

Cambridge University Press

978-0-521-17332-2 - Mitigation of Hazardous Comets and Asteroids

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Excerpt

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Recent progress in interpreting the nature of the
near-Earth object population

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1 Introduction

Over the last several decades, evidence has steadily mounted that asteroids and comets have impacted the Earth over solar system history. This population is commonly referred to as “near-Earth objects” (NEOs). By convention, NEOs have perihelion distances $q \leq 1.3$ AU and aphelion distances $Q \geq 0.983$ AU (e.g., Rabinowitz *et al.* 1994). Sub-categories of the NEO population include the Apollos ($a \geq 1.0$ AU; $q \leq 1.0167$ AU) and Atens ($a < 1.0$ AU; $Q \geq 0.983$ AU), which are on Earth-crossing orbits, and the Amors (1.0167 AU $< q \leq 1.3$ AU) which are on nearly-Earth-crossing orbits and can become Earth-crossers over relatively short timescales. Another group of related objects that are not yet been considered part of the “formal” NEO population are the IEOs, or those objects located inside Earth’s orbit ($Q < 0.983$ AU). To avoid confusion with standard conventions, we treat the IEOs here as a population distinct from the NEOs. The combined NEO and IEO populations are comprised of bodies ranging in size from dust-sized fragments to objects tens of kilometers in diameter (Shoemaker 1983).

It is now generally accepted that impacts of large NEOs represent a hazard to human civilization. This issue was brought into focus by the pioneering work of Alvarez *et al.* (1980), who showed that the extinction of numerous species at the Cretaceous–Tertiary geologic boundary was almost certainly caused by the impact of a massive asteroid (at a site later identified with the Chicxulub crater in the Yucatan peninsula) (Hildebrand *et al.* 1991). Today, the United Nations, the US Congress, the European Council, the UK Parliament, the IAU, NASA, and ESA have all made official statements that describe the importance of studying

and understanding the NEO population. In fact, among all worldwide dangers that threaten humanity, the NEO hazard may be the easiest to cope with, provided adequate resources are allocated to identify all NEOs of relevant size. Once we can forecast potential collisions between dangerous NEOs and Earth, action can be taken to mitigate the potential consequences.

In this chapter, we review the progress that has been made over the last several years by our team to understand the NEO population, to quantify the collision hazard, and to determine the possibility that existing or near-future surveys may detect/catalog all dangerous NEOs. As such, we employ theoretical and numerical models that can be used to estimate the NEO orbital and size distributions. Our model results are constrained by the observational efforts of numerous NEO surveys, which constantly scan the skies for as yet unknown objects. The work presented here is primarily based on three papers: Bottke *et al.* (2002a), Morbidelli *et al.* (2002a), and Jedicke *et al.* (2003). The interested reader should also examine Morbidelli *et al.* (2002b).

2 Dynamical origin of NEOs

2.1 The near-Earth asteroid population

Dynamical studies over the last several decades have shown that asteroids located in the main belt between the orbits of Mars and Jupiter can reach planet-crossing orbits by increasing their orbital eccentricity under the action of a variety of resonant phenomena (e.g., J. G. Williams, see Wetherill 1979; Wisdom 1983). (Main belt asteroids are believed to enter resonances via the thermal drag forces called the Yarkovsky effect; for a review, see Bottke *et al.* 2002b). Here we classify resonances according to two categories: “powerful resonances” and “diffusive resonances,” with the former distinguished from the latter by the existence of associated gaps in the main belt asteroid semimajor axis, eccentricity, and inclination (a, e, i) distribution. A gap is formed when the timescale over which a resonance is replenished with asteroidal material is far longer than the timescale which resonant asteroids are transported to the NEO region. The most notable resonances in the “powerful” class are the ν_6 secular resonance at the inner edge of the asteroid belt and several mean motion resonances with Jupiter (e.g., 3:1, 5:2, and 2:1 at 2.5, 2.8, and 3.2 AU respectively). Because the 5:2 and 2:1 resonances push material onto Jupiter-crossing orbits, where they are quickly ejected from the inner solar system by a close encounter with Jupiter, numerical results suggest that only the first two resonances are important delivery pathways for NEOs (e.g., Bottke *et al.* 2000, 2002a). For this reason, we focus our attention here on the properties of the ν_6 and 3:1 resonances.

