage actually get here,

1 Correlations between volcanism, extinctions and bombardment

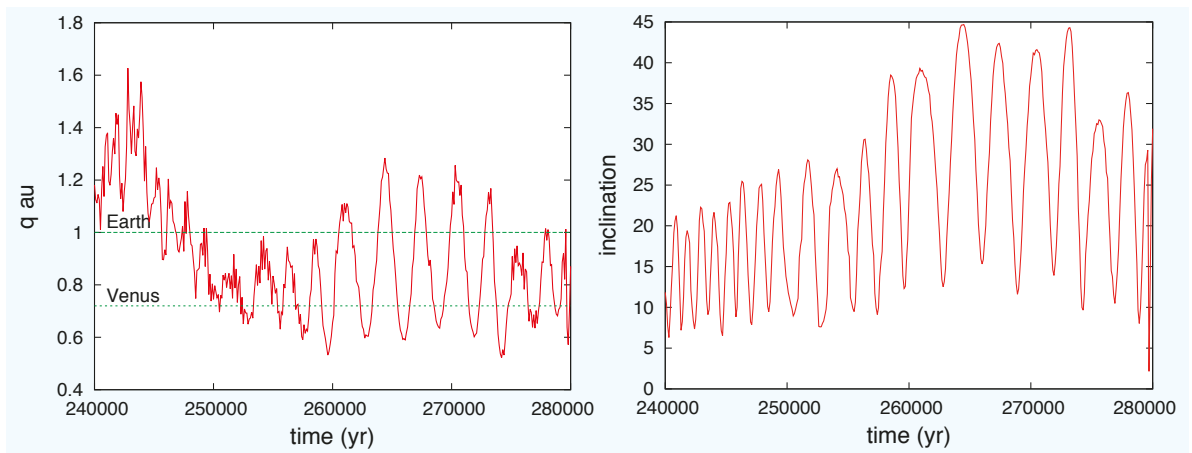
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109–119					
122–122	122			●	
132–134					
	146	144	●		
	166				
180–183	183				●
199–202	200	200	●	●	●
250–253	251	255	(●)	(●)	●
257–260	260				●
	322				
	360				
364–367					
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	375	377	●		
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Table Correlations over the last ~500 Ma between peak activity of large igneous provinces (V; Bond & Wignall 2014), marine genera mass extinctions (E; Bambach 2006) and bombardment episodes (B; Napier 2015). Dates are in Ma. Temporal coincidences within measurement errors are marked by ● or by (●) where one impact has been identified. There is an empirical three-way correlation between bombardment episodes, the creation of some large igneous provinces and mass extinctions, implying that some massive volcanisms may have been induced or exacerbated by such episodes. Richards *et al.* (2015) have shown that the Chicxulub crater formed within 0.1 Myr of a major outburst of Deccan volcanism.

most being weeded out along the way by the influences of the giant planets.

Neglecting physical destruction and non-gravitational effects, about one in ten centaurs in Chiron-like orbits become Earth-crossers, often repeatedly (Horner *et al.* 2004ab, Napier 2015): an example is shown in figure 1. The rate of arrival of ≥ 100 km centaurs into short-period,

1 The evolution of perihelion distance (left) for a modelled centaur with integrated Earth-crossing lifetime $\sim 22\,000$ years. Over the bulk of this interval, the semimajor axis is ~ 3 au, corresponding to an orbital period ~ 5 years. The orbit has many low-inclination phases, providing opportunities for terrestrial encounters with its debris trail.



Earth-crossing orbits is of order one per 30 000 yr (Napier 2015). Integrating the orbits of 100 Chiron clones, the mean total dynamical lifetime in an Earth-crossing configuration was found to be $\sim 17\,400$ yr, with a highly skewed distribution, the median lifetime being 6700 yr (figure 2). Substantial physical disintegration is likely over such an interval (Di Sisto *et al.* 2009).

A prime form of disintegration, as opposed to sublimation of volatiles and complete outgassing, appears to be gross fragmentation, either through internal processes such as thermal stresses or, on occasion, passage through the Roche limit of Jupiter or the Sun. A large centaur may hold 10^2 – 10^3 times the mass of the current near-Earth asteroid system, and an episode of bombardment may be expected whose duration is defined by the dynamical or physical lifetime of the comet and its fragments, whichever is the shorter.

