Dealing with the Impact Hazard

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Abstract

The small fraction of the asteroids with Earth-crossing or Earth-approaching orbits is of special interest to us because many will eventually impact our planet. The time-averaged impact flux as a function of projectile energy can be derived from lunar cratering statistics, although we have little information on the possible variability of this flux over time. Alternatively, we can use current observations of Near Earth Asteroids (NEAs) to derive the size distribution and flux of impactors. The effects of impacts of various energies can be modeled, using data from historic impacts (such as the K-T impactor 65 million years ago) and the observed 1994 bombardment of Jupiter by fragments of Comet Shoemaker-Levy 9. Such models confirm that the terrestrial biosphere is highly vulnerable to severe perturbation from impacts, so that even such a small event as the K-T impact (by a projectile 10-15 km in diameter) can lead to a mass extinction. Combining the impact flux with estimates of environmental and ecological effects reveals that the greatest contemporary hazard is associated with impactors near one million megatons energy. The current impact hazard is significant relative to other natural hazards, and arguments can be developed to illuminate a variety of public policy issues. These include the relative risk of different impact scenarios and the associated costs and probabilities of success of countermeasures. It is generally agreed that the first step is to survey and catalogue the larger NEAs, and we review the status of the Spaceguard Survey, which has already discovered more than half of the NEAs larger than 1 km diameter, out of a total polulation estimated to be between 1000 and 1200. We compare the efficiency of survey approaches and consider the challenges of international coordination and the problems and opportunities associated with communicating the results with the press and the public. It is also important to reflect on how the impact hazard might be dealt with by both national governments and international decision-making bodies, and to anticipate ways of mitigating the danger if a NEA were located on an apparent Earth-impact trajectory. As the most extreme known example of a natural risk with low probability but

severe global consequences, the NEA impact hazard calls for the most careful consideration and planning.

1. INTRODUCTION

Among the asteroids, those populations that can impact the Earth have a special status. We generally refer to them as Near Earth Asteroids (NEAs), a category that includes many objects (with perihelion out to q = 1.3 AU) that are not currently on threatening orbits (*Chapman et al.*, 1994, *Rabinowitz et al.*, 1994, *Shoemaker et al.*, 1994). Closer to home are the Earth-crossing asteroids (ECAs) or their subgroup the potentially hazardous asteroids (PHAs). In this chapter we will generally use the broader term, NEAs, or even NEOs (near-Earth objects), a term that embraces comets as well. Because of their unstable, planet-approaching orbits, the NEAs have impacted the surfaces of the planets in the inner solar system, including the Earth, influencing both geological and biological evolution. Since there is reason to expect further impacts in the future, the NEAs are a topic with profound political and societal overtones. The impact hazard represents the intersection of asteroid science with public welfare and governmental policy. As Carl Sagan frequently pointed out (*e.g., Sagan*, 1994), the long-term future of human civilization is linked to our ability to understand and ultimately to control the impact environment of our planet.

It is only during the past two decades that scientists have become aware of the scope of the asteroid impact hazard. This topic was broadly reviewed in 1993, leading to publication of a thousand-page book *Hazards Due to Comets and Asteroids* (*Gehrels*, 1994) that remains the primary reference in this field. With surprising speed, this concern has been communicated to governments and the public (*e.g.*, *Morrison et al.*, 1994). Due to the advocacy of NEA researchers (with timely publicity from the collision of Comet Shoemaker-Levy 9 with Jupiter and two feature movies), policy makers and their constituents are aware that impacts are possible. It is less clear, however, that decision-makers are convinced that any major action needs to be taken to deal with the impact hazard. The advocacy role of the science community is pivotal, because the abstract nature of the low-probability threat diminishes the likelihood of a response by either policy makers or their constituents. In this chapter we discuss both the "facts" of the impact hazard and the associated issues of public perception and governmental response.

Much of the material in this chapter is associated with estimating the frequency of impacts and evaluating their consequences, particularly for the Earth's biosphere. In the abstract, the hazard lends itself to such statistical analysis. However, from a policy perspective we do not need precise estimates of either the frequency of impacts or their consequences. We recognize that the actual risk is not statistical; if there is any sizable NEA on a collision course with the Earth, it can be found and the impact predicted decades (or more) in advance. If and when this happens, our attention will focus on that particular object and the circumstances of its predicted impact.

At first, there was considerable skepticism toward proposals for a comprehensive survey to identify any potential impactor decades in advance. Perhaps influenced by their experience with antimissile concepts, many members of the U.S. and Russian defense communities proