Chapter 9

Understanding the Near-Earth Object Population: the 2004 Perspective

William F. Bottke, Jr.

9.1 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). Subcategories 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) that are on nearly-Earth-crossing orbits and can become Earth-crossers over relatively short timescales. Another group of related objects that have 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, I 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 civilisation. 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). Today, the United Nations, the U.S. Congress, the European Council, the UK Parliament, the IAU, OECD, NASA, and ESA have all made official statements that describe the importance of studying and understanding the NEO population. In fact, among all world-wide 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 paper, I review the progress that has been made over the last several years to understand the NEO population. As such, I employ theoretical and numerical models that can be used to estimate the NEO orbital and size distributions. The model results are constrained by the observational efforts of numerous NEO surveys that constantly scan the skies for as of yet unknown objects. The work presented here is based on several papers (Bottke et al. 2002a; Morbidelli et al. 2002a; Morbidelli et al. 2002b; Jedicke et al. 2003) as well as a recent report prepared for NASA entitled "Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters" by Stokes et al. (2003).

9.2
Dynamical Origin of NEOs

9.2.1
Near-Earth Asteroids

The dynamics of bodies in NEO space are 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 an amount that depends on both the speed/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.

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). Most asteroidal NEOs, or near-Earth asteroids (NEAs) for short, are believed to be collisional fragments that were driven out of the main belt by a combination of Yarkovsky thermal forces (i.e. see Bottke et al. 2002b for a review) and secular/mean motion resonances (e.g. J. G. Williams, see Wetherill 1979; Wisdom 1983). In a scenario favored by many scientists, main belt asteroids with diameter $D < 20$–30 km slowly spiral inward and outward via the Yarkovsky effect until being captured by a dynamical resonance capable of increasing their orbital eccentricity enough to reach planet-crossing orbits. Hence, by understanding the populations of asteroids entering and exiting the most important main belt resonances, we can compute the true orbital distribution of the NEAs as a function of semimajor axis a, eccentricity e, and inclination i.

Here I 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 over which resonant asteroids are transported to the NEO region. The most notable resonances in the "powerful" class are the υ_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, I focus my attention here on the properties of the υ_6 and 3 : 1 resonances.

9.2.1.1
The υ_6 Resonance

The υ_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 Chap. 7 of Morbidelli 2002). The υ_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 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 υ_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 υ_6 bodies often reach $a < 2$ AU orbits where they often reside for tens of Myr (Bottke et al. 2002a). The mean collision probability of objects from the υ_6 resonance with Earth, integrated over their lifetime in the Earth-crossing region, is ~1% (Morbidelli and Gladman 1998).

9.2.1.2
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 Chap. 11 of Morbidelli 2002). For a population initially uniformly distributed inside the resonance, the median time required to cross the orbit of the Earth is ~1 My, whereas the median lifetime is ~2 My. Typical end-states for test bodies include 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 ~0.2% (Morbidelli and Gladman 1998).

9.2.1.3
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; Nesvorny et al. 2002), and mean motion resonances with Mars (Morbidelli and Nesvorny 1999). The typical width of each of these resonances is of order of a few 10^{-4}–10^{-3} AU.

Because of these resonances, many, if not most, main belt asteroids are chaotic (e.g. Nesvorny 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 Nesvorny (1999) found 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 4 times the size of the NEO population, is predominately resupplied by diffusive resonances in the main belt (Migliorini et al. 1998; Morbidelli and Nesvorny 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, Nesvorny and Morbidelli (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, $i < 15°$, and $q < 2.6$ AU for 100 My. They found that ~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.