One consequence of the hypothesis argued herein, that large comets arrive sporadically, then disintegrate and produce enhanced terrestrial bombardment episodes, is that impact cratering should be episodic. Such episodes may be distinguished from those arising from comet showers (Bailey *et al.* 1990) or groups of main belt asteroids (Zappalà *et al.* 1998) by their duration. Short-period comet disintegration may occur over ~ 0.01 – 0.1 Myr; a shower of comets from the Öpik–Oort cloud will be spread over ~ 2 Myr; and that from the formation of an asteroid family lasts ~ 5 – 100 Myr. The enhancement in flux of ≥ 1 km asteroids on Earth-approaching orbits following a large main-belt asteroid break-up is small in relation to the background (Napier & Asher 2009) because of the spread in time over which such objects are injected onto inner solar system paths.

We tested this conjecture with the available terrestrial impact database (Earth Impact Database 2014). We used 41 impact structures over 3 km in diameter from the past 500 Myr (i.e. the Phanerozoic), radiometrically dated to precision $2\sigma \leq 5$ Myr. Frequentist and Bayesian analyses confirm

that there is indeed a strong tendency for impacts to occur in tight clusters (Napier 2015). There are 27 craters of this dataset with differential ages $\delta t \leq 2$ Myr, and 22 with $\delta t \leq 1.5$ Myr, comparable with the RMS sum of their quoted radiometric age uncertainties. In all, nine impact episodes have been identified (figure 3). Paradoxically, the bombardment episodes emerge more strongly where the dataset is sparse, namely for the 16 impact craters older than 100 Myr. Their mean age separation is 25 Myr and yet 12 of the 16 belong to crater pairs with $\delta t < 1.6$ Myr, a result which has chance probability of $\sim 0.7\%$. With the more thorough erasure of impact craters at these more remote epochs, most impact episodes will go unrecorded and only the strongest are likely to have surviving multiple craters.

Stratigraphic studies

Relative dating through stratigraphic studies has the potential to provide a much tighter constraint on the duration of impact episodes. It is available for only two pairs of craters: the 150 km Chicxulub crater in the Gulf of Mexico and the 24 km Boltysh crater in Ukraine, at the end-Cretaceous; and the 90 km Popigai crater in Siberia and the 40 km Chesapeake Bay crater in the eastern USA, in the Late Eocene. The end-Cretaceous craters are separated in age by $\lesssim 2500$ yr (Jolley *et al.* 2010), and the Late Eocene ones by 10–20 000 yr (Koeberl 2009). The latter pair may be joined by two other craters of similar age (Napier 2015); this episode is associated with a peak in cosmic dust input at 35.8 Myr ago, determined from helium-3 laid down in ocean sediments (Farley 2009).

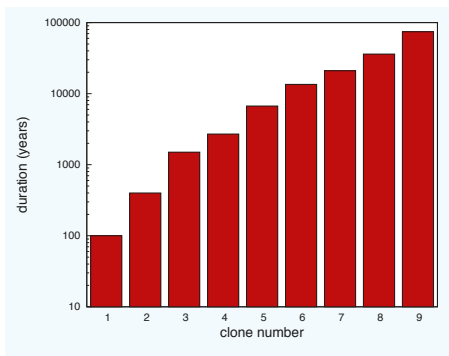
Chicxulub is the largest crater in the dataset of 41 impactors employed. Monte Carlo trials reveal that the odds of its near-synchronicity with a crater at least as large as Boltysh are 2500:1 against. The odds that Popigai, the second largest, coincides in time with a crater as large as that at Chesapeake Bay are around 1000:1 against.

These near-synchronicities are difficult to reconcile with the impactors as fragments arriving from the disintegration of a main-belt asteroid (lasting ~ 5 – 100 Myr), or as independent comets, even within a comet shower (duration ~ 2 Myr). They are most easily understood in terms of the arrival and disintegration of a Chiron-sized Earth-crossing comet, in a Jupiter family or Encke-like orbit, into hundreds or thousands of short-lived cometary fragments. Di Sisto *et al.* (2009) showed that the perihelion distribution q of the current Jupiter family population requires strong

erosion at small q to match the observations, along with a high rate of cometary splittings and outbursts. Such evolution is to be expected for the Jupiter family throughout geological history.

The Popigai/Chesapeake Bay impactors had different chemical compositions, H and L chondrite respectively, which is not easily reconciled with their provenance from the break-up of a single asteroid. The near-synchronicity of two large, unrelated asteroids is dynamically unlikely even as part of a break-up event in the main belt (and no asteroid family at that date is known). The distinct compositions may be consistent with the break-up of a contact binary comet formed from a gentle merger, as appears to be the case with 67P/Churyumov-Gerasimenko (Rickman *et al.* 2015), a morphologically diverse comet (Thomas *et al.* 2015). The elemental abundance of material recovered from Comet 81P/Wild 2 by the Stardust spacecraft was that of CI chondrites, with the presence of minerals formed at high temperatures indicating large-scale radial mixing of material at its time of formation. This opens up the prospect that large comets may form by the aggregation of building blocks from a variety of locations, but their provenance, chemical and isotope compositions are too uncertain for strong statements. A group of large near-Earth asteroids, in orbits similar to that of 2P/Encke, have spectra matching those of ordinary chondrites

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“Large comets may form by the aggregation of building blocks from various locations”



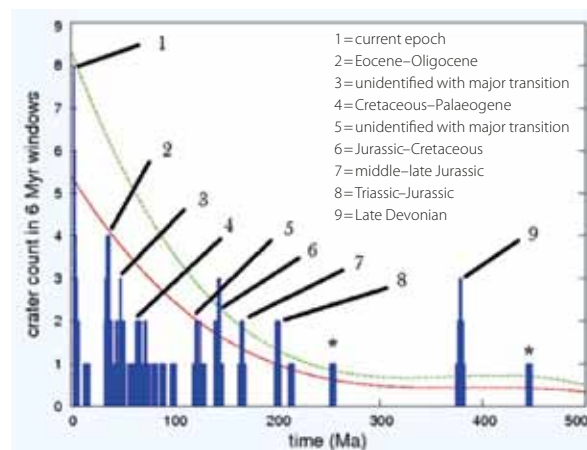
2 The integrated durations of the $q < 1$ au phases for nine clones based on the orbit of (2060) Chiron.

(Popescu *et al.* 2014). Five bright Taurid fireballs observed between 2010 and 2012, of undoubted cometary provenance, had spectra compatible with a chondritic composition (Madiedo *et al.* 2014).

Figure 3 reveals an apparent gap in the impact record between 5 and 35 Myr ago. This dearth extends to the 184 impact structures in the Earth Impact Database: only the 24 km Ries crater, from an achondritic impactor, is securely placed in this time interval. Models involving random arrival times suggest that about 50 impacts capable of forming a crater >20 km across should have taken place over this period, 17 of them on land (Bland & Artemieva 2006). For such a recent interval, most craters should have been identified. The probability is ~ 0.001 that such a gap would exist by chance anywhere during the interval 0–100 Myr. Conversely, there seems to have been an enhancement in impact cratering in the past 5 Myr relative to the longer-term average. Such dips and surges suggest that the largest impactors are derived from the break-up of large comets, because their mass distribution is top-heavy and their input is erratic and episodic. To the contrary, Menichella *et al.* (1996), dynamically modelling the supply from the main belt of near-Earth asteroids down to bodies 0.1 km across, find that the population is unlikely to vary by more than a factor of two over timescales of 10 Myr and longer.

A 100 km comet has a mass ~ 100 times that of the contemporary NEO population, and entry of such a body into a short-period, Earth-crossing orbit is anticipated with a characteristic timescale ~ 30000 yr. This timescale estimate is conservative because non-gravitational forces were neglected, these increasing the rate of transfer into orbits uncoupled from Jupiter by a factor of a few (Asher *et al.* 2001). The current clearance time of the zodiacal dust cloud is ~ 20000 yr as a result of the Poynting–Robertson effect and collisional processes (Grün *et al.* 1985, Steel & Elford 1986). It is thus reasonable to expect that the zodiacal dust cloud will be subject to

3 (Right) Probable bombardment episodes identified in Napier (2015). In addition, two single craters, marked by asterisks, coincide within dating uncertainties with the Permo–Triassic (250 Ma) and Ordovician–Silurian extinctions. The curves are cubic fits to the data; there is no unique best fit. The decline in crater numbers as one goes into the past is presumably due to subduction, erosion and overlaying by sedimentation.



large fluctuations, following the arrival and disintegration of large bodies, and that the remnants of a large comet may still be orbiting among the overall NEO population (Clube & Napier 1984), which includes not only near-Earth asteroids, but also boulder- and meteoroid-sized objects down to submillimetre dimensions. Such appears to be the case, as we indicate below; we also discuss the implications over timescales relevant to civilization.

