Extreme albedo comets and the impact hazard

W. M. Napier,[1,2][⋆] J. T. Wickramasinghe[2] and N. C. Wickramasinghe[2][⋆]

[1]*Armagh Observatory, College Hill, Armagh, Northern Ireland BT61 9DG*
[2]*Cardiff Centre for Astrobiology, Cardiff University, 2 North Road, Cardiff CF10 3DY*

ABSTRACT

Dynamical balance arguments that involve the capture of long-period comets from the Oort cloud imply that there should be ~ 1000 times more Halley-type objects than are actually observed. If the active comets rapidly become dormant, with albedos comparable to those of known cometary surfaces, hundreds of such bodies should by now have been detected whereas in fact only a few have been found. If, on the other hand, they disintegrate to dust, we show here that the debris would create a bright, near-spherical zodiacal cloud and ~ 15–30 strong annual meteor showers, also contrary to observation. Here we demonstrate that the surfaces of inactive comets, if composed of loose, fluffy organic material like cometary meteoroids, develop reflectivities that are vanishingly small in visible light. The near-Earth objects may therefore be dominated by a population of fast, multi-kilometre bodies too dark to be seen with current near-Earth object surveys. Deflection strategies that assume decades or centuries of warning before impact are inapplicable to this hazard.

Key words: comets: general – meteors, meteoroids – Oort Cloud.

1 INTRODUCTION

The Oort cloud has long been recognized as the source of long-period comets that enter the planetary system (Oort 1950). They are driven inwards primarily by galactic tides, which act continuously (Byl 1986; Clube & Napier 1996), although passing stars and nebulae will generate sporadic comet showers on time-scales of order 100 million years. Massive nebulae have a violently disruptive effect on time-scales of order one gigayear (Bailey, Clube & Napier 1990). The near-parabolic flux of comets brighter than $H_{10} = 7$ was estimated by Emel'yanenko & Bailey (1998) to be $\sim 0.2 \, \mathrm{au}^{-1} \mathrm{yr}^{-1}$ at 1 au. A more recent assessment increases this rate by a factor of about four (Hughes 2001). Here H_{10} is the absolute magnitude of the active comet, i.e. nucleus and coma combined.

Once a long-period comet arrives at the outer reaches of the planetary system, its dynamical evolution comes under the control of the planets. It is possible then to calculate the proportion of arriving comets that are thrown into 'Halley-type' orbits ($20 < P < 200$ yr). Emel'yanenko & Bailey (1998) found that in the range $0 < q < 4$ au, the capture probability from the Oort cloud into a Halley-type orbit was ~ 1 per cent, rising to ~ 2 per cent if non-gravitational forces were allowed for. This led them to calculate that there should be ~ 3000 comets brighter than $H_{10} = 7$ in Halley-type orbits, 400 times more than are observed. A similar discrepancy was found by Levison et al. (2002). If the higher influx of Hughes (2001) is

adopted, then the discrepancy becomes a factor ~ 1600. The problem is then: where have the other ~ 99.9 per cent gone?

Emel'yanenko & Bailey (1998) proposed that Halley-type comets simply become dormant after their first few perihelion passages through the inner planetary system. However, assuming a mean albedo $p = 0.04$ for the dormant comets, Levison et al. (2002) estimated that about 400 such bodies should have been detected, whereas – at epoch 2002 January – only nine were known. They proposed instead that at least 99 per cent of Halley-type comets disintegrate completely during their first few perihelion passages, a comet evolving into an orbit with $q < 1$ au having a 96 per cent chance of disrupting before its next perihelion passage. Such disintegrations happen, albeit rarely (Sekanina 1984; Boenhardt 2001). A clear counter-example is Comet Halley itself, which may have taken over 2000 perihelion passages to produce its meteoroid stream (Hughes 1985).

2 DISINTEGRATION OF HALLEY-TYPE COMETS

We show here that if active Halley-type comets do disintegrate as proposed, creating debris typical of cometary tails, they would generate a roughly spherical zodiacal cloud of mass comparable to or greater than the one observed.

