The Tunguska impact event and beyond

Bill Napier and David Asher discuss the Tunguska event of 1908. **Assessing the impact hazard requires an understanding of the effect of the solar system's galactic environment on the Oort comet cloud.**

Abstract

Current strategies for dealing with the impact hazard are geared towards the detection and deflection of near-Earth asteroids, which typically have approach speeds ~20 km s^{-1} and involve decades of warning. However, galactic signals in the age distribution of well-dated impact craters suggest that the globally destructive impactors (diameters between 1.5 and 2 km and upwards) ultimately derive from the Oort cloud. Warning times are then measured in months or days, and characteristic approach speeds are ~55 km s^{-1}. Concentrations of sub-kilometre debris in meteor streams may also be a significant regional hazard. Intersection with the debris of a large short-period comet may account for the widespread biological and cultural dislocation in North America around 12 900 BP.

Table 1: Possible impact effects based on energy

	10 000 Mt	1 million Mt	100 million Mt
impactor	500 m	1–2 km	10 km
scope	regional	civilization-destroying	species-destroying
land	fires, blast, and earthquake over 250–1000 km	destructive blast, quake and possibly fire over continental dimensions	global conflagration and destructive earthquake
sea	uncertain	(mega)tsunamis around ocean rims	ocean rim devastation; cities replaced by mudflats; oceans acidified
air	Sun obscured	agriculture collapses; ozone depletion; acid rain; sky darkened for years	land and sea ecologies collapse; ozone depletion; acid rain; sky black for years
climate	possible brief cooling	global warming followed by sharp cooling	global warming followed by cosmic winter

Uncertainties attend all these thumbnail descriptions. Timescales are also open to debate, as discussed in the text.

The Tunguska impact of 30 June 1908, which destroyed 2000 square kilometres of conifer forest in a sparsely populated region, the Central Siberian Plateau, had the energy of a large hydrogen bomb (figure 1). No meteorite crater associated with it has been securely identified. A number of conferences in Moscow, held around the centenary of the event, brought home that even this fairly recent, much explored impact holds many mysteries.

It is occasionally pointed out that if the 1908 impact had taken place over a metropolitan area, huge damage would have been inflicted. In the case of an impact on London, a bolide brighter than the Sun, and leaving a thick trail of smoke, would have been seen approaching from half way across France. The gunfire-like bangs of the impact would have been heard across Britain to Ireland, north to Orkney and Denmark, and over Europe as far as Switzerland. People would have had their hats knocked off in Glasgow and Edinburgh, topsoil would have been stripped from fields in Cheshire, trains would have been derailed throughout central England, and people in Oxford would have been thrown through the air and severely burned. An incandescent column of matter would have been thrown 20 km into the air over London, and the city itself would have been destroyed about as far out as the present-day M25 ring road. The political ramifications that would have followed the destruction of Edwardian London are a matter for speculation; one may question whether the British Empire would have survived.

The impact energy of the event remains uncertain. It might have been as low as 3 Mt (megatons TNT equivalent) – some simulations suggest this, with fierce vortex winds responsible for destroying an already weak Siberian forest. On the other hand, seismic and barometric data have consistently been interpreted as pointing to a higher impact energy, typically 10–15 Mt (Ben-Menahem 1975). The occurrence of 20 impacts from a fragmented comet, D/1993 F2 (Shoemaker-Levy 9), on Jupiter as recently as July 1994 demonstrates that planetary impacts are common at high energies too – the characteristic energy of the fragments was about 100 000 Mt (Asphaug and Benz 1996), enough to cause devastation on continental scales on Earth.

Estimates, all of them uncertain, have been made of the damage expected from impactors of various sizes (see table 1). The threshold for a civilization-destroying impact, killing over a billion people, comes in at a 1 or 2 km diameter bolide. Above a certain energy (~10^6 Mt), vaporized material thrown out from the impact punches out through the atmosphere and spreads globally. Everywhere on the surface of the Earth, the sky is red hot and a global conflagration results. Once the initial heat pulse has passed, micron-sized dust particles and vapour condensates in the atmosphere may take characteristically between 1 and 10 years to settle down, collapsing food chains in the meantime. And, because about 100 million people live within 2 km of a shoreline, large ocean impacts have the potential to cause severe tsunami devastation.

Nature of the Tunguska bolide

If we rule out crashed spacecraft, black holes, antimatter particles, natural H-bombs and

1: The explosion due to an incoming cosmic body over the Tunguska region of Siberia in 1908 flattened trees over 2000 square km.

geophysical explosions as causes of the Tunguska impact, we are down to a comet or asteroid.

In 1930, the British meteorologist F J W Whipple suggested that the Tunguska body was a small comet, and this view has generally been supported by Russian astronomers. Hughes (1976) likewise considered that the object was probably a small comet. The American astronomer Fred Whipple (1975) – not the meteorologist – thought it more likely that the bolide was an inactive, low-density, friable body. The suggestion by Kresák (1978) that the body was a fragment of the short-period comet 2P/Encke, and therefore part of the Taurid Complex, was supported by the coincidence in the date of impact (30 June) with the Earth's annual passage through the daytime β Taurids. The trajectory of the bolide moreover lies within 20° of that of the comet, a difference explicable by planetary perturbations (Asher and Steel 1998). Sekanina (1983), however, argued that a body composed of weak cometary material could not have survived intact on a journey into the lower atmosphere, and proposed instead that the object was dense and rocky, probably from the asteroid belt.

Recent hydrocode simulations by both Russian and American groups revealed that, from the perspective of impact mechanics, the object could have been either cometary or asteroidal. The forward momentum of a large fireball breaking up even at high altitude can bring it close to the ground. The severe dearth of cosmic material on the ground may be due to the updraught of the fireball, which forms a rapidly rising, near-spherical plume. Debris from the plume may be spread over about 1500 km, and scattered sunlight from this debris could account for the widely reported reading of newspapers, overnight cricket, midnight photography and the like during the night of 30 June 1908 in England. The simulations show that the object could have been a 50–60 m diameter stony asteroid, or an 80–100 m comet: either would produce similar effects at the Tunguska site. A 70 m comet falling vertically could reach the ground, whereas one up to 1 km across, coming in at 5° to the horizontal, would unload nearly all its kinetic energy into the atmosphere.