The Taurid Complex

The Taurid meteoroid stream has long been recognized as an ancient, widely dispersed system through which the Earth takes several weeks to pass each year, in contrast to most meteor showers, which persist for only a few days. It can be separated observationally into northern and southern branches, radiants being a few degrees above and below the ecliptic (e.g. Wright & Whipple 1950, Štohl & Porubčan 1992). There are four branches in all (figure 4), post-perihelion encounters producing day-time meteors: the ζ Perseids radiate from north of the ecliptic, the β Taurids from south. Planetary perturbations over millennia cause the argument of perihelion ω of a Taurid-type orbit to cycle through 360° (Whipple 1940), so that all ω values are now present within the stream, which we term the Taurid Complex (TC). The four shower branches represent the Earth-intersecting cross-sections of the TC.

To develop the range of ω precession required to span the four branches takes ~ 5 kyr (Babadzhanov *et al.* 1990, Babadzhanov & Oubrov 1992). In fact precession has occurred through more than one complete ω cycle, with a full cycle before the main four Taurid branches and a cycle after; correspondingly longer than 5 kyr is required. The observed night-time showers are known as Piscids (the ω cycle before) and χ Orionids (after), both with northern and southern branches (Olsson-Steel 1987, Babadzhanov *et al.* 1990, Babadzhanov & Oubrov 1992). Further, a correlation of semimajor axis with longitude

(Babadzhanov *et al.* 1990, Steel *et al.* 1991, Porubčan & Kornoš 2002) is apparent in accurate, double station TC meteor orbits. Babadzhanov *et al.* computed that up to 18 kyr is needed to induce this relative longitude precession. This may be taken as a lower age limit for a system. The TC is embedded in the broader and more massive (Štohl) sporadic stream, although if we regard the TC as broad enough to contain 12 showers over three ω cycles then there is no precise dividing line, the terms TC vs Štohl simply describing a more-structured versus somewhat more-dispersed stream. Overall we can associate a timeframe of ~ 20 kyr for the formation of this broad complex of meteoroids on cis-jovian, moderate eccentricity ($e \sim 0.8$) orbits. This is also consistent with the 10–20 kyr required for dynamical evolution into small- q orbits so as to explain the observed excess calcium emission in Mercury’s exosphere as being due to the TC (Christou *et al.* 2015).

Splitting events and multiple fragmentations are a prime disintegration route for comets (Sekanina 1997, 2002, Sekanina & Chodas 2004, Williams 2011). By studying the association of dormant comets with meteoroid streams, Jenniskens (2008a, 2008b) argued that discrete break-up/fragmentation events dominate continuous cometary activity in the creation of streams and indeed comprise the main replenishing source for the zodiacal cloud. This is in line with the finding of Di Sisto *et al.* (2009) that the observed structure of the Jupiter family of comets is best explained by physical disintegration as well as dynamical evolution, with splitting a major process. With the passage of time, meteoroids – lose the memory of their origins, and merge into the zodiacal cloud, becoming sporadics. A long-standing issue is that the zodiacal cloud is substantially overmassive in relation to current inputs, which largely come from short-period comets, in particular 2P/Encke. The idea of a zodiacal cloud imbalance has a long history, Hughes (1996) concluding that “at some time in the last 10^3 to

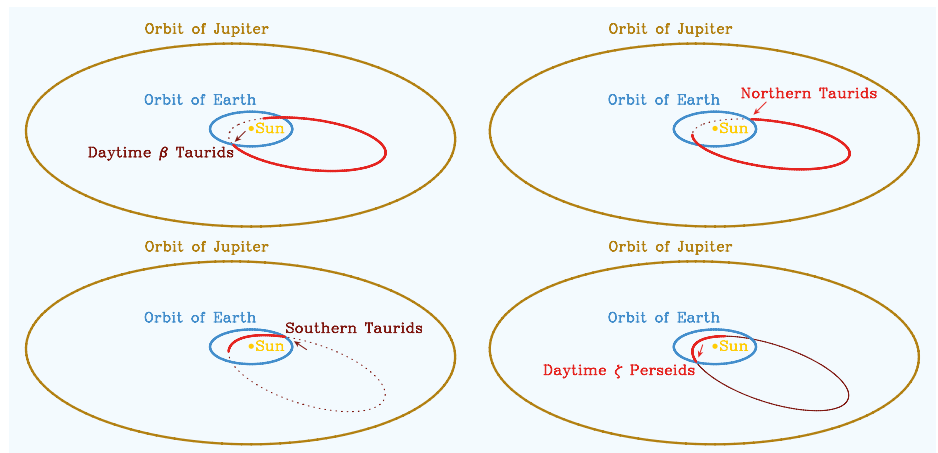
10^5 yr, the cloud has benefited from a large and unusual mass enhancement”, in accord with long-term fluctuations in its mass deriving from a simple model of comet arrival and disintegration (Napier 2001).