9.2.2
Near-Earth Comets

Numerical simulations suggest that comets residing in particular parts of the Transneptunian region are dynamically unstable over the lifetime of the solar system (e.g. Levison and Duncan 1997; Duncan and Levison 1997). Comets also contribute to the NEO population. Comets can be divided into two groups: those coming from the Transneptunian region (the Kuiper belt or, more likely, the scattered disk; Levison and Duncan 1994; Levison and Duncan 1997; Duncan and Levison 1997) and those coming from the Oort cloud (e.g. Weissman et al. 2002). Some NEOs with comet-like properties may come from the Trojan population as well, though it is believed their contribution is small compared to those coming from the Transneptunian region and 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, the Tisserand parameter becomes (Kresak 1979):

$$T = \frac{a_{\text{Jup}}}{a} + 2\cos i \sqrt{\frac{a}{a_{\text{Jup}}}\left(1 - e^2\right)}$$ #check this please#

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.

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 Myr), a small component of this population achieves NEO status (Levison and Duncan 1997). The orbital distribution of the ecliptic comets has been well characterised using numerical integrations by Levison and Duncan (1997), who find that most JFCs are confined to a region above $a = 2.5$ AU. Comets that are gravitationally decoupled from Jupiter ($T > 3$), like 2P/Encke, are thought to be rare. It is believed that comets reach these orbits via a combination of non-gravitational forces and close encounters with the terrestrial planets.

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 Transneptunian 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, a complete understanding of their dynamical source region (e.g. Levison et al. 2001) is lacking.

To understand the population of ecliptic comets and nearly isotropic comets, an understanding of more than cometary dynamics is needed. 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 that 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 amidst the ecliptic and nearly isotropic comet populations must be understood to gauge the absolute impact hazard to the Earth. We return to this issue in Sect. 9.5.

9.2.3 Evolution in NEO Space

In general, NEOs with $a < 2.5$ AU 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 My 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 re-supplied by fresh main belt material and newly-arriving Jupiter-family comets.

9.3 Quantitative Modeling of the NEO Population

Although there is currently a good working understanding of NEO dynamics, it is still challenging to deduce the true orbital distribution of the NEOs. There are two main reasons for this: (*i*) it is not obvious which source regions provide the greatest contributions to the steady state NEO population, and (*ii*) the observed orbital distribution of the NEOs, which could be used to constrain the contribution from each NEO source, is biased against the discovery of objects on some types of orbits. Given the pointing history of a NEO survey, however, 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 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:

$$N(a,e,i,H) = \frac{n(a,e,i,H)}{B(a,e,i,H)}$$

where n is the number of objects detected by the survey. The problem, however, is that there are rarely enough observations to obtain more than a coarse understanding of the debiased NEO population (i.e. the number of bins in a 4-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 (Bottke et al. 2000; 2002a). 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. The method used by Bottke et al. (2002a) is described below. 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 all the prominent NEO sources: the ν_6 resonance, the 3 : 1 resonance, the population coming from numerous diffusive resonances in the main belt, and the Jupiter family comets. The overall NEO orbital distribution was then constructed as a linear combination of these distributions, with the contribution of each source dependent on a weighting function. (Note that the nearly isotropic comet population was excluded in this model, but its contribution is discussed in Sect. 9.5).

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 resulting best-fit model nicely matches the distribution of the NEOs observed by Spacewatch (see Fig. 10 of Bottke et al. 2002a).

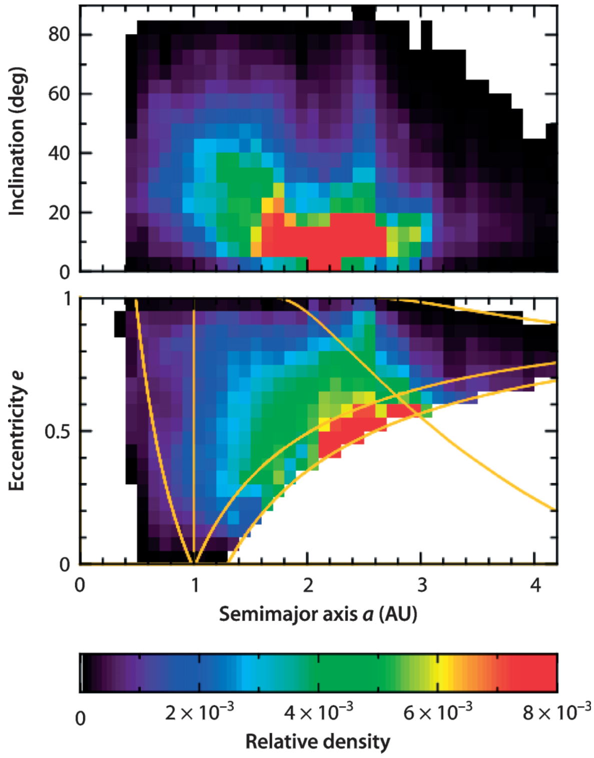
Once the values of the parameters of the model are computed by fitting the observations of *one* survey, the steady state orbital-magnitude distribution of the *entire* NEO population is determined. This distribution is also valid in regions of orbital space that have never been sampled by any survey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