2.2 The ν_6 resonance

The ν_6 secular resonance occurs when the precession frequency of the asteroid's longitude of perihelion is equal to the sixth secular frequency of the planetary system. The latter can be identified with the mean precession frequency of Saturn's longitude of perihelion, but it is also relevant in the secular oscillation of Jupiter's eccentricity (see Morbidelli 2001: ch. 7). The ν_6 resonance marks the inner edge of the main belt. In this region, asteroids have their eccentricity increased enough to reach planet-crossing orbits. The median time required to become an Earth-crosser, starting from a quasi-circular orbit, is about 0.5 My. Accounting for their subsequent evolution in the NEO region, the median lifetime of bodies started in the ν_6 resonance is ~ 2 My, with typical end-states being collision with the Sun (80% of the cases) and ejection onto hyperbolic orbit via a close encounter with Jupiter (12%) (Gladman *et al.* 1997). The mean time spent in the NEO region is 6.5 My, longer than the median time because ν_6 bodies often reach $a < 2$ AU orbits where they can reside for tens of millions of years (Bottke *et al.* 2002a). The mean collision probability of objects from the ν_6 resonance with Earth, integrated over their lifetime in the Earth-crossing region, is ~ 0.01 (Morbidelli and Gladman 1998).

2.3 The 3:1 resonance

The 3:1 mean motion resonance with Jupiter occurs at ~ 2.5 AU, where the orbital period of the asteroid is one-third of that of the giant planet. The resonance width is an increasing function of the eccentricity (about 0.02 AU at $e = 0.1$ and 0.04 AU at $e = 0.2$), while it does not vary appreciably with the inclination. Inside the resonance, one can distinguish two regions: a narrow central region where the asteroid eccentricity has regular oscillations that bring them to periodically cross the orbit of Mars, and a larger border region where the evolution of the eccentricity is wildly chaotic and unbounded, so that the bodies can rapidly reach Earth-crossing and even Sun-grazing orbits. Under the effect of Martian encounters, bodies in the central region can easily transit to the border region and be rapidly boosted into the NEO space (see Morbidelli: 2001 ch. 11). For a population initially uniformly distributed inside the resonance, the median time required to cross the orbit of the Earth is ~ 1 My, and the median lifetime is ~ 2 My. Typical end-states for test bodies including colliding with the Sun (70%) and being ejected onto hyperbolic orbits (28%) (Gladman *et al.* 1997). The mean time spent in the NEO region is 2.2 My (Bottke *et al.* 2002a), and the mean collision probability with the Earth is ~ 0.002 (Morbidelli and Gladman 1998).

The diffusive resonances are so numerous that they cannot be effectively enumerated. Therefore, we only discuss their generic dynamical effects below.

2.4 Diffusive resonances

In addition to the few wide mean motion resonances with Jupiter described above, the main belt is also crisscrossed by hundreds of thin resonances: high-order mean motion resonances with Jupiter (where the orbital frequencies are in a ratio of large integer numbers), three-body resonances with Jupiter and Saturn (where an integer combination of the orbital frequencies of the asteroid, Jupiter, and Saturn is equal to zero) (Nesvorný *et al.* 2002), and mean motion resonances with Mars (Morbideilli and Nesvorný 1999). The typical width of each of these resonances is of the order of a few 10^{-4} – 10^{-3} AU.

Because of these resonances, many, if not most, main belt asteroids are chaotic (e.g., Nesvorný *et al.* 2002). The effect of this chaoticity is very weak, with an asteroid's eccentricity and inclination slowly changing in a secular fashion over time. The time required to reach a planet-crossing orbit (Mars-crossing in the inner belt, Jupiter-crossing in the outer belt) ranges from several 10^7 years to billions of years, depending on the resonances and the starting eccentricity. Integrating real objects in the inner belt ($2 < a < 2.5$ AU) for 100 My, Morbidelli and Nesvorný (1999) showed that chaotic diffusion drives many main belt asteroids into the Mars-crossing region. The flux of escaping asteroids is particularly high in the region adjacent to the ν_6 resonance, where effects from this resonance combine with the effects from numerous Martian mean motion resonances.