Radar and optical studies indicate that the current zodiacal cloud has a total mass $\sim 4 \times 10^{19}$ g, to within about 50%. Around 10^{20} g of material (cf. Whipple 1967, Hughes 1996) must have been supplied to the zodiacal cloud on 10^4 yr timescales. The presence of the Štohl stream suggests that the TC progenitor is the cometary source. The latter cannot be supplied by 2P/Encke in its present state, whose mass loss is only about one-hundredth of that required for steady-state replenishment (Nesvorný *et al.* 2011). The dominance and structure of the TC in the zodiacal cloud suggests that the bulk of it has been supplied by the hierarchic disintegration of an erstwhile large comet. If assembled into a single body of bulk density 0.4 g cm^{-3} and an equal mass of lost volatiles is assumed, a progenitor comet of diameter ~ 100 km is implied. An early estimate of 25–30 km was given by Sekanina (1972), provided the 2P/Encke progenitor was captured ~ 20000 years ago. How much material has been lost altogether is unknown; the possibility that the progenitor of the TC was rather larger cannot be excluded.

Interplanetary dust

Analysis of the ages of the lunar microcraters (“zap pits”) on rocks returned in the Apollo programme indicate that the near-Earth interplanetary dust (IPD) flux has been enhanced by a factor of about ten over the past ~ 10 kyr compared to the long-term average, if one assumes that the heavy ion solar cosmic ray (SCR) flux has been constant. The IPD flux and its time-variation were inferred from the SCR-produced nuclear track densities in the melt-glass floors of the microcraters, which allow them to be dated, Hartung & Storzer (1974) suggesting that the abundance of such young microcraters might be linked to the arrival of the progenitor of 2P/Encke. Measurements of the space-exposure ages of IPD collected in the stratosphere ($\sim 10^4$ yr: Bradley *et al.* 1984) provide supplementary support for this notion. Zook (1978) argued to the contrary, postulating that the IPD flux has been more-or-less constant, and it is the SCR flux that has varied – without support from solar physicists.

The TC population extends upwards to macroscopic (asteroid-sized) bodies (Asher *et al.* 1994, Napier 2010), some of which have meteor showers associated with them (Babadzhanov 1998, 2001, Babadzhanov *et al.* 2008). 2P/Encke is a 5 km diameter comet (Boehnhardt *et al.* 2008) and the mass in the TC and Štohl stream, including large



4 Four Taurid Complex branches (meteor showers). The separation into branches is not real within the physical stream; it is an artifact of the fact that the Earth’s path in space only intersects orbits with particular parameters: for a given size and shape of orbit, the argument of perihelion ω must take one of four values, corresponding to northern and southern branches, before and after perihelion. Part of orbit above ecliptic drawn thicker, solid; part below ecliptic thinner.

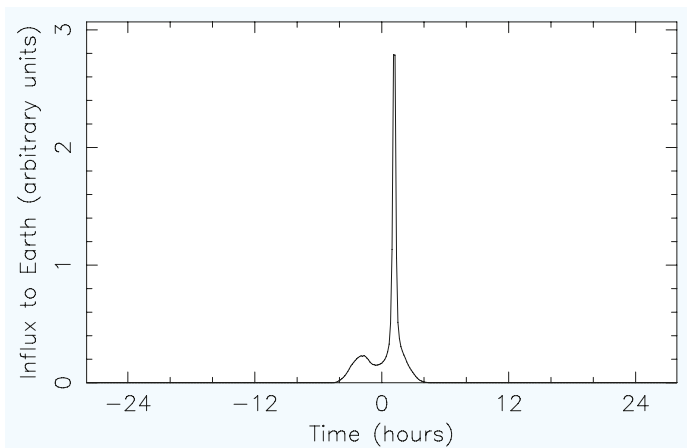
objects, is 2×10^{19} g (Asher *et al.* 1994, Napier & Asher 2009). The disintegration of the original progenitor comet thus appears to have given rise to a hierarchy of fragmentations, including debris trails as well as short-lived comets. In summary, a total mass loss, first into the TC and then via the Štohl stream into the zodiacal cloud, of 10^{20} g in the past ~ 20 kyr may be deduced.