An interesting debate has been stimulated as to whether there is in fact an impact crater at the site. A group in Bologna (Gasperini *et al.* 2007) has suggested that Lake Cheko, a 300 m lake 8 km downrange from the epicentre, may be such. It is steep-sided and bowl-shaped, and cone-shaped at depth. It does not seem to be a meander lake or volcanic depression, and it is not shown on an 1883 map of the area. A seismic anomaly exists just below the bed of the lake. On the other hand, there is no evidence around the lake of high shock pressure or temperature and no sign of ejected material. Further, it seems that no trees were affected by the postulated impact even at the edge of the lake. Numerical simulations by Collins *et al.* (2008) have failed to reconcile these conflicting factors.

Analyses of peat columns in the catastrophe layers have revealed isotopic composition shifts for carbon-13 and deuterium in addition to enhanced iridium and enriched siderophile elements. These have been interpreted as evidence of a cometary origin for the Tunguska cosmic body (Kolesnikov and Rasmussen 2008).

Impact frequencies

Estimates of Tunguska-like impact frequencies have varied enormously over the years. Kresák (1978), extrapolating from fireball data, thought that such events might happen at about 50-year intervals. Hughes (1976) considered them to be once in 2000-year events on the assumption that the impactor was a small active comet, a figure which has also been derived on the basis of Spaceguard survey observations (table 2).

What appear to be records of similar impacts are to be found throughout early mythological literature. Hellenistic myth, for example, includes the story of Phaethon, who borrowed the chariot of his father Helios, but was unable to control its horses as they crossed the sky, with the result that the chariot crashed to the ground in a blinding light, flattening and burning forests, poisoning rivers and darkening the sun. Various commentators over the years have regarded these and similar myths as referring to one or more real events (Plato, Goethe, Kugler, Engelhardt). Similar tales are to be found in the earliest Sanskrit literature, throughout the near East and as far away as China. The earliest recorded literature containing such material is to be found in Babylonian cosmology, going back to 2000 BC but probably based on preliterate oral traditions. Megaton-class impacts may therefore have impressed themselves from time to time on early cultures.

Beginning in the 1970s, helped by satellite observations of the Earth and Schmidt telescope surveys, quantitative assessments of the impact rate became possible. One approach, then, is to extrapolate from the known impact craters on Earth, using some energy–diameter scaling relation.

Many impact craters are so large that they are not easily recognized from the ground, the crater diameters extending far beyond the visible horizon (as in the case of Lake Manicouagan in Quebec, which is about 100 km across). About 170 impact structures are known on Earth, with another dozen or so candidates. They are very unevenly distributed, being concentrated around the Baltic and Canadian Shields as well as desert areas. Throughout India, Pakistan, Tibet, China and the Far East, there is only one recorded impact crater: the Lonar Crater in central India, about 1 km across, 50 000 years old and already heavily eroded – it will disappear in the blink of a geological eye. Thus the data set of terrestrial impact craters is extremely incomplete. Moreover, sub-kilometre bodies will tend to disintegrate in the atmosphere and will be underrepresented in the impact cratering record. They may nevertheless generate damaging airbursts, and on timescales of immediate human interest may be the most dangerous class of impact.

Table 2: Impact frequency estimates

author	year	entity	collisions	method
Sekanina and Yeomans	1984	active comets	43 Myr (mostly $\gtrsim$1 km)	historic comet encounters
Bailey and Emel'yanenko	1998	Halley-type comets	"comparable with NEAs"	comet dynamics
Nurmi *et al.*	2001	captured Oort cloud comets	<200 000 yr (>1 km)	comet dynamics
Rickman *et al.*	2001	Jupiter family	~1 Myr (>1 km)	comet dynamics
Morbidelli *et al.*	2002	1000 Mt	63 000 ± 8000 yr	Spaceguard
Hughes	2003	1000 Mt	3000 yr	close encounters with NEAs
Stokes *et al.*	2003	LP/NEA	~1%	close encounters with comets
Stuart and Binzel	2004	10 Mt impacts	2000–3000 yr	Spaceguard
		1000 Mt	56 000 ± 6000 yr	
Asher *et al.*	2005	10 Mt impacts	<300 yr	lunar meteorites
		1000 Mt	500–5000 yr	close encounters with NEAs

Estimates of impact frequencies at various energy levels, from various approaches. NEA = near-Earth asteroids; LP = long-period comets.

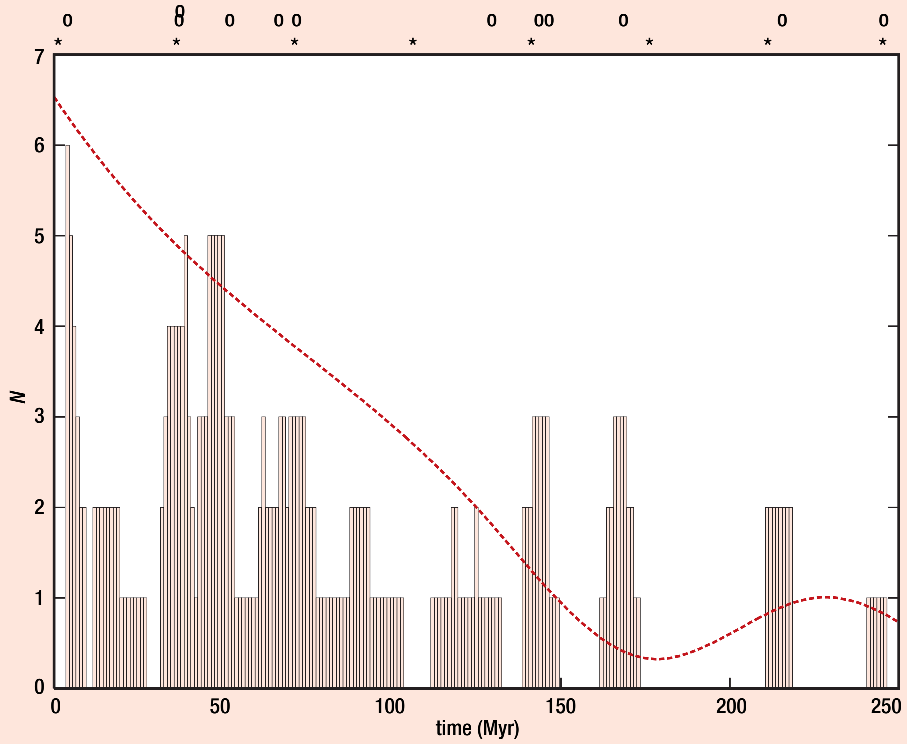
Estimates of the collision hazard posed by interplanetary bodies on short timescales may be arrived at in other ways. One procedure is to extrapolate the known population of near-Earth objects (NEOs) currently being revealed by several comet and asteroid search programmes (such as the Spacewatch, LINEAR and Catalina surveys). From these surveys, it is generally considered that completeness of discovery has now approached 100% for bodies >3 km in diameter, ~80% for >1 km diameter, declining rapidly to a fraction of a percent for objects around 100 m or less.