It has been shown that the population of asteroids solely on Mars-crossing orbits, which is roughly four times the size of the NEO population, is predominately resupplied by diffusive resonances in the main belt (Migliorini *et al.* 1998; Morbidelli and Nesvorný 1999; Michel *et al.* 2000; Bottke *et al.* 2002a). We call this region the “intermediate-source Mars-crossing region,” or IMC for short. To reach an Earth-crossing orbit, Mars-crossing asteroids random walk in semimajor axis under the effect of Martian encounters until they enter a resonance that is strong enough to further decrease their perihelion distance below 1.3 AU. The mean time spent in the NEO region is 3.75 My (Bottke *et al.* 2002a).

The paucity of observed Mars-crossing asteroids with $a > 2.8$ AU is not due to the inefficiency of chaotic diffusion in the outer asteroid belt, but is rather a consequence of shorter dynamical lifetimes within the vicinity of Jupiter. For example, Morbidelli and Nesvorný (1999) showed that the outer asteroid belt – more specifically the region between 3.1 and 3.25 AU – contains numerous high-order mean motion resonances with Jupiter and three-body resonances with Jupiter and Saturn, such that the dynamics are chaotic for $e > 0.25$. To investigate this, Bottke *et al.* (2002a) integrated nearly 2000 observed main belt asteroids with $2.8 < a < 3.5$ AU, $i < 15^\circ$, and $q < 2.6$ AU for 100 My. They found that $\sim 20\%$ of them entered the NEO region. Accordingly, they predicted that, in a steady-state scenario, the outer main

belt region could provide ~600 new NEOs per My, but the mean time that these bodies spend in the NEO region was only ~0.15 My.

2.5 Near-Earth comets

Comets also contribute to the NEO population. They can be divided into two groups: those coming from the trans-Neptunian region (the Kuiper belt or, more likely, the scattered disk) (Levison and Duncan 1994; Duncan and Levison 1997) and those coming from the Oort cloud (e.g., Weissman *et al.* 2002). Some NEOs with comet-like properties may also come from the Trojan population as well, though it is believed their contribution is small compared to those coming from the trans-Neptunian region and the Oort cloud (Levison and Duncan 1997). The Tisserand parameter T , the pseudo-energy of the Jacobi integral that must be conserved in the restricted circular three-body problem, has been used in the past to classify different comet populations (e.g., Carusi *et al.* 1987). Writing T with respect to Jupiter, we get (Kresak 1979):

$$T = (a_{\text{JUP}}/a) + 2 \cos(i) [(a/a_{\text{JUP}})(1 - e^2)]^{1/2} \tag{1.1}$$

where a_{JUP} is the semimajor axis of Jupiter. Adopting the nomenclature provided by Levison (1996), we refer to $T > 2$ bodies as ecliptic comets, since they tend to have small inclinations, and $T < 2$ bodies as nearly isotropic comets, since they tend to have high inclinations.

Numerical simulations suggest that comets residing in particular parts of the trans-Neptunian region are dynamically unstable over the lifetime of the solar system (e.g., Levison and Duncan 1997; Duncan and Levison 1997). Those ecliptic comets that fall under the gravitational sway of Jupiter ($2 < T < 3$) are called Jupiter-family comets (JFCs). These bodies frequently experience low-velocity encounters with Jupiter. Though most model JFCs are readily thrown out of the inner solar system via a close encounter with Jupiter (i.e., over a timescale of ~0.1 My), a small component of this population achieves NEO status (Levison and Duncan 1997). The orbital distribution of the ecliptic comets has been well characterized using numerical integrations by Levison and Duncan (1997), who find that most JFCs are confined to a region above $a = 2.5$ AU. To create comets with orbits like 2P Encke, which have $T > 3$, it may be necessary to invoke non-gravitational forces.

Nearly isotropic comets, comprised of the long-period comets and the Halley-type comets, come from the Oort cloud (Weissman *et al.* 2002) and possibly the trans-Neptunian region (Levison and Duncan 1997; Duncan and Levison 1997). Numerical work has shown that nearly isotropic comets can be thrown into the inner solar system by a combination of stellar and galactic perturbations (Duncan

et al. 1987). At this time, however, we lack a complete understanding of their dynamical source region (e.g., Levison *et al.* 2001).

To understand the population of ecliptic comets and nearly isotropic comets, we need to understand more than cometary dynamics. Comets undergo physical evolution as they orbit close to the Sun. In some cases, active comets evolve into dormant, asteroidal-appearing objects, with their icy surfaces covered by a lag deposit of non-volatile dust grains, organics, and/or radiation processed material which prevents volatiles from sputtering away (e.g., Weissman *et al.* 2002). Accordingly, if a $T < 3$ object shows no signs of cometary activity, it is often assumed to be a dormant or possibly extinct comet. In other cases, comets self-destruct and totally disintegrate (e.g., comet C/1999 S4 (LINEAR)). The fraction of comets that become dormant or disintegrate among the ecliptic and nearly isotropic comet populations must be understood to gauge the true impact hazard to the Earth. These issues will be discussed in greater detail below.