As well as splitting, sublimation is a major route of cometary disintegration. The zodiacal cloud is fed by way of debris trails, which are a common feature of short-period comets. The trails are dominated by millimetre-sized particles, although a fly-by of 103P/Hartley 2 revealed that icy fragments of 15–20 cm dimensions were being ejected from its surface (A’Hearn *et al.* 2011), and metre-sized bodies in bound orbits have been detected close to the nucleus of 67P/Churyumov-Gerasimenko (Rotundi *et al.* 2015). The maximum size of dust aggregate that can be lifted from a comet comes from a balance between gravity and sublimation (gas outflow) pressure; in the case of a comet, say, 50 km in diameter in an Encke-like orbit, metre-sized fragments may be released around perihelion. These, and smaller (\sim cm) meteoroids, are then collisionally eroded (on timescales of order 10^4 yr: Steel & Elford 1986) to produce a major fraction of the zodiacal dust cloud. If the zodiacal cloud were, say, 100 times as massive as the current one, erosion would be more rapid, and icy aggregates up to metre dimensions could be lost on that same timescale (Napier 2004). Numerical modelling reveals that, without replenishment, radiative and collisional processes will reduce the mass of a substantial zodiacal cloud by an order of magnitude within this 10^4 yr timescale (Napier 2001), although particles of high tensile strength may persist for longer.

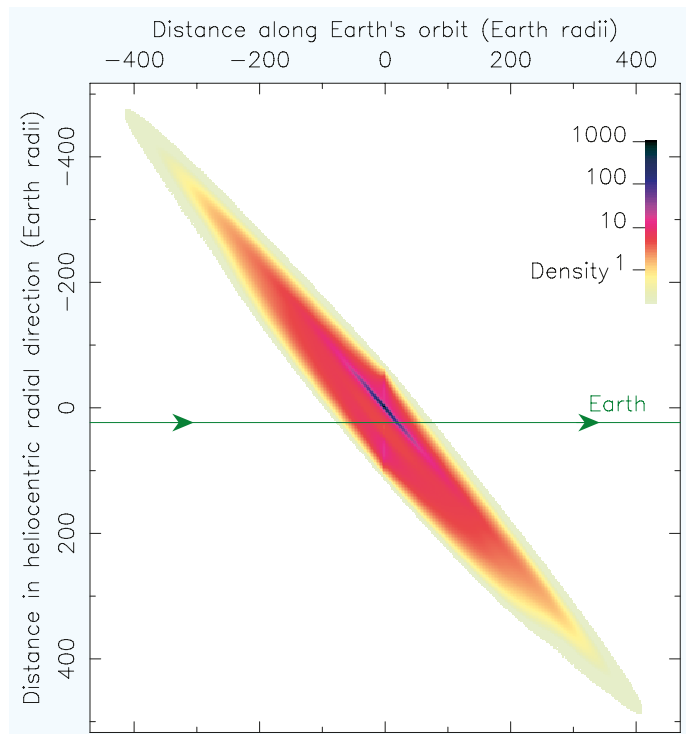
Concentrations of material within the debris trails persist due to resonances, leading to episodes of high-intensity bombardment when the Earth runs through such material. The most prominent meteoroid swarm impacting the Moon during the years of the Apollo seismic experiment occurred in late June 1975 (Oberst & Nakamura 1991), coinciding with the β Taurid shower: as many boulders struck the Moon over a five-day period as struck it over the other five years of the experiment’s data collection. This, along with evidence of the night-time Taurids having higher activity in specific years (Asher & Izumi 1998, Beech *et al.* 2004, Johannink & Miskotte 2006, Dubietis & Arlt 2007), indicates that there are concentrations of material in the TC. The years of this higher observed activity are as predicted if a meteoroid swarm exists in the 7:2 jovian resonance (Asher & Clube 1993), a strong dynamical influence in the TC (Soja *et al.* 2011).