A movie of the known NEOs (an animation by Scott Manley is at http://star.arm.ac.uk/neos/anim.html) would reveal that there is a brisk movement of material between the main asteroid belt and the inner planetary system. It is known furthermore that asteroids deflected from the main belt on timescales ~10^6 yr (Morbidelli 1999) are a prime source of hazardous bodies. Generally missing from such movies are comets; and yet the number of NEAs (near-Earth asteroids) more than about 5 km in diameter capable of striking the Earth is tiny – at present the only bodies in Earth-crossing orbits with diameters of this order are comets. It may be that below a certain threshold, asteroids diverted from the main belt are the prime hazard, while above this, comets are dominant.

By some accounts, long-period comets are responsible for only ~1% of terrestrial impacts (Stokes *et al.* 2003). Considering that the end of civilization, and perhaps even the human species, might be at stake, even this background hazard may be seen as a matter for concern. Moreover, others set the "global catastrophe" comet impact rate at a level comparable with that of the NEAs (Bailey and Emel'yanenko 1998), and perhaps even dominant (Rickman *et al.* 2001).

To understand the hazard better, we need to know the relative contribution of asteroids and comets at different energy levels. This matters because, mass for mass, comets have an order of magnitude more impact energy (the mean impact speed of a comet in a Halley-type orbit is ~55 km s^{-1} as against ~20 km s^{-1} for an NEA); because the warning time for an incoming comet may be measured in months or weeks rather than centuries or decades as we would expect from a well-mapped out NEA population; and because dormant comets may be extremely hard to detect. Another consideration is that, although we could in principle map out hazardous bodies in asteroid-like orbits within a decade or two, mapping of a population of dark bodies in, say, high-eccentricity Halley-type orbits to 90% completion would take between 1000 and 2000 years with present-day technology. They thus constitute an essentially unpredictable hazard.

Table 2 lists various estimates of impact rates,



2: The age distribution of 40 impact craters 3km or more in diameter, with ages less than 250Myr known to precision better than 10Myr (data smoothed in this plot by a window of width 8Myr). Impacts occur in discrete episodes of bombardment. The circles represent the formation date for 12 craters over 40km across with ages measured to precision 2.6Myr or better. The asterisks mark out a best-fitting periodicity of ~35Myr for those 12. (See figure 5.)

their method of derivation and the nature of impactor or energy yield referred to. If we consider historic encounters with comets and close approaches with active comets, we find comfortably long intervals between collisions. Higher impact rates tend to be estimated from considerations of the migration or evolution between various sub-populations of comets that inhabit the planetary system. The number of bodies in a reservoir, and the rate at which they are calculated to transfer between reservoirs, yield theoretical estimates of population based on the assumption of equilibrium. These mass balance calculations lead to much higher impact estimates, typically by two powers of ten, than those obtained from direct observations of the arrival of active comets from the various reservoirs. Table 2 shows that this discrepancy holds even down to 10 Mt (Tunguska-sized) impactors.

If we consider close encounters of small interplanetary bodies with the Earth, which may be less subject to various modelling uncertainties, then the estimates of impact rate become substantially higher. A Tunguska-like impact then becomes something like a 300-year event, as against a 2000 or 3000-year one as deduced from Spaceguard surveys (the latter implying that such an impact a mere century ago was something of a statistical fluke). A more direct estimate comes from the three dozen or so meteorites ejected from the Moon and found in desert and Antarctic regions. Assuming that it takes a $\gtrsim$10 Mt impact on the Moon to dislodge material at escape velocity with the potential to land on Earth, and from the likeliest survival times on Earth, Asher *et al.* (2005) deduced a lunar impact rate which translated to Tunguska impacts at <300-year intervals on Earth.

In summary, there seems to be a discrepancy between what is inferred mainly from population dynamics of comets, and what is observed in the Spaceguard surveys.

A case study: IRAS-Araki-Alcock

In the NEO Science Definition Report of 2003, it was pointed out that only two comets passed within 0.1 AU of the Earth during the 20th century, as compared with 155 NEAs over the same period. Hence the impact ratio between comets and asteroids was taken to be 2/155, ≈1%. However, one of the two comets, C/1983 H1 (IRAS-Araki-Alcock), passed within 0.03 AU of the Earth (730 Earth radii), and so in terms of numbers the ratio is about 1/17. Further, comet IAA had dimensions of 11×7×7 km, close to that of 1P/Halley, and an encounter speed ~44 km s^{-1}. The impact energy of such a body would be ~200 million Mt. Clearly, in making the comparison, like is not being compared with like. Based on, for example, the Sekanina and Yeomans (1984) encounter rate with comets, such a passage involving an active comet of this size is expected about once in 5600 years, and the fact that the passage occurred in 1983 indicates that we are faced with either another statistical fluke or a hazard that is somehow being underestimated.

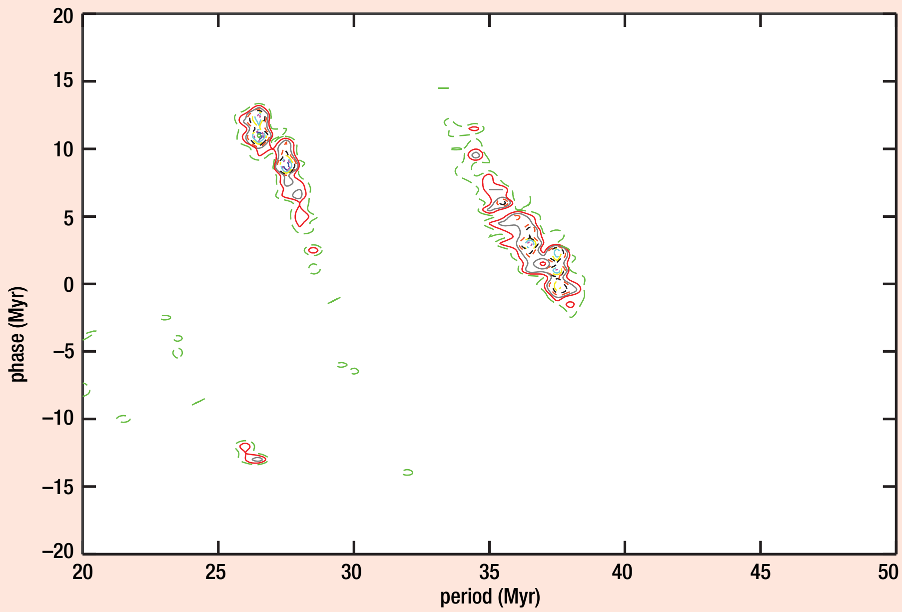
IAA was a peculiar comet with very low activity, only about 1% of its surface being active. It was discovered only two weeks before its closest approach to Earth. The suggestion here is that we may be dealing with a population of dark objects, carrying a lot of kinetic energy, which are not being properly picked up in the Spaceguard surveys.