2.6 Evolution in NEO space

The dynamics of bodies in NEO space is strongly influenced by a complicated interplay between close encounters with the planets and resonant dynamics. Encounters provide an impulse velocity to the body's trajectory, causing the semimajor axis, eccentricity, and inclination to change by a quantity that depends on both the geometry of the encounter and the mass of the planet. Resonances, on the other hand, keep the semimajor axis constant while changing a body's eccentricity and/or inclination.

In general, NEOs with $a \sim 2.5$ AU or smaller do not approach Jupiter even at $e \sim 1$, so that they end their evolution preferentially by an impact with the Sun. Particles that are transported to low semimajor axes ($a < 2$ AU) and eccentricities have dynamical lifetimes that are tens of millions of years long (Gladman *et al.* 1997) because there are no statistically significant dynamical mechanisms to pump up eccentricities to Sun-grazing values. To be dynamically eliminated, the bodies in the evolved region must either collide with a terrestrial planet (rare), or be driven back to $a > 2$ AU, where powerful resonances can push them into the Sun. Bodies that become NEOs with $a > 2.5$ AU, on the other hand, are preferentially transported to the outer solar system or are ejected onto hyperbolic orbit by close encounters with Jupiter. This shorter lifetime is compensated by the fact that these objects are constantly resupplied by fresh main belt material and newly arriving Jupiter-family comets.

3 Quantitative modeling of the NEO population

The observed orbital distribution of NEOs is not representative of the real distribution, because strong biases exist against the discovery of objects on some types

of orbits. Given the pointing history of a NEO survey, the observational bias for a body with a given orbit and absolute magnitude can be computed as the probability of being in the field of view of the survey with an apparent magnitude brighter than the limit of detection (Jedicke 1996; Jedicke and Metcalfe 1998; see review in Jedicke *et al.* 2002). Assuming random angular orbital elements of NEOs, the bias is a function $B(a, e, i, H)$, dependent on semimajor axis, eccentricity, inclination, and on the absolute magnitude H . Each NEO survey has its own bias. Once the bias is known, in principle the real number of objects N can be estimated as

$$N(a, e, i, H) = n(a, e, i, H)/B(a, e, i, H) \tag{1.2}$$

where n is the number of objects detected by the survey. The problem, however, is that we rarely have enough observations to obtain more than a coarse understanding of the debiased NEO population (i.e., the number of bins in a four-dimensional orbital-magnitude space can grow quite large), though such modeling efforts can lead to useful insights (Rabinowitz 1994; Rabinowitz *et al.* 1994; Stuart 2001).

An alternative way to construct a model of the real distribution of NEOs relies on dynamics. Using numerical integration results, it is possible to estimate the steady-state orbital distribution of NEOs coming from each of the main source regions defined above. Here we describe the method used by Bottke *et al.* (2002a). First, a statistically significant number of particles, initially placed in each source region, is tracked across a network of (a, e, i) cells in NEO space until they are dynamically eliminated. The mean time spent by these particles in those cells, called their residence time, is then computed. The resultant residence time distribution shows where the bodies from the source statistically spend their time in the NEO region. As it is well known in statistical mechanics, in a steady-state scenario, the residence time distribution is equal to the relative orbital distribution of the NEOs that originated from the source. This allowed Bottke *et al.* (2002a) to obtain steady-state orbital distributions for NEOs coming from five prominent NEO sources: the ν_6 resonance, the 3:1 resonance, the IMC population (which is a clearinghouse for all of the diffusive resonances in the main belt up to $a = 2.8$ AU), the outer main belt, which includes numerous powerful and diffusive resonances between 2.8 and 3.5 AU, and the Jupiter-family comets. The overall NEO orbital distribution was then constructed as a linear combination of these five distributions, with the contribution of each source dependent on a weighting function. The nearly isotropic comet population was excluded in this model, but its contribution will be discussed below.

The NEO magnitude distribution, assumed to be source-independent, was constructed so its shape could be manipulated using an additional parameter. Combining the resulting NEO orbital-magnitude distribution with the observational biases associated with the Spacewatch survey (Jedicke 1996), Bottke *et al.* (2002a) obtained a model distribution that could be fit to the orbits and magnitudes of

the NEOs discovered or accidentally re-discovered by Spacewatch. A visual comparison showed that the best-fit model adequately matched the orbital-magnitude distribution of the observed NEOs. The fitting procedure for the determination of the parameters was improved by considering additional constraints on the ratios among the populations in the NEO region, in the IMC region, and in the considered portion of the outer belt. The resulting best-fit model nicely matches the distribution of the NEOs observed by Spacewatch (see Bottke *et al.* 2002a: Fig. 10).

Note that once the values of the parameters of the model are computed by best-fitting the observations of *one* survey, the steady state orbital-magnitude distribution of the *entire* NEO population is determined. This distribution is valid also in regions of orbital space that have never been sampled by any survey because of extreme observational biases. This underlines the power of the dynamical approach for debiasing the NEO population.

4 The debiased NEO population

This section is strongly based on the results of the modeling effort by Bottke *et al.* (2002a). Unless explicitly stated, all numbers reported below are taken from that work.

The total NEO population contains 960 ± 120 objects with absolute magnitude $H < 18$ (roughly 1 km in diameter) and with $a < 7.4$ AU. These results are consistent with other recent estimates (Rabinowitz *et al.*, 2000; D'Abramo *et al.*, 2001; Stuart, 2001). Current observational completeness of this population is $\sim 55\text{--}60\%$. The NEO absolute magnitude distribution in the range $13 < H < 22$ is $N(H) = 13.9 \times 10^{0.35(H-13)} dH$, implying $24\,500 \pm 3000$ NEOs with $H < 22$; the error bar on the exponent is ± 0.02 . Assuming that the albedo distribution is not dependent on H , this magnitude distribution implies a cumulative size distribution with exponent -1.75 ± 0.1 . This distribution agrees with estimates obtained by Rabinowitz *et al.* (2000), who directly debiased the magnitude distribution observed by the NEAT (New Earth Asteroid Tracking) survey. Also, it is consistent with the crater size distributions of young surfaces on Venus, Earth, Mars, and the Moon.

The Bottke *et al.* (2002a) model implies that $37 \pm 8\%$ of the NEOs come from the ν_6 resonance, $25 \pm 3\%$ from the IMC population, $23 \pm 9\%$ from the 3:1 resonance, $8 \pm 1\%$ from the outer belt population, and $6 \pm 4\%$ from the Transneptunian region. Thus, the long-debated cometary contribution to the NEO population from the Jupiter-family comets does not exceed 10%. Note that the Bottke *et al.* model was constrained in the JFC region by several objects that are almost certainly dormant comets. For this reason, factors that have complicated discussions of previous JFC population estimates (e.g., issues of converting cometary magnitude to nucleus diameters, etc.) are avoided. Note, however, that the Bottke *et al.* model does not

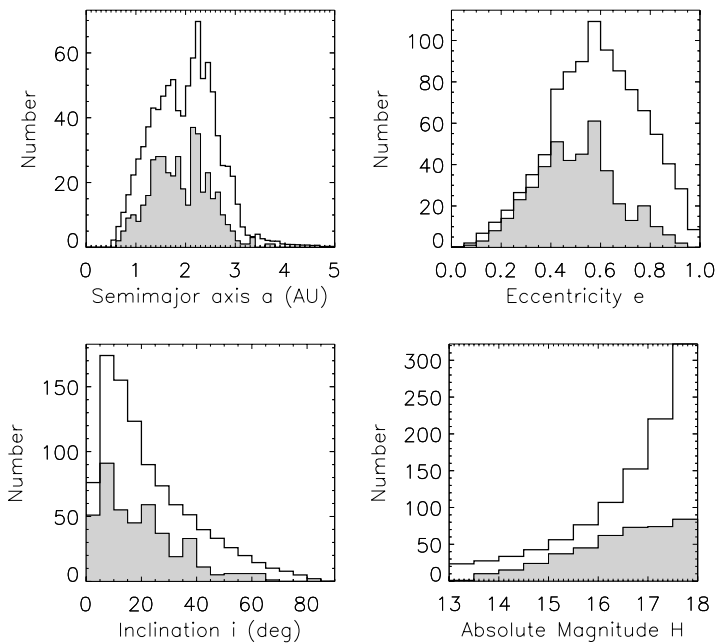


Figure 1.1 The debiased orbital and size distribution of the NEOs for $H < 18$. The predicted NEO distribution (dark solid line) is normalized to 960 NEOs. It is compared with the 426 known NEOs (as of December 2000) from all surveys (shaded histogram). NEO observational completeness was $\sim 44\%$ at the time this plot was created. Most discovered objects have low e and i . From Bottke *et al.* (2002a).

account for the contribution of comets of Oort cloud origin. This issue will be discussed below.