9.4 The Debiased NEO Population

The model results indicate that 37 ± 8% of the NEOs come from the ν_6 resonance, 23 ± 9% from the 3 : 1 resonance, 33 ± 3% from the numerous diffusive resonances stretched across the main belt, and 6 ± 4% come from the Jupiter-family comet region. The model results were constrained in the JFC region by several objects that are almost certainly dormant comets. For this reason, factors that have complicated the 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. (2002a) model does not account for the contribution of comets of Oort cloud origin. This issue will be discussed in Sect. 9.5.

Figure 9.1 displays the debiased (a, e, i) NEO population as a residence time probability distribution plot. To display as much of the full (a, e, i) distribution as possible in two dimensions, the i bins were summed before plotting the distribution in (a, e), while the e bins were summed before plotting the distribution in (a, i). The color scale depicts the expected density of NEOs in a scenario of steady state replenishment from the main belt and transneptunian region. Red colors indicate where NEOs are statistically most likely to spend their time. Bins whose centers have perihelia $q > 1.3$ AU are not used and are colored white. The gold curved lines that meet at 1 AU divide the NEO region into Amor (1.0167 AU < q < 1.3 AU), Apollo (a > 1.0 AU; q < 1.0167 AU) and Aten (a < 1.0 AU; Q > 0.983 AU) components. IEOs (Q < 0.983 AU) are inside Earth's orbit.

Fig. 9.1.
A representation of the probability distribution of residence time for the debiased near-Earth object (NEO) population



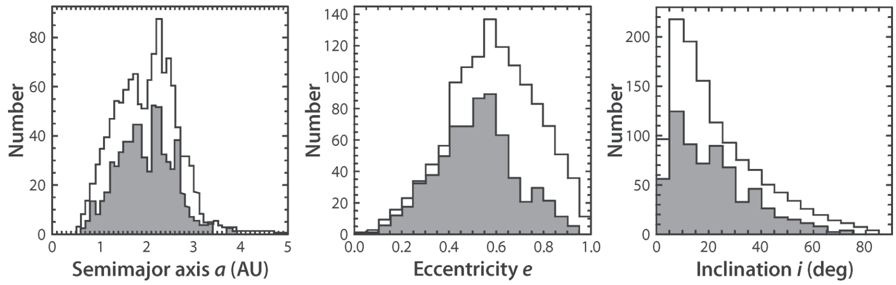


Fig. 9.2. The debiased orbital distribution for NEOs with absolute magnitude $H < 18$. The predicted NEO distribution (*dark solid line*) is normalised to 1200 NEOs. It is compared with the 645 known NEOs (as of April 2003) from all surveys (*shaded*)

The Jupiter-family comet region is defined using two lines of constant Tisserand parameter $2 < T < 3$. The curves in the upper right show where $T = 2$ and $T = 3$ for $i = 0$ deg.

Figure 9.2 displays the debiased distribution of the NEOs with absolute magnitude $H < 18$ as a series of three one-dimensional plots (see Bottke et al. 2002a for other representations of these data). For comparison, the figure also reports the distribution of the objects discovered up to $H < 18$, all surveys combined, as of 2003. For objects with an absolute magnitude brighter than about 18, the object's diameter would be expected to be larger than one kilometer.