The dust trail observed by IRAS in the thermal infrared (Sykes *et al.* 1986) close to 2P/Encke’s orbit may be interpreted in terms of the same resonance (Asher & Clube 1993), implying that the material released in the present epoch occupies orbits well away from Earth intersection. In any epoch, the TC’s densest region will comprise a concentrated trail close to the parent orbit. Orbital precession, specifically the ω precession described above, brings this trail or core to Earth intersection during particular epochs: the ω intersections occur in pairs a couple of centuries apart, successive pairs separated by a few millennia (Asher *et al.* 1994, Steel & Asher 1996).

Given the presence of such a large, disintegrating comet in our environment throughout the Holocene and earlier, we may ask about the probability and



5 Recently released cometary material is not dispersed evenly into the comet's debris stream, but remains concentrated within dense, narrow trails. Shown is the density profile (cross-section in the ecliptic plane, then along Earth's assumed path) within a Taurid trail, computed following Asher (2008). Earth is likely to have passed close to the centre of a Taurid trail once or more during the Holocene.



consequences of passage through a debris trail. While trail cross-sectional shapes vary from stream to stream (Asher 2010, Asher & Steel 2012), the common feature is a high spatial density of meteoroids if Earth encounters a trail's central region. The Leonid meteor storms (Brown 1999) prove that meteor activity from a stream need not be uniform, and that substantial fractions of the total mass input can arrive during the Earth's rare, deep encounters with dense trails (Kondrat'eva & Reznikov 1985, McNaught & Asher 1999, Lyytinen & Van Flandern 2000). Figure 5 shows a Taurid trail cross-section and an example traverse through it by the Earth. Overall we should expect enhanced mass influxes during TC ω -intersection epochs. For a 10^{20} g comet undergoing a hierarchical disintegration across $\sim 10^4$ yr, there is an expectation of one encounter (or at most a few) with a debris trail sufficient to dump $\gtrsim 10^{14}$ g (cf. Napier 2010 section 3) into the atmosphere.

Terrestrial consequences

The effects of running through the debris trail of a large comet are liable to be complex, and to involve both the deposition of fine dust into the mesosphere and, potentially, the arrival of hundreds or thousands of megaton-level bolides over the space of a few hours. Incoming meteoroids and bolides may be converted to micron-sized smoke particles (Klekociuk *et al.* 2005), which have high scattering efficiencies and so the potential to yield a large optical depth from a small mass. Modelling of the climatic effects of dust and smoke loading of the atmosphere has focused on the injection of such particulates in a

nuclear war (Crutzen *et al.* 1984, Robock *et al.* 2007). Dusting of this intensity is expected to reduce the level of sunlight to that of moonlight, and result in a global cooling sufficient to destroy commercial agriculture (Robock *et al.* 2007). Such work has implications for atmospheric dusting events of cosmic origin, although there are significant differences, of course. Hoyle & Wickramasinghe (1978) considered that the acquisition of $\sim 10^{14}$ g of comet dust in the upper atmosphere would have a substantial effect on the Earth's climate. Such an encounter is a reasonably probable event during the active lifetime of a large, disintegrating comet in an Encke-like orbit (Napier 2010). If the meteoric smoke has absorption coefficient $\kappa \sim 10^5$ cm²g⁻¹, comparable with that of soot, then passage through $\sim 10^{14}$ g of dust would yield a veil of substantial optical depth for as long as the smoke persisted (Hoyle & Wickramasinghe 1978). The effect is comparable with the darkening expected from an asteroid land impact of energy 10^6 megatons, expected at ~ 2 Myr intervals according to Chapman & Morrison (1994).

Societal collapses in antiquity often followed abrupt climatic coolings of unknown origin, persisting for decades and leading to drought and famine (Weiss & Bradley 2001). Two such collapses have been linked, albeit controversially, with cosmic disturbances. Around 2350 BC the earliest civilizations, throughout the near East, northern India and China, collapsed simultaneously, apparently driven by cooling and drought. Courty *et al.* (2007) have found evidence for the dispersal of hot, viscous impact ejecta over hemispheric dimensions (Peru, Spain, Syria etc) at this time, with nanodiamonds

and other geochemical anomalies that they attribute to an oceanic impact in the southern Indian Ocean. Estimates of the duration of the cooling vary from a decade to two centuries.