A problem of mass balance

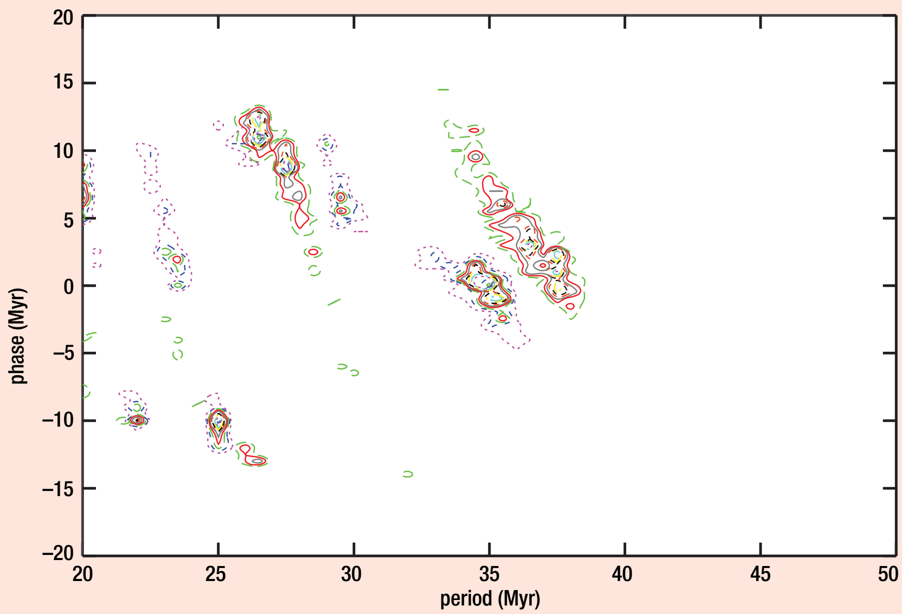
We know that about one bright comet (of absolute magnitude as bright as 7, comparable to Halley's Comet) arrives in the visibility zone (perihelion $q < 5$ AU, say) each year from the Oort cloud. It seems to be securely established that ~1–2% of these are captured into Halley-type (HT) orbits (Emel'yanenko and Bailey 1998). The dynamical lifetime of a body in such an orbit can be estimated, from which the expected number of HT comets is perhaps ~3000. The actual number of active HT comets is ~25. This discrepancy of at least two powers of 10 in the expected impact rate from comets as deduced from this theoretical argument on the one hand, and observations on the other, is an aspect of the well-known fading problem of cometary dynamics. A similar problem holds with regard to Jupiter family comets (orbital periods <20 years): many more dormant comets should exist in such orbits than are observed (Rickman *et al.* 2001).

Three ways in which comets might fade out have been discussed in the literature. Firstly, the comets may disintegrate to dust (Levison *et al.* 2002). To avoid conflict with observation, however, the disintegration needs to proceed with ~99% disruption efficiency within one or two perihelion passages, and this is not observed. Comets on the way out look much as they did on the way in: the archetype, Halley's Comet, has been reliably observed for almost 30 revolutions, and all the major meteor streams have an active or dormant source comet embedded within them. Another difficulty with the hypothesis is that the dust from the disintegrated comet would be observed as a glowing disc in the sky after sunset or before dawn. A third problem is that the greatest dearth of comets is found at larger perihelia, whereas one would expect disintegration to proceed most efficiently for comets that reach small perihelion distances (Rickman 2005).

Secondly, the comets may become dormant, developing dark mantles (Bailey and Emel'yanenko 1998). The problem here is that even for albedos $p \approx 0.04$, characteristic of the inactive surfaces on comets, the Spaceguard surveys should by now have detected ~400 dark comets >2.5 km across. However, only ~25, the



3: Retrieving the periodicity. The motion of the Sun around the galaxy has been simulated using galactic plane data derived from Hipparcos. The flux of comets from the Oort cloud varies pro rata with the local galactic tide and also has random components due to encounters with molecular clouds which exist preferentially in the galactic plane. Synthetic impact craters are extracted from the dynamical model, assuming impact probability to be proportional to the flux of comets from the Oort cloud, and taking account of the disappearance of terrestrial impact craters with time. The synthetic data are then analysed for periodicity (de-trending and applying power spectrum analysis to bootstrapped data). The inbuilt periodicity in the model is well retrieved ($P \approx 36$ Myr, $\phi \approx 2$ Myr). Phase ϕ is defined as the time elapsed since the most recent episode. Other sets of harmonic solutions sometimes arise, depending on the vagaries of the randomly selected data. In the example above a second group of solutions appears strongly, $P \approx 26$ Myr, $\phi \approx 11$ Myr. Interestingly, this is a close match to the periodicity which Raup and Sepkoski (1984) claimed to exist in the extinction record of marine families.



4: Bootstrap analysis applied to large (D>40 km) terrestrial impact craters. Within the range of uncertainty the most probable period and phase – $(P,\phi) \approx (35,0)$ Myr – are as expected from the dynamical model, but weaker harmonic solutions are also present.