Consider firstly the bright comets ($H_{10} < 7$), 3000 of which, in a steady state, are supposed to be resident in Halley-type orbits but to have disintegrated to dust (we adopt the lower, conservative influx of Emel'yanenko & Bailey 1998). The differential mass distribution

of long-period comets may be fitted by a power law:

$$n(m)\, dm \propto m^{-\alpha}\, dm, \tag{1}$$

where $\alpha \sim 1.47$ (Weissman & Lowry 2001). Within the errors this does not differ significantly from the best-fitting $\alpha \sim 1.38$ obtained from the few known objects in Halley-type orbits (Levison et al. 2002). Bailey (1990) finds a least-squares fit to the masses and absolute magnitudes of 27 long-period comets:

$$\log M = 21.13 - 0.48H, \tag{2}$$

assuming a mean albedo $p = 0.05$ and density $\rho \sim 0.5\,\mathrm{g\,cm^{-3}}$. This yields $M \sim 3.5 \times 10^{17}$ g for a comet of absolute magnitude 7 if the mean density is adjusted downwards to 0.3 g cm^{-3} (Greenberg & Remo 1994).

We carried out numerical trials in which 3000 comets were randomly extracted from a system with these parameters. These trials revealed that the mean mass of the comets so extracted was ~ 300 times that of the minimum, i.e. $\sim 10^{20}$ g. Thus the total mass for the disintegrated Halley-type system is $\sim 3000 \times \bar{M} \sim 3 \times 10^{23}$ g. For a typical period $P = 60$ yr and eccentricity $e = 0.96$, one finds that the cometary material spends ~ 1.6 yr within 4 au of the Sun. Then the mass of material within this sphere deriving from the bright comets alone is of order $3 \times 10^{23} \times 1.6/60 \sim 8 \times 10^{21}$ g. This is 30–300 times the estimated total mass of the zodiacal cloud within 3.5 au (Hughes 1996). Such a dust sphere, scattering Sunlight, would create a strong visible glow in the night sky, but this is not observed. About 95 per cent of the zodiacal light is due to scattering from particles with radii less than 100 μm; counting up to particles of this radius, the zodiacal cloud has mass $\sim 10^{17}$ g (Leinert, Röser & Buitrago 1983; Love & Brownlee 1993).

En route to joining the dust sphere, and before planetary perturbations dispersed them, debris from the postulated disintegrations would form streams, some of which might intersect the Earth to produce annual meteor showers. The dynamical model of Levison et al. (2002) predicts that, without disruption, there would be 46 000 active and dormant Halley-type comets with $q < 1.3$ au, with absolute magnitudes (nucleus only) $H < 18$ corresponding to diameters $\gtrsim 2.4$ km. If we take 30 000 Halley-type objects to have $q < 1.0$ au and mean periods 60 yr, then we expect 500 such bodies to pass within the Earth's orbit each year, and ~ 100 nodes of erstwhile dormant comets to come within ± 0.05 au of the Earth's orbit. The characteristic width of a strong meteor stream is ~ 0.05 au, and so the number of recognizable streams from disintegrated comets is of order $N \sim 100 L_\mathrm{m}/L_\mathrm{c}$, where $L_\mathrm{c} \sim 100$ kyr represents the mean dynamical lifetime of the dormant comets and L_m is that of their associated meteor streams.