The debiased (a, e, i, H) distribution of the NEOs with $H < 18$ is shown in Fig. 1.1 as a series of four one-dimensional plots (see Bottke *et al.* (2002a) for other representations of this data). For comparison, the figure also reports the distribution of the objects discovered up to $H < 18$, all surveys combined. As one sees, most of the NEOs that are still undiscovered have H larger than 16, e larger than 0.4, a in the range 1–3 AU, and i between 5 and 40 degrees. The populations with $i > 40^\circ$ and $a < 1$ AU or $a > 3$ AU have a larger relative incompleteness, but contain a much more limited number of undiscovered bodies. Of the total NEOs, $32 \pm 1\%$ are Amors, $62 \pm 1\%$ are Apollos, and $6 \pm 1\%$ are Atens; and $49 \pm 4\%$ of the NEOs should be in the evolved region ($a < 2$ AU), where the dynamical lifetime is strongly enhanced. As far as the objects inside Earth’s orbit, or IEOs, the ratio between the IEO and the NEO populations is about 2%. Thus, there are only about 20 IEOs with $H < 18$.

With this orbital distribution, and assuming random values for the argument of perihelion and the longitude of node, about 21% of the NEOs turn out to have a

Minimal Orbital Intersection Distance (MOID) with the Earth smaller than 0.05. The MOID is defined as the closest possible approach distance between the osculating orbits of two objects, provided there are no protective resonances in action. NEOs with MOID < 0.05 AU are called Potentially Hazardous Objects (PHOs), and their accurate orbital determination is considered top priority. About 1% of the NEOs have a MOID smaller than the Moon's distance from the Earth, while the probability to have a MOID smaller than the Earth's radius is 0.025%. Thus, of the 24 500 NEOs with $H < 22$ (approximately 150 m in diameter) about six should have MOIDs smaller than the Earth's radius. This result does not necessarily imply that a collision with Earth is imminent, though, since both the Earth and the NEO still need to rendezvous at the same location, which is unlikely.

We estimate that, on average, the Earth collides with an $H < 18$ NEO once every 0.5 My. By applying the same collision probability calculations to the $H < 18$ NEOs discovered so far, we find that the known objects carry about 47% of the total collisional hazard. Thus, the current completeness of the population computed in terms of collision probability is about the same as that computed in terms of number of objects. This seems to imply that the current surveys discover NEOs more or less evenly with respect to the collision probability with the Earth. The most dangerous and still largely undetected NEO sub-population is that with $0.8 < a < 2.2$ AU and $i < 15^\circ$, with little dependence on the eccentricity.

5 Nearly isotropic comets

We now come to the issue of the contribution of nearly isotropic comets (NICs) to the NEO population (and the terrestrial impact hazard). Dynamical explorations of the orbital distribution of the nearly isotropic comets (Wiegert and Tremaine 1999; Levison *et al.* 2001) indicate that, in order to explain the orbital distribution of the observed population, NICs need to rapidly “fade” (i.e., become essentially unobservable). In other words, physical processes are needed to hide some fraction of the returning NICs from view. One possible solution to this so-called “fading problem” would be to turn bright active comets into dormant, asteroidal-appearing objects with low albedos. If most NICs become dormant, the potential hazard from these objects could be significant. An alternative solution would be for cometary splitting events to break comets into smaller (and harder-to-see) components. If most returning NICs disrupt, the hazard to the Earth from the NIC population would almost certainly be smaller than that from the near-Earth asteroid population.

To explore this issue, Levison *et al.* (2002) took several established comet dynamical evolution models of the NIC population (Wiegert and Tremaine 1999; Levison *et al.* 2001), created fake populations of dormant NICs from these models, and ran these fake objects through a NEO survey simulator that accurately mimics the performance of various NEO surveys (e.g., LINEAR, NEAT) over a time period