Table 3: Impacts resulting from main belt asteroids

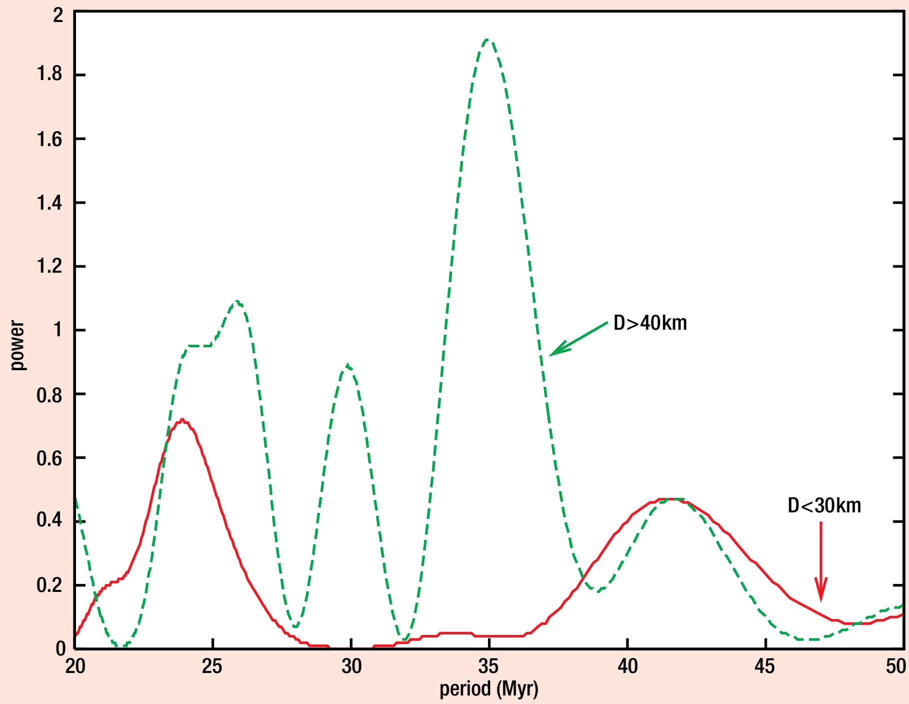
family	% hitting Earth	episode duration (Myr)	no. of >1 km impacts
Flora	1.5	30	4
Vesta	0.2	10	0
Eunomia	0.2	10	12
Gefion	0.02	5	2
Dora	0.02	5	2
Koronis	0.02	5	0
Eos	0.007	140	2
Themis	0.0026	90	3

Terrestrial impacts expected from main belt asteroid disintegrations over 10^8–10^9 yr (Zappalá *et al.* 1998). These generally cannot reproduce the sharpness and amplitude of the observed bombardment episodes.

so-called Damocloids, have been found so far.

Thirdly, the comets may develop super-dark mantles, with albedos $p < 0.01$ (Napier *et al.* 2004). This is possible if the comet nucleus becomes covered with organic grains ~10^{-5} cm comprising a bird's nest structure with porosity ~0.7 or more, consistent with that observed in Brownlee particles of probable cometary origin. If sublimation of ices leaves such a structure, then vanishingly small albedos become possible. The nucleus of Comet 19P/Borrelly has developed patches of albedo ~0.008, blacker than anything on Earth outside of nano-engineered surfaces, and if the entire nucleus became this dark we would probably not know that the comet existed. However, nearly all HT comets would have to become this dark for the problem to be solved. We do not yet know whether this happens.

The exact nature of the hazard due to this cometary material captured to HT orbits from the Oort cloud depends on the size of the individual bodies or fragments where the mass is predominantly hidden. For a randomly distributed population of N high-eccentricity bodies with orbital periods P years, the mean interval between collisions with the Earth is $\delta t \approx 330\, P/N$ Myr. For a population of $N = 3000$ dark bodies in HT orbits with $\langle P \rangle = 60$ yr, the current impact interval is then $\delta t \approx 7$ Myr. The long-term interval between such species-destroying impacts may be 30–60 Myr, but as we are currently immersed in an impact episode (figure 2), this temporarily high rate appears to



5: Power spectrum analysis of well-dated impact craters. There is a clear galactic signal among the 12 impact craters >40km in diameter, but little or none for smaller craters. The interpretation is that impacting bodies 1.5–2km across are comets – active or dormant – but that smaller craters are predominantly formed by impacting asteroids.

be compatible with the cratering record.

Hierarchic disintegration is a common mode of comet decay, and fragments that would make Tunguska-sized projectiles are a common product of these break-ups (such as in the Kreutz sungrazing family, just one example of a split comet). Such bodies, if dormant, would largely avoid telescopic detection. Could the fading problem be resolved by assuming that comets disintegrate into unseen Tunguska-sized objects with physical lifetimes in excess of their dynamical ones? While it is plausible that such bodies are produced, wholesale conversion of cometary mass to such bodies would yield Tunguska-like impacts at ~10 yr intervals.

The era of wide-area automated surveys has been under way for only about 10 years. If we are to extrapolate from such a short time base to impact probabilities at the 10^{-3}–10^{-6} per annum level, then statistical completeness becomes an issue: that is, we have to ask whether all significant types of hazard have manifested themselves over this period. The sporadic nature of comet disintegration, for example, is a potential source of failure of the "statistical completeness" assumption. Such disintegrations are not uncommon and may yield scores – and in extreme cases perhaps thousands – of sub-km fragments. These fragments may or may not be short-lived, but it is clearly necessary to see whether such events comprise a significant, and perhaps even dominant, impact hazard on timescales of interest to civilization. Otherwise we might be monitoring a swarm of bees while standing on a railway line with an express train due! The surveys themselves cannot answer questions about their own statistical completeness: we have to take a broader perspective.

It seems fair to say that, until we understand the fading problem, it would be unsafe to assume that the population of dark objects constitutes a negligible impact hazard at any energy level.

Signatures in cratering record

A quite different approach to the dark comet problem, which avoids the uncertainties involved in the fading function, is to look for galactic signatures in the impact cratering record. Since the main asteroid belt is impervious to galactic perturbations, any such signatures would be diagnostic of cometary impacts.

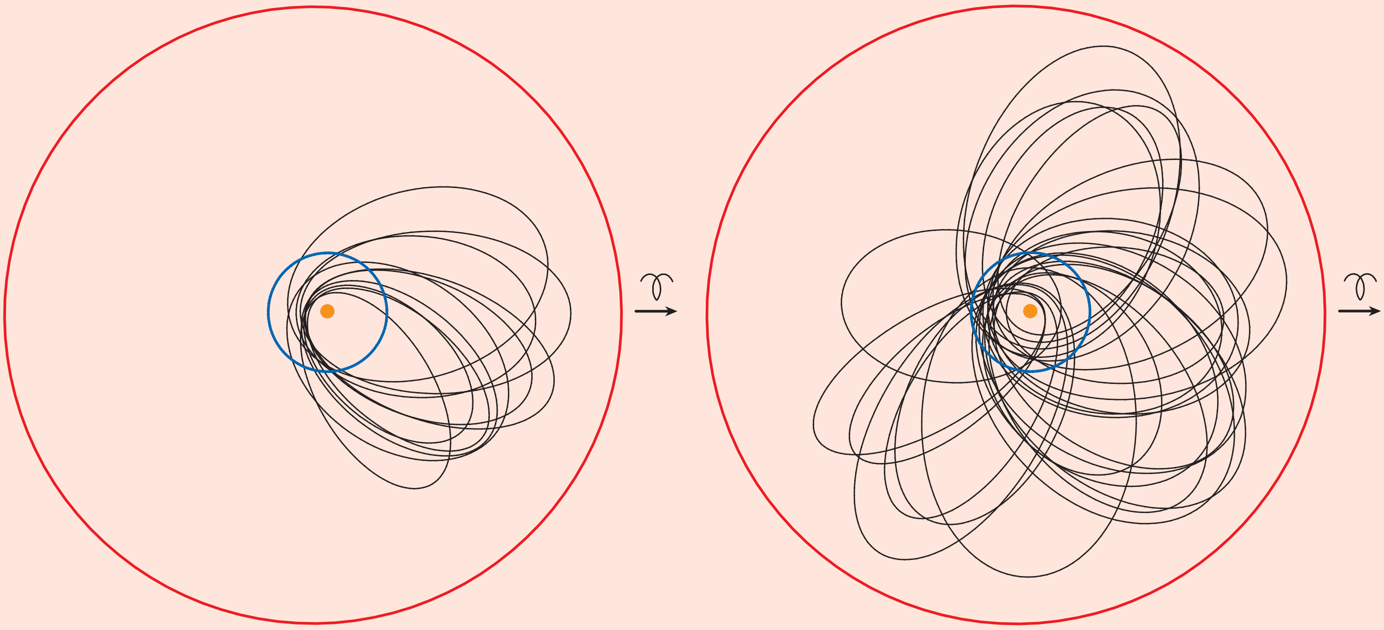
The Oort Cloud comprises $\sim 5\times10^{11}$ comets (down to 1 km diameter) with aphelia in the range 3000–100 000 AU. The long-period comets in the cloud are only just bound to the solar system and so are sensitive to galactic disturbances. These arise primarily from encounters with nebulae, and from a variable, periodic galactic tide coming from the vertical motion of the solar system as it bobs up and down in its orbit around the galaxy. About a third of the mass of the galaxy is in the form of nebulae, with cold, dense molecular clouds; although encounters with these nebulae have a strong sporadic component, they do tend to concentrate near the galactic plane ($Z \approx 50$–60 pc). The influx of comets to the planetary system varies pro rata with the galactic tide T, which is in turn proportional to the ambient density $\rho(z)$ of disc material at the vertical distance z from the galactic plane: thus $T \propto -4\pi G\rho(z)$. The flux of comets from the Oort cloud may be modelled by adopting a combination of variable tide and sporadic encounters with nebulae. Long-period comets feed into other comet reservoirs (Biryukov 2007, Emel'yanenko *et al.* 2007) and so the overall comet impact rate on Earth will reflect the ambient galactic forces acting on the Oort cloud. Here we adopt a mean in-plane density $0.15\,M_\odot\,pc^{-3}$ and a molecular cloud density which declines exponentially with scale height 60 pc (Wickramasinghe and Napier 2008). This yields a predicted cometary flux of amplitude a few with periodicity $P \sim 36$ Myr. Since we passed through the galactic plane only one or two million years ago, we should be in or just past the peak of an impact episode now. Extracting crater ages randomly from this flux, we find that the inbuilt periodicity of the model may be recovered from these synthetic datasets using standard procedures of power spectrum analysis (figure 3).

Examination of the 40 well-dated impact structures ($\sigma < 10$ Myr) of the past 250 million years reveals that the larger craters (say $\gtrsim 40$ km in diameter) in particular were formed in sharp, discrete, statistically significant episodes (figure 2 and Napier 2006) interspersed by long, quiet intervals. These episodes are too frequent and too strong to have come from the breakup of main belt asteroids (table 3). If we now apply the periodicity-hunting procedure to those 40 craters, a periodicity around 35 Myr emerges, close to that predicted from the model (figure 4). The phase is also close to zero, consistently with our recent passage through the galactic plane and implying that we are currently in a higher than average period of risk.

If we now divide up the craters by size, we find that the periodicity is strongly concentrated in craters more than about 30–40 km in diameter, whereas smaller ones show little sign of galactic modulation (figure 5). The break-even point of 30–40 km corresponds to impactors of between 1.5 and 2 km diameter. This is around the threshold for global catastrophe, in which one contemplates the destruction of a quarter of mankind by the impact. It seems that below this size, the main impactors are probably asteroids, whereas above it, comets dominate the record. Hence comets, active or dormant, seem to be a major global hazard.

Major airbursts of the 20th century

Recent estimates based on Spaceguard discoveries have suggested a deficiency in relation to downward extrapolation of the larger objects. This can be understood at a qualitative level, since the Yarkovsky effect (a thermal effect due to solar heating) will tend to hinder the effects



6: Chance alignment? (Left): Representative orbits of meteor sub-streams in the Taurid Complex; orbital elements taken from Kronk (1988). (Right): Large NEAs (orbits from the IAU Minor Planet Center) selected only on the basis of orbital *size, shape* and *inclination* being similar to Taurid meteors. Orbits of Earth and Jupiter also shown. Do the NEA orbits have any tendency to cluster in *longitude* around the TC meteors?

of resonances which drive asteroids out of the main belt. The sub-kilometre population is almost completely unknown, and yet airbursts from such bodies may be the most dangerous of impact phenomena for civilization. We can, however, glean something from three significant airbursts known to have occurred in the 20th century (Steel 1995).

One such took place around eight o'clock in the morning of 13 August 1930, in the neighbourhood of the River Curuça in the Brazilian Amazon. The associated energy is uncertain but may have been in the range 0.2–2 Mt. Another took place on the evening of 11 December 1935, this time in British Guiana (now Guyana). Even less is known of the energy of this impact, but a local pilot reported seeing an elongated area of destroyed forest more than 20 miles across. And of course there is the Tunguska impact itself. All three occurred when the Earth passed through or close to a major meteor stream (table 4).

The occurrence of three airbursts – that we know about – in the 20th century, each of which had the potential to cause huge damage, does imply that our increasingly crowded planet faces a significant level of risk from sub-kilometre bodies imbedded in meteor streams (table 5).

Table 4: Airbursts and meteor streams

airburst	date	meteor stream	peak
Tunguska River	30 June 1908	β Taurids	30 June
Curuça River	13 August 1930	Perseids	12 August
British Guiana	11 December 1935	Geminids	13 December

Coincidence? The three greatest known airbursts of the 20th century all occurred when the Earth was passing through major meteor streams.

A large Holocene short-period comet

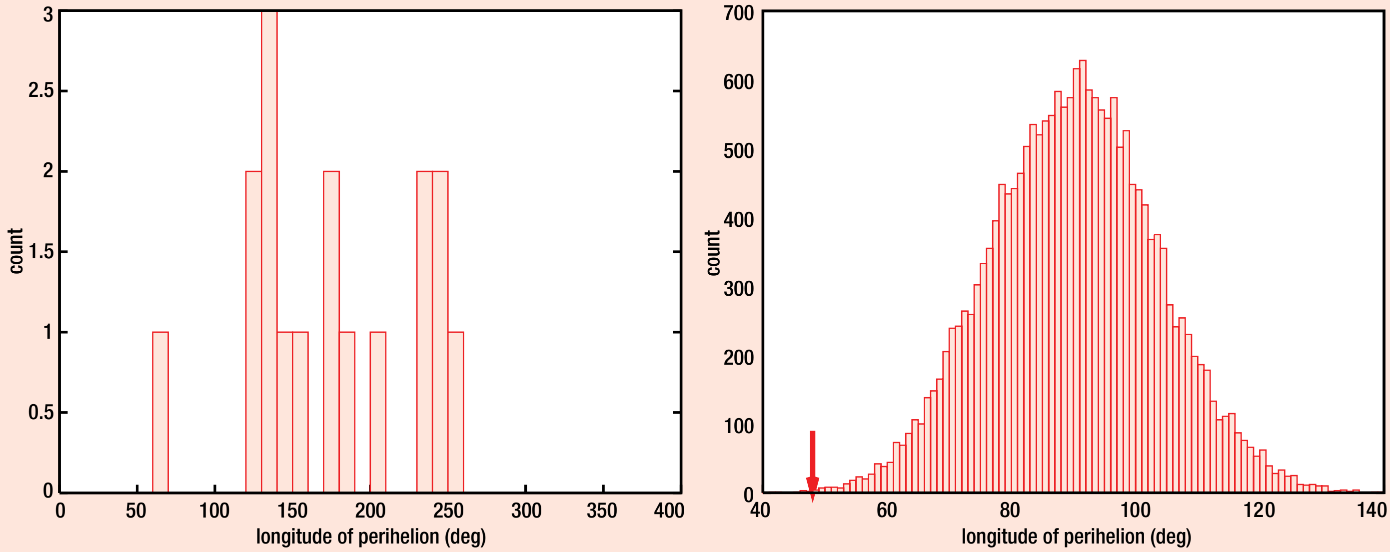
The evidence for a large comet in a short-period, low-inclination orbit, and continuously disintegrating over the last ~10^4–10^5 yr, includes the fact that current replenishing sources are about two powers of ten inadequate to yield the mass of the zodiacal cloud (Whipple 1967, Hughes 1996). Since the lifetime of the zodiacal cloud against collisional grinding and radiative effects is ~10^4 yr, an injection of ~10^{19} g of dust has been required, more if the injection took place more remotely in time. A comet of mass, say, 5×10^{19} g with the density of water has diameter ~50 km.

Chiron-sized (≳100 km across) cometary bodies, having mass a hundred times that of the entire current NEA system, may be injected into short-period, Earth-crossing orbits with recurrence time of around 100 000 yr (Bailey *et al.* 1994). Thus the capture of such large comets to the inner planetary system does happen. But how high a lower bound can we put on the diameter of this Holocene comet, based on what is now observed to remain of it?

The Taurid Complex (TC) – a low-inclination, broad meteor stream spread over 120° of sky – fits the picture of this large comet's remnant debris stream. Not only the Northern and Southern Taurids, but several other meteor showers such as the Northern and Southern χ Orionids (Babadzhanov and Obrubov 1992), are genetically related components of this complex which derives from a single parent object. The existence of northern and southern shower branches, which need 10^4 yr to develop separately, confirms the TC's age.

The present-day active comet known in the TC is 2P/Encke. This comet or its progenitor (there are no records of Encke itself before 1786) has been feeding meteoroidal material into the TC for at least a few 10^4 yr. Over this timescale this material both undergoes collisions (Steel and Elford 1986) as well as being dispersed by gravitational and radiative effects, eventually reaching the zodiacal cloud via a broad, sporadic stream (Stohl 1986) surrounding the Taurids. The sporadic stream produces the well known helion (HE) and antihelion (AH) sources seen in radar meteor data (Taylor and Elford 1998, Campbell-Brown 2008). Wiegert *et al.* (2008) found Encke to be by far the dominant contributor to the HE and AH flux.

The diameter of Encke is ~5 km (Fernández *et al.* 2000), while the total mass in the TC – in 1 m and smaller meteoroids alone – can be shown from meteor observations combined with stream modelling to be somewhat more than this. These reasons imply a minimum 10 km diameter progenitor, while to satisfy the mass balance of the zodiacal cloud, and noting the absence of other obvious candidates in the past 10^5 yr, at least,



7 (left): Among brighter NEAs ($H<16.5$) we extract the 15 objects with semi-major axis a from 1.85–2.7 AU, eccentricity e from 0.65–1.0 and inclination i from 0–14°. These are distributed as shown, with a mean absolute difference of 48° from Comet Encke's longitude of perihelion ϖ which is 161°. (Right): If ϖ is uniformly random around 360°, the mean difference from Encke should be 90°. This Monte Carlo simulation (20000 trials) indicates that a difference as small as 48° arises by chance only once in 2000 trials.

say, 30 km is required. A similarly substantial original size may also follow depending on the amount of mass in larger bodies, through Tunguskas up to possible NEAs comparable to Encke. Are these macroscopic bodies present?

Taurid NEAs

When the set of discovered NEAs started to grow as a result of modern surveys, at Palomar and later elsewhere, it became possible to verify the expectation that inert bodies of significant size should exist in orbits similar to the comet Encke meteor stream (Clube and Napier 1984). Subsequent papers, as the NEA catalogue expanded, identified further objects aligned with Encke and the TC.

Following the "reduced D-criterion" method (a formal way to define orbital similarity) described by Asher *et al.* (1994), but using a new, up to date NEA dataset, we illustrate the TC alignment in figure 6. Valsecchi (1999) demonstrated an interesting observational selection effect that could favour the discovery of high-eccentricity, low-inclination NEAs at certain longitudes. In figure 6 we therefore restrict the NEAs to absolute magnitude $H<16.5$, corresponding to a minimum diameter of 1–3 km depending on albedo, so that observational incompleteness is less of a problem: $H<16.5$ objects are now being discovered at an annual rate of less than 10, compared to well over 20 a few years ago soon after the LINEAR asteroid survey began. In figure 7 we adopt a slightly simpler definition of orbital similarity than the D-criterion (the alignment, if real, should not be sensitive to the exact technique used) and illustrate the statistical significance. Figure 7 allows us to reject the null hypothesis that longitude of perihelion ϖ is randomly distributed around 360° in favour of the hypothesis that bright NEOs whose (a, e, i) are close to that of Comet Encke also tend to have ϖ close to that of Encke. So there does seem to be an NEA stream, and it does seem to lie rather close to the TC. The perihelion distances of all these objects are a little greater than those of observed Taurid meteors and none of those for which the taxonomic type has been determined are among the small fraction of NEAs whose types correspond to extinct comet nuclei (further discussion on p464 of Jenniskens 2006), but in fact the internal constitution of the large TC progenitor is quite unknown.