To estimate the latter, we carried out simulations in which comets were randomly extracted from the 'dormant comet' parameter space computed by Levison et al. (2002). Each comet was broken into 27 pieces at perihelion, representing the meteoroids, the fragments being given random speeds up to δV in random directions. Laboratory experiments on simulated comet nuclei indicate that the ejection speeds of dust particles in the range 1–100 micron are a few metres per second when irradiated at a heliocentric distance of $\lesssim 1.5$ au (Ibadinov 1989), and two cases are illustrated in Fig. 1, namely $\delta V = 2$ and 10 m s^{-1}. The fragments were followed for 100 000 yr or until they had fallen into the Sun, collided with a planet or been hyperbolically ejected. A significant proportion of the meteor streams so created remained coherent throughout their evolution as measured by standard similarity functions. The known strong meteor streams have $D \lesssim 0.2$ (Lindblad 1971), where D is the criterion due to Southworth & Hawkins (see Galligan 2001, who compares various
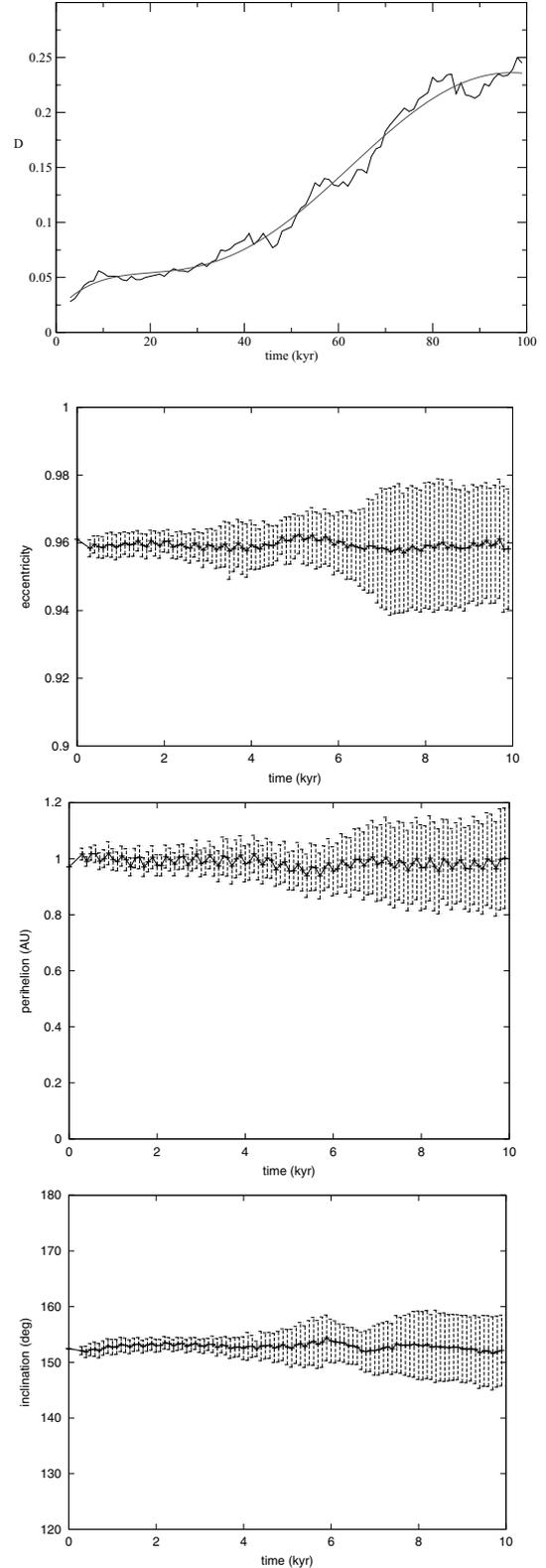