It has been proposed that a sudden global cooling at 12800 BP, which persisted for 1300 years, led to cultural reorganizations of earlier societies in southwest Asia (Moore *et al.* 2000) and North America (Anderson *et al.* 2011), and a substantial decline of large mammals in North America, Europe and Australia. This event, at the Younger Dryas (YD) boundary, was accompanied by a peak in microspherule deposition over at least that 10% of the Earth's surface so far investigated (Wittke *et al.* 2013), the presence of high-temperature melt glass ($>2100^\circ\text{C}$) at several locations, a thin carpet of nanodiamonds laid down synchronously (to within ~ 100 yr) with the onset of the cooling (Kinzie *et al.* 2014, Kennett *et al.* 2015), a large platinum spike of non-terrestrial provenance in the GRIP ice core (Petaev *et al.* 2013), and other indicators of cosmic disturbance. There is additionally an abundance of charcoal and soot at the boundary, likely to be indicative of extensive wildfires. Sharp ammonium and nitrate spikes in Greenland ice cores, the largest in 300 000 years, have been linked to this boundary; these may have been produced by extensive biomass burning, atmospheric chemistry induced by incoming fireballs, or direct deposition of cometary material (Melott *et al.* 2010). Whatever their origin, they confirm that the YD cooling was an exceptional event over at least this timescale. To match the 1300 yr cooling of the YD, a quasi-equilibrium perturbation

2 Bombardment episodes

diameter (km)	in	out
>20	15	7
10–20	4	6
3–10	6	3

Membership of bombardment episodes for the 41 accurately dated terrestrial impact craters. There is no evidence of a systematic trend with diameter.

of the terrestrial environment induced by such comet dusting would be required, as proposed by Hoyle (1981), but no one mechanism on its own explains the YD cooling (Renssen *et al.* 1981).

Apart from their effects on atmospheric opacity, a swarm of Tunguska-level fireballs could yield wildfires over an area of order 1% of the Earth's surface (Napier 2010). Large comets in Encke-like orbits may sporadically generate a substantial population of small, albeit short-lived, impactors. To test this idea, the 41 craters culled from the Earth Impact Database were divided by membership of bombardment episodes and crater diameter. The

results are shown in table 2. The statistics reveal no significant difference between the temporal behaviour of large and small craters over the size range tested, 3 km upwards, corresponding to bolides of ≥ 200 m dimensions. On this evidence, large comets arrive accompanied by a flotilla of fragments, and we do not receive a steady rain of small bolides through time. Further evidence of current nonequilibrium among the sub-km meteoroids comes from the fireball study of Brown *et al.* (2013), who find that the number of impactors with diameters of tens of metres may be an order of magnitude higher than estimates based on telescopic surveys and lunar counts. They suggest that there is a departure from equilibrium in the NEO population for objects between 10 and 50 m in diameter. The current Tunguska-level rate inferred from their study is in line with an assessment based on lunar impact counts (Asher *et al.* 2005). All three major 20th-century impacts (Tunguska, British Guiana, Curuçà River) coincided with our passage through major meteoroid streams (respectively the β Taurids, Geminids and Perseids); the odds against this arising by chance are about 1000:1 (Napier & Asher 2009).

Other existential hazards

The main existential hazards to be faced over the next few centuries are likely to be anthropogenic (Bostrom 2013), but these can in principle be countered. No natural existential risks are known to be imminent, although solar superflares and cometary encounters are currently unpredictable. A centaur arrival carries the risk of injecting, into the atmosphere, from above, a mass of dust and smoke comparable to that assumed in nuclear winter studies. Thus, in terms of magnitude, its ranking among natural existential risks appears to be high. Further, according to the analysis presented here, such events happen at least a hundred times more frequently than globally incinerating asteroid impacts. Whether the calamities at 2350 BC and 12800 BP were in fact due to passages through cometary debris is a matter for further enquiry; irrespective of this, there is a need for a more thorough exploration of the centaur population from both theoretical and observational points of view, and for a better understanding of the environmental consequences of encountering a dense complex of cosmic dust and meteoroids. ●

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DEDICATION

This article is dedicated to the memory of Ernst Öpik (1893–1985), a long-term staff member at the Armagh Observatory, on the 30th anniversary of his death.

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