The absolute magnitude and size-frequency distributions of the NEO population are discussed in the next section. 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 5–40°. The populations with $i > 40°$, $a < 1$ 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 ± 1% are Amors, 62 ± 1% are Apollos, and 6 ± 1% are Atens. Some 49 ± 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 AU. The MOID is defined as the closest possible approach distance between the osculating orbits of two objects. NEOs with MOID < 0.05 AU are defined as 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; the probability of having a MOID smaller than the Earth's radius is 0.025%. This result does not necessarily imply that a collision with Earth is imminent since both the Earth and the NEO still need to rendezvous at the same location, which is unlikely.

9.5 Nearly Isotropic Comets

I now address 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, nearly-isotropic comets (NIC) 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 NEA 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 artificial populations of dormant NICs from these models, and ran these artificial objects through a NEO survey simulator that accurately mimics the performance of various NEO surveys (e.g. LINEAR, NEAT) over a time period stretching from 1996–2001 (Jedicke et al. 2003). Levison et al. (2002) then compared their model results to the observed population of dormant comets found over the same time period. For example, the survey simulator discovered 1 out of every 22 000 dormant NICs with orbital periods > 200 years, $H < 18$, and perihelion $q < 3$ AU. This result, combined with the fact that only 2 dormant objects with comparable parameters had been discovered between 1996–2001, led them to predict that there are a total of 44 000 ± 31 000 dormant nearly-isotropic comets with orbital periods $P > 200$ years, $H < 18$, and perihelion $q < 3$ AU.

Levison et al. (2002) then used these values to address the fading problem by comparing the total number of artificial dormant nearly isotropic comets discovered between 1996–2001 to the observed number. The results indicated that dynamical models that fail to destroy comets over time produce ~100 times more dormant nearly isotropic comets than can be explained by current NEO survey observations. Hence, to resolve this paradox, Levison et al. (2002) concluded that, as comets evolve inward from the Oort cloud, the vast majority of them must physically disrupt.

Assuming there are 44 000 dormant comets with $P > 200$ years, $H < 18$, and perihelion $q < 3$ AU, Levison et al. (2002) estimated that they should strike the Earth once per 370 Myr. In contrast, the rate that active comets with $P > 200$ years strike the Earth (both new and returning) is roughly once per 32 Myr (Weissman 1990; Morbidelli 2002). For comets with $P < 200$ years, commonly called Halley-type comets (HTCs), Levison et al. (2002) estimate there are 780 ± 260 dormant objects with $H < 18$ and $q < 2.5$ AU. This corresponds to an Earth impact rate of once per 840 Myr. Active HTCs strike even less frequently, with a rate corresponding to once per 3500 Myr (Levison et al. 2001, 2002). Hence, since all of these impact rates are much smaller than that estimated for $H < 18$ NEOs (one impact per 0.5 Myr; Bottke et al. 2002a; Morbidelli et al. 2002a), we conclude that nearly-isotropic comets currently represent a tiny fraction of the total impact hazard.

Another way to look at the issue is as follows. If we assume the bulk densities for a cometary nucleus and an S-type NEA are 0.6 and 2.6 g cm^{-3}, respectively, and the mean Earth impact velocities for long-period comets and NEAs are 55 and 23 km s^{-1}, respectively, then the average impact energy of a long-period comet impact would be only 30% more than a similarly-sized NEA that impacts the Earth. Stokes et al. (2003), using these results as well as methods described in Sekanina and Yeomans (1984) and Marsden (1992), showed that the threat of long-period comets is only about 1% the threat from NEAs. Thus, asteroids rather than comets provide most of the present-day impact hazard.

9.6
NEA Size-Frequency Distribution

Many groups have made estimates of the NEO population in the recent literature (Stuart 2001; D'Abramo et al. 2001; Bottke et al. 2002; Brown et al. 2002; Stuart and Binzel 2004; Bottke et al. 2004). Despite using a wide variety of techniques, all tend to yield comparable results. To keep things simple, it is useful to adopt in this paper the estimate made by Stokes et al. (2003), that, within limits of reasonable uncertainty, fits the NEO absolute magnitude H distribution to a constant power law in logarithmic units:

$$\log[N(<H)] = -5.414 + 0.4708\,H$$

In units of diameter, taking an equivalence of $H = 18$ to be equal to $D = 1$ km (i.e. Morbidelli et al. 2002a) and Stuart and Binzel (2004) estimate that the mean NEO albedo should be ~0.13–0.14, which would implying an equivalence of $H = 17.75$–17.85 to $D = 1$ km), we obtain the relationship:

$$N(D) = 1148\,D^{-2.354}$$

This population model lies slightly above the number currently estimated for the population of NEOs larger than 1 km (1000–1100). Its main advantage is that it lies within about a factor of 2 (on the high side) of numerous NEO small body population estimates for $D > 1$ m. This estimate is used in computing the NEO hazard studies described below.

9.7 Conclusion

The question of how to deal with the threat represented by comets and asteroids was recently reviewed by Near-Earth Object Science Definition Team (Stokes et al. 2003). They found that searching for potential Earth-impacting objects could help eliminate the statistical risk associated with the hazard of impacts. Even though the impact rate of hazardous objects on Earth is low, the "average" rate of destruction due to impacts was deemed large enough to merit additional interest.

Stokes et al. argued that the cost/benefit ratio for finding such objects was favorable enough to warrant the construction of a new NEO search survey. This goal of this new survey would be to discover and catalog the potentially hazardous population enough to eliminate 90% of the remaining hazard (i.e., 90% of the $D > 170$ m objects). This same survey program would also find essentially all of the undiscovered $D > 1$ km objects remaining in the NEO population, thus eliminating the global risk from these larger objects. Once the above goal was met, the average casualty rate from impacts would be reduced from about 300 per year to less than 30 per year. Systems capable of meeting this goal over a period of 7–20 years would likely cost between $ 236 million and $ 397 million, comparable to NASA Discovery-class missions.

The costs of a new survey system, which are tiny relative to the costs of proposed missions to deflect NEOs, could be considered a form of term life insurance taken out by humanity against the hazard represented by infrequent but potentially dangerous impacts. It seems prudent to approach the problem from this direction before taking additional steps that could be both costly and dangerous.

References

Alvarez LW, Alvarez W, Asaro F, and Michel HV (1980) Extraterrestrial cause for the Cretaceous Tertiary extinction. Science 208: 1095–1099

Bland PA, Artemieva NA (2003) Efficient disruption of small asteroids by Earth's atmosphere. Nature 424:288–291

Boslough MBE, Crawford DA (1997) Shoemaker-Levy 9 and plume-forming collisions on Earth. In: Remo JL (ed) Near-Earth Objects. The United Nations International Conference: Proceedings of the International Conference held April 24–26, 1995, in New York, NY. Annals of the New York Academy of Sciences 822:236–282