Figure 1. Evolution of a meteor stream. The orbital evolution of 27 fragments of a Halley-type comet assumed to have disintegrated at perihelion. A standard similarity function (the D-criterion) is computed for each of the 27 orbits taken in pairs, and the average is plotted. The orbits gradually diverge under the influences of the planets. Characteristically a meteor stream will be recognized as such when $D \lesssim 0.2$ and so in this case the disintegrated comet (initial $q = 1.0$, $e = 0.96$, $I = 152°$) would yield annual meteor showers over the full 10^5 yr of the integration.
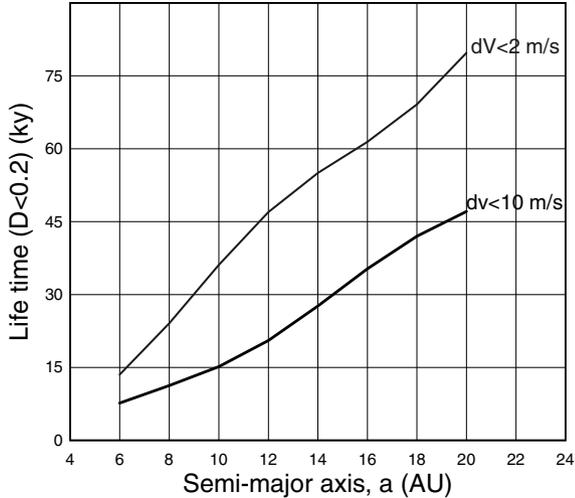
Figure 2. Lifetimes of meteor streams with initial eccentricities in the range $0.96 \leqslant e \leqslant 0.98$, averaged and smoothed. 'Lifetime' is here defined as in the text, with $D_{crit} = 0.2$. Lifetimes are shown for initial velocity dispersions, at perihelion, of $\delta V \leqslant 2 \text{ m s}^{-1}$ (upper curve) and $\leqslant 10 \text{ m s}^{-1}$ (lower).

similarity criteria). Adopting $D_{crit} = 0.2$ as the cut-off for recognizing a strong meteor stream, and weighting with the semi-major axis distribution of the dormant Halley-type comet populations (Levison et al. 2002), the overall mean ratio of lifetimes is given by $L_m/L_c \sim 0.15$ (Fig. 2). Thus if the characteristic width of a meteor stream is ~ 0.1 au, the number of strong Halley-type meteor streams intersecting the Earth's orbit is ~ 15. A meteor stream may be observed as more than one annual shower (Comet Halley yields the Orionids and η Aquarids), with octuple-crossers (e.g. P/Macholz 1) being possible.

The somewhat diffuse meteoroid stream associated with Comet Halley has a mass estimated at $\sim 5 \times 10^{17}$ g (McIntosh & Hajduk 1983). The 30 000 Earth-crossing comets that are supposed to disintegrate completely have mean mass of this order or greater. One would then expect to observe streams of Orionid or η Aquarid strength (hourly visual rate ~ 20), unconnected with any visible comet, at weekly to monthly intervals, contrary to observation.

Instead of crumbling to meteoric dust, it is conceivable that the disintegration of the Halley-type comets would proceed to 'Tunguska-sized' (~ 0.1-km) bodies, comparable with the dimensions of the smaller Kreutz Sungrazers and with the fragments observed to split from Comet Hyakutake (Desvoivres et al. 2000). Consider an isotropic distribution of N bodies of mean period P yr, near-parabolic orbits and perihelia <1 au. The mean collision probability of the Earth with such bodies is $\sim 3 \pm 1 \times 10^{-9}$ per perihelion passage (Steel 1993). Thus with N/P passages per annum, collisions with the Earth occur at mean intervals δt yr given by

$$\delta t \sim 3.3 \times 10^8 P/N \tag{3}$$

to within about 30 per cent. With the mass distribution (1) and $\alpha = 1.47$, the mean mass of such an Earth-crosser is found to be $\sim 6.6 \times 10^{17}$ g. If all 30 000 comets break into 10^{11} g objects comparable to the mass of the Tunguska impactor, then one expects $\sim 2 \times 10^{11}$ fragments that, with $P \sim 60$ yr, would yield about ten Tunguska-like impacts on Earth every year.

Detection of the debris might be avoided if the comets disintegrate into sub-mm particles. Entering at 50–70 km s^{-1} corresponding to Halley-type orbits, these would ablate in the high ionosphere and escape detection by both visual observations and radar. It would

be necessary for 99 per cent of comets in short-period orbits to be reduced to particles $\lesssim 0.1$ mm in diameter within a few perihelion passages, a requirement that hardly seems plausible and for which there is no independent evidence.

There is therefore a paradox: assuming a steady-state, the case for a large discrepancy rests only on Newtonian dynamics and the rate of influx of long-period comets, which is known to within a factor of a few (cf. Emel'yanenko & Bailey 1998; Hughes 2001). One should thus expect to see thousands of Halley-type comets along with their decay products, either dormant bodies or annual meteor showers, along with a bright, near-spherical zodiacal cloud; but all these entities are either absent or under-represented by two or three powers of ten.

There is no good reason to assume detailed balance between the long-period and Halley populations. However, to account for the discrepancy the imbalance must be extremely large, of order 400–1600. Surges of this magnitude may occur at intervals $\sim 10^8$ yr when a star penetrates the hypothetical dense inner Oort cloud. However, comets in such a shower would have aphelia strongly concentrated around the region of sky where the perturbing star made its closest approach (Fernandez & Ip 1987), and this is not observed. In addition the equilibration time between the long-period and Halley populations is only ~ 0.1 Myr and so the hypothesis would require us to live in a very special epoch, when a shower was under way but had not yet populated the Halley-type system.

3 EXTREMELY DARK COMETS

We propose, as a solution to the paradox, that the surfaces of inert comets become extremely dark. It is likely that the final stages of the accumulation of comets involved the mopping up of debris of micron or submicron sizes from the molecular cloud or a protoplanetary disc that was dominated by elongated refractory interstellar organic grains $\sim 10^{-5}$ cm across, possessing volatile mantles (Wickramasinghe 1974; Bailey et al. 1990). Although silicate dust is also doubtless present, estimates of their mass fraction relative to the organic component could be as small as 15 per cent (Crovisier et al. 1997; Wickramasinghe & Hoyle 1999). This is also consistent with mass spectra of interstellar dust obtained on instruments aboard the NASA spacecraft Stardust that showed an overwhelming dominance of heteroaromatic polymers and no evidence of minerals (Krueger et al. 2004). On the grain model we consider, sublimation of volatiles would build up into a vacuous fairy-castle or aerogel structure. It is possible to envisage many metres of such a structure developing with little or no compaction, except perhaps through the agency of collisions with meteoroids. It is of interest in this connection that particles of probable cometary origin entering the ionosphere and stratosphere have a fluffy, porous structure, with vacuum filling factors ~ 0.75–0.95 (Rietmeijer 2002; Wickramasinghe et al. 2003).

A tarry medium of refractive index $m_1 = n_1 - \mathrm{i}k_1$, within which are distributed vacuum spheres of refractive index 1 occupying a fraction f of the total volume of material, behaves as one of complex refractive index m given by

$$m^2 = m_1^2 \left[1 + \frac{3f\left(1 - m_1^2\right)/\left(1 + 2m_1^2\right)}{1 - f\left(1 - m_1^2\right)/\left(1 + 2m_1^2\right)} \right], \tag{4}$$

where $m = n - \mathrm{i}k$, n, k being the real and imaginary refractive indices (Bohren & Wickramasinghe 1977). For normal incidence the reflectivity R of a slab of this material is given by the formula
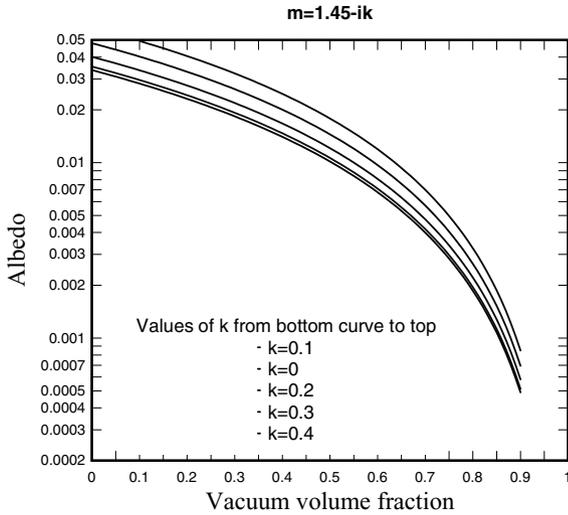
Figure 3. The reflectivity of an aggregate of organic particles 10^{-5} cm in diameter as a function of porosity. For comparison, the nuclei of active comets have albedos $p \sim 0.02$–0.04, while dark spots on Comet Borrelly have $p \sim 0.008$ (Nelson et al. 2004).

from classical electromagnetic theory (Abraham & Becker 1950):

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}. \tag{5}$$

For a prescribed tarry matrix and for given values of the vacuum volume fraction f we can readily solve for m from (4), and thus compute R. We take $n = 1.45$, and $k = 0 - 0.1$ at optical wavelengths, as being representative of organic polymers (e.g. kerogen). The results of numerical calculations are given in Fig. 3.

It is evident that very low values of R can be achieved with vacuum fractions in line with existing estimates for loose aggregations of interstellar dust grains: the bulk porosities of interplanetary dust particles are ~ 0.75 and those of Type III fireballs of cometary origin are ~ 0.95 (Rietmeijer 2002). The fading function required by the observations may thus be achieved when a comet's surface, comprising a loose aggregate of interstellar dust grains, loses ice between the interstices. An active periodic comet loses gas and dust primarily through active areas on its surface. Some of this falls globally back on to the cometary surface (Wallis & Al-Mufti 1996). In due course, with depletion of volatiles, the comet loses its coma and becomes dormant. The ice remaining in the volume between the surface grains sublimates, without replenishment, the cometary surface becomes an aerogel, and the albedo rapidly falls to very low values (Fig. 3).

With this model, it has been found experimentally that the thickness of the crust on the surface of a comet increases in proportion to the square root of the insolation time, while the gas production rate proceeds in inverse proportion to the thickness of the crust (Ibadinov, Rahmonov & Bjasso 1991). Laboratory and numerical work (Ibadinov 1993 and references therein) shows that the rate of fading of short-period comets, and its dependence on perihelion distance, are well reproduced by a nucleus of graphite particles embedded in water ice, with 80 per cent porosity and thermal conductivity 0.05 W^{-1} K^{-1}. In this case, for a comet in a Halley-type orbit, the crust grows at ~ 5 cm yr^{-1}. The pressure of the escaping water vapour is insufficient to break such a crust (*loc. cit.* and Kührt & Keller 1996).

The possibility that the surfaces of dark comets are continually reactivated by sporadic meteor impacts needs to be assessed. Col-

lisions with sporadic meteors seem to dominate over those with the stream generated by the comet (Williams et al. 1993). Hughes (1993) estimates that $\sim 6 \times 10^4$ g of sporadic meteors impact on the surface of Comet Halley per orbital revolution, at a mean speed ~ 60 km s^{-1}. If a sporadic meteor excavates $\sim 10^5$ times its own volume, then the mass removed is, for a surface density 0.5 g cm^{-3}, $\sim 6 \times 10^4 \times 10^5 \times 0.5 \sim 3 \times 10^9$ g per orbit. However, for P/Halley, a crustal thickening rate of ~ 5 cm yr^{-1} implies that 7.5×10^{12} g is added to the crust each year. Thus gardening by the sporadic meteor flux is inadequate by about three powers of ten to reactivate the surface of a dark comet, although of course individual impacts by large meteoroids may cause temporary outgassing.

The volume of space out to which a body of albedo p is detectable varies as $p^{3/2}$ and so, if there is an expectation that 400 dormant comets with canonical $p = 0.04$ should by now have been detected, the actual number of detections when $p = 0.002$ say is ~ 5 (cf. nine detections to date): thus the expected albedos of the carbonaceous aerogels are consistent with the presence of a large dark Halley population. The nearest known extraterrestrial albedos of this order are the dark spots on Comet Borrelly, which have $p \sim 0.008$ (Nelson, Soderblom & Hapke 2004). If the predicted population of dark Halleys had this albedo, ~ 40 would by now have been discovered. There is clearly a strong selection effect against the discovery of astronomical objects in the solar system with albedos $p \ll 0.008$ (Jewitt & Fernandez 2001).

4 CURRENT IMPACT HAZARD

An immediate consequence of the above solution of the 'missing comet' problem is that there exists a large population of extremely dark comets in Earth-crossing orbits, which are undetectable with current near-Earth object (NEO) search programmes but are nevertheless impact hazards (cf. Bailey & Emel'yanenko 1998).

Levison et al. (2002) computed that, without disintegration, there would be a population of $N \sim 3 \times 10^4$ dormant Halley-type comets with diameters $D > 2.4$ km and perihelia $q \lesssim 1$ au. Adopting $\bar{P} \sim 60$ yr, then from (3) the mean interval between impacts of such bodies is ~ 0.67 Myr, with impact energies $\gtrsim 1.5 \times 10^6$ Mt, for a mean impact speed ~ 60 km s^{-1} (Jeffers et al. 2001). Impacts of at least 1.5×10^7 Mt energy are expected at mean intervals ~ 2.3 Myr.

These rates are well in excess of those expected from the NEO system currently being mapped out (mainly S-type asteroids: Morbidelli et al. 2002). Hughes (2003) has argued that there is no room for a significant cometary contribution, active or dormant, on the grounds that the impact rate from the near-Earth asteroid population is adequate to produce the known rate at which terrestrial craters are produced. This argument depends on a scaling relation between the diameter of the impactor and the crater which it forms, which is uncertain to an order of magnitude. Rickman et al. (2001), on the other hand, find that comets yield a large, perhaps dominant, contribution to km-sized impactors, estimating for example a terrestrial impact rate of about one Jupiter family comet (active or dormant) per Myr. While the uncertainties are large, it seems unavoidable that, if the present hypothesis is correct, a dormant Halley population represents a major if not dominant global impact hazard at the present time.

The expected impact rate is also significantly higher than has been inferred from lunar cratering data (Neukum & Ivanov 1994). However if the Halley-type population is derived in large part by capture of comets from the long-period system (Bailey & Emel'yanenko 1998), then perturbations of the Oort cloud may yield an upsurge in the dark Halley population, and ultimately in the flux of impactors

on the Earth. The Oort cloud is demonstrably sensitive to Galactic perturbers of various sorts – stars, nebulae and tides (Napier & Staniucha 1982; Byl 1986, etc.). Nurmi, Valtonen & Zheng (2001) find that the flux of comets from the Oort cloud, and hence the impact rate, may fluctuate by an order of magnitude arising from the motion of the Sun with respect to the Galactic mid-plane. As we are at present passing through the plane of the Galaxy, it is expected that the current impact rate is several times higher than that deduced from the lunar cratering record, which is time-averaged over one or two Gyr.

The dark Halleys, on this hypothesis, are a link in the chain between Galactic disturbances and huge impacts. That passages of the Sun through the spiral arms of the Galaxy might induce terrestrial disturbances has been discussed by a number of authors (e.g. McCrea 1975). Napier & Clube (1979) specifically proposed that bombardment episodes might occur during such passages, leading to mass extinctions and other trauma. Leitch & Vasisht (1998) have shown that, indeed, the Sun was passing through a spiral arm during the Cretaceous-Tertiary and Permo-Triassic extinctions of 65 and 250 million years ago, which also coincided with the Deccan and Siberian trap flood basalts. On this model, each of these was caused, not by a stray asteroid, but by an episode of cometary bombardment. For at least some of the great mass extinctions, multiple impacts coupled with climatic trauma appear to have been involved (e.g. McGhee 1996; Keller 2002).

Current detection and deflection strategies involve the assumption that decades or centuries of warning will be available following the discovery of a threat asteroid. However if the major impact hazard indeed comes from this essentially undetectable population, the warning time of an impact is likely to be at most a few days. A typical Halley-type dormant comet spends 99 per cent of its time beyond the orbit of Mars and so a full mapping of this population is beyond current technology.

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