Among fainter NEAs observational incompleteness increases; when one reaches Tunguska size the vast majority are still undiscovered. It turns out moreover that a statistically significant alignment is presently hard to find within the current dataset. Nevertheless, Porubčan *et al.* (2006) have demonstrated the association of identifiable filaments in the Taurid meteor orbit database with several specific, known NEAs in the hundreds of metre to 2 km size range. Babadzhanov *et al.* (2008) found further examples of meteor shower associations with asteroidal Taurid objects.

Bombardment epochs

The 15 sub-streams or filaments recognized in meteor orbit data by Porubčan *et al.* (2006), who also identified times over the past several 10^3 yr when they may have originated, are direct observational evidence of fine structure within the TC, at least in the component of the complex that is Earth-intersecting and can produce meteors. Furthermore, structure in the TC as a whole is an inevitable consequence of meteor stream dynamics. If a large comet was captured to cis-Jovian space a few 10^4 yr ago, and if at least some products of its continuous disintegration are still present as a coherent, Earth-crossing meteor stream, what structure should this stream have?

Spectacular Leonid meteor displays a few years ago helped to reinforce our understanding of the fine structure in streams. Narrow trails exist within the overall stream; they are essentially the least dispersed components of the stream and have an extremely high spatial density of meteoroidal material.

There is an important difference between the Leonid and Taurid streams. The orbit of the Leonid parent, comet 55P/Tempel-Tuttle, is quite close to Earth orbit intersection at the present epoch. Small displacements (due to planetary perturbations) of narrow trails, relative to the comet orbit, can bring the trails to precise Earth intersection and allow the planet to encounter dense concentrations of meteoroids. Encke in contrast misses the Earth's orbit by quite some distance, at the present epoch. Assuming the densest concentrations of Taurid material to lie close to Encke's orbital plane (and in the absence of evidence against, this is the most reasonable assumption), we simply do not encounter these trails at present.

This has changed in the past, and will do so again. Jupiter's gravity causes the orbits of Encke and of Taurid particles to precess, or twist around in 3-D space. When the orbits have turned around enough, they cut through the Earth's orbit. So orbital precession makes the Earth intersect dense trails of Taurid material every few millennia. Dynamical calculations set the spacing of these intersection epochs at three millennia or so, with the next such epoch due around AD 3000. Meteors we are seeing now come from outlying parts of a very broad complex. A fair number of Taurid meteors occur at present, even from low-density regions of the stream, because the whole complex really is massive.

Hierarchic disintegration and fragmentation constitute an important evolutionary route for comets (Jenniskens 2008). If large comets disintegrate hierarchically (cf. progenitors of the TC and of the Kreutz sungrazing comets), then sub-kilometre objects may concentrate in comet trails, either from recent breakup or trapping in resonances. A dramatic example of a comet splitting in recent years was Comet 73P/Schwassmann-Wachmann 3 (period ~5.4 yr). At its 1995 return at least three additional nuclei were identified, and two revolutions later at the 2006 apparition the disintegration had yielded around 60 pieces. The Taurid bombardments every few millennia are likely to involve multiple Tunguska impacts.

A possible Holocene cosmic impact

A carbon-rich black layer, ~12 900 years old, has been identified at many sites across North America (Haynes 2008). It is closely coincident in age with the abrupt cooling known as the Younger Dryas, as well as with large-scale mammoth extinctions and "rapid human behavioural shifts", the latter taking place over decades or less. Evidence for an extraterrestrial cause has been given by Firestone *et al.* (2007) in the form of a contemporaneous thin layer at numerous North American sites, containing sharp peaks of iridium-bearing magnetic grains, magnetic microspherules, nanodiamonds, fullerenes containing extraterrestrial helium, and other indicators. They consider these to be evidence for a shower of cometary airbursts (Tunguska-like and larger) producing the widespread extinctions, the abrupt climate downturn and extensive biomass burning, along with abrupt cultural changes and a decline in the human population. The evidence for an extraterrestrial cause has more recently expanded into Greenland and Europe (Allen, personal communication), implying a disturbance on a global rather than continental scale. We are currently running simulations to determine whether the Taurid Complex can be convincingly proposed as the cause of this event.

Conclusions

On the evidence of the galactic signatures in the impact cratering record of the past 250 Myr, comets down to ~2 km diameter seem to be the major contributors to the global impact hazard. Active comets may be too rare to fulfil that role, and so it seems likely that dormant bodies are the major contributors. Detection, deflection and mitigation strategies have not yet been developed for this class of hazard. Rare, large comets are occasionally thrown into the inner planetary system. In terms of mass, they dominate the interplanetary environment in the course of their disintegration. There seems to be a smoking gun, in the form of the Taurid Complex and a zodiacal cloud which is substantially overmassive in relation to known sources. Disintegrating dormant comets could provide a major fraction of the dust, but the fact that over half the mass of the sporadic meteors are in a broad stream encompassing the Taurid Complex implies that a single large comet was the major contributor. On the evidence of the three major airbursts known to have taken place in the 20th century, it seems likely that the most dangerous regional hazards – sub-kilometre impactors – tend to concentrate in meteor showers associated with this erstwhile comet and with other active comets.

Claims have been made by a small ad hoc group of geoscientists, the Holocene Impact Working Group (http://tsun.sscc.ru/hiwg/hiwg.htm), that impacts have been much more frequent throughout the Holocene than expected from Spaceguard surveys. It remains to be seen whether these claims will continue to hold up; but on the basis of the astronomical evidence described here, they cannot yet be excluded. ●

Table 5: Guilty by association?

meteor stream	associated body	period (years)	encounter speed (km/s)
βTaurids	Comet Encke	3.3	30
Perseids	Comet Swift-Tuttle	120	60
Geminids	Phaethon	1.6	35

Parents, or possibly siblings, of the 20th-century impactors. All three are in cometary orbits with high encounter speeds and short warning times.

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