Bottke WF, Jedicke R, Morbidelli A, Petit JM, Gladman B (2000) Understanding the distribution of near-Earth asteroids. Science 288:2190–2194
Bottke WF, Morbidelli A, Jedicke R, Petit J, Levison HF, Michel P, Metcalfe TS (2002a) Debiased orbital and absolute magnitude distribution of the near-Earth objects. Icarus 156:399–433
Bottke WF, Vokrouhlicky D, Rubincam DP, Broz M (2002b) The effect of Yarkovsky thermal forces on the dynamical evolution of asteroids and meteoroids. In: Bottke WF, Cellino A, Paolicchi P, Binzel RP (eds) Asteroids III. Univ of Arizona Press, Tucson, pp 395–408
Brown P, Spalding RE, ReVelle DO, Tagliaferri E, Worden SP (2002) The flux of small near-Earth object colliding with the Earth. Nature 420:294–296
Carusi A, Kresak L, Perozzi E, Valsecchi GB (1987) High order librations of Halley-type comets. Astron Astrophys 187:899
Chesley SR,Ward SM (2003) A quantitative assessment of the human and economic hazard from impact-generated tsunami. J Environmental Hazards ###
Chyba CF, Thomas JP, Zahnle KJ (1993) The 1908 Tunguska explosion – atmospheric disruption of a stony asteroid. Nature 361:40–44
D'Abramo G, Harris AW, Boattini A, Werner SC, Valsecchi JB (2001) A simple probabilistic model to estimate the population of near-Earth asteroids. Icarus 153:214–217
Duncan MJ, Levison HF (1997) A scattered comet disk and the origin of Jupiter family comets. Science 276:1670–1672
Duncan M, Quinn T, Tremaine S (1987) The formation and extent of the solar system comet cloud. Astron J 94:1330–1338
Duncan M, Quinn T, Tremaine S (1988) The origin of short-period comets. Astrophysical Journal Letters 328:L69–L73
Gladman BJ, Migliorini F, Morbidelli A, Zappala V, Michel P, Cellino A, Froeschle C, Levison HF, Bailey M, Duncan M (1997) Dynamical lifetimes of objects injected into asteroid belt resonances. Science 277:197–201
Harris AW (2002) A new estimate of the population of small NEAs. Bulletin of the American Astronomical Society 34:835
Hills JG, Goda MP (1993) The fragmentation of small asteroids in the atmosphere. Astron J 105:1114–1144
Ivezic Z, 32 colleagues (2001) Solar system objects observed in the Sloan Digital Sky survey commissioning data. Astron J 122:2749–2784
Jedicke R (1996) Detection of near-Earth asteroids based upon their rates of motion. Astron J 111:970
Jedicke R, Metcalfe TS (1998) The orbital and absolute magnitude distributions of main belt asteroids. Icarus 131:245–260
Jedicke R, Larsen J, Spahr T (2002) Observational selection effects in asteroid surveys. In: Bottke WF, Cellino A, Paolicchi P, Binzel RP (eds) Asteroids III. Univ of Arizona Press, Tucson, pp 71–87
Jedicke R, Morbidelli A, Petit J-M, Spahr T, Bottke WF (2003) Earth and space-based NEO survey simulations: prospects for achieving the Spaceguard goal. Icarus 161:17–33
Kresak L (1979) Dynamical interrelations among comets and asteroids. In: Gehrels T (ed) Asteroids. Univ of Arizona Press, Tucson, pp 289–309
Levison HF (1996) Comet taxonomy. In: Rettig TW, Hahn JM (eds) Completing the inventory of the solar system. ASP Conf Series 107:173–191
Levison HF, Duncan MJ (1994) The long-term dynamical behavior of short-period comets. Icarus 108: 18–36
Levison HF, Duncan MJ (1997) From the Kuiper belt to Jupiter-family comets: the spatial distribution of ecliptic comets. Icarus 127:13–32
Levison HF, Dones L, Duncan MJ (2001) The origin of Halley-type comets: probing the inner Oort cloud. Astron J 121:2253–2267
Levison HF, Morbidelli A, Dones L, Jedicke R, Wiegert PA, Bottke WF (2002) The mass disruption of Oort cloud comets. Science 296:2212–2215 [for a detailed treatment, see *http://www.boulder.swri.edu/~hal/PDF/disrupt.pdf*]
Marsden BG (1992) To hit or not to hit. In: Canavan GH, Solem JC, Rather JDG (eds) Proceedings, Near-Earth Objects Interception Workshop. Los Alamos National Laboratory, Los Alamos, NM, pp 67–71

Melosh HJ (2003) Impact-generated tsunamis: an over-rated hazard. Lunar and Planetary Science XXXIV:2013

Michel P, Migliorini F, Morbidelli A, Zappala V (2000) The population of Mars-crossers: classification and dynamical evolution. Icarus 145:332–347

Migliorini F, Michel P, Morbidelli A, Nesvorny D, Zappala V (1998) Origin of Earth-crossing asteroids: a quantitative simulation. Science 281:2022–2024

Morbidelli A (2002) Modern celestial mechanics: aspects of solar system dynamics. Taylor & Francis, London

Morbidelli A, Nesvorny D (1999) Numerous weak resonances drive asteroids toward terrestrial planets orbits. Icarus 139:295–308

Morbidelli A, Jedicke R, Bottke WF, Michel P, Tedesco EF (2002a) From magnitudes to diameters: the albedo distribution of near Earth objects and the Earth collision hazard. Icarus 158:329–342

Morbidelli A, Bottke WF, Froeschle CH, Michel P (2002b) Origin and evolution of near-Earth objects. In: Bottke WF, Cellino A, Paolicchi P, Binzel RP (eds) Asteroids III. Univ of Arizona Press, Tucson, pp 409–422

Morrison D (1992) The Spaceguard survey: report of the NASA international near-Earth-object detection workshop. NASA, Washington, DC

Nesvorny D, Ferraz-Mello S, Holman M, Morbidelli A (2002) Regular and chaotic dynamics in the mean motion resonances: implications for the structure and evolution of the main belt. In: Bottke WF, Cellino A, Paolicchi P, Binzel RP (eds) Asteroids III. Univ of Arizona Press, Tucson, pp 379–394

Rabinowitz DL, Bowell E, Shoemaker EM, Muinonen K (1994) The population of Earth-crossing asteroids. In: Gerhels T (ed) Hazards due to comets and asteroids. Univ of Arizona Press, Tucson, pp 285–312

Rabinowitz DL, Helin E, Lawrence K, Pravdo S (2000) A reduced estimate of the number of kilometre-sized near-Earth asteroids. Nature 403:165–166

Sekanina Z, Yeomans DK (1984) Close encounters and collisions of comets with the Earth. Astron J 89: 154–161

Shoemaker EM (1983) Asteroid and comet bombardment of the Earth. Annual Review of Earth and Planetary Sciences 11:461–494

Stokes GH, Yeomans DK, Bottke WF, Chesley SR, Evans JB, Gold RE, Harris AW, Jewitt D, Kelso TS, McMillan RS, Spahr TB, Worden SP (2003) Report of the Near-Earth Object Science Definition Team: a study to determine the feasibility of extending the search for near-Earth objects to smaller limiting diameters. NASA-OSS-Solar System Exploration Division (*http://neo.jpl.nasa.gov/report.html*)

Stuart JS, (2001) A near-Earth asteroid population estimate from the LINEAR survey. Science 294: 1691–1693

Stuart JS (2003) Observation constraints on the number, albedos, sizes, and impact hazards of the near-Earth asteroids. MIT PhD thesis

Stuart JS, Binzel RP (2004) Bias-corrected population, size distribution, and impact hazard for the near-Earth objects. Icarus 170:295–311

Toon OB, Zahnle K, Morrison D, Turco RP, Covey C (1997) Environmental perturbations caused by the impacts of asteroids and comets. Reviews of Geophysics 35:41–78

Van Dorn WG, LeMehaute B, Hwant L-S (1968) Handbook of explosion-generated water waves, vol 1: state of the art. Tetra Tech, Pasadena, CA

Ward SN, Aspaugh E (2000) Asteroid impact tsunami: a probabilistic hazard assessment. Icarus 145: 64–78

Weissman PR, Bottke WF, Levison H, (2002) Evolution of comets into asteroids. In: Bottke WF, Cellino A, Paolicchi P, Binzel R (eds) Asteroids III. Univ of Arizona Press, Tucson, pp 669–686

Wetherill, GW (1979) Steady state populations of Apollo-Amor objects. Icarus 37: 96–112.

Wiegert P, Tremaine S (1999) The evolution of long-period comets. Icarus 137:84–121

Wisdom J (1983) Chaotic behavior and the origin of the 3/1 Kirkwood Gap. Icarus 56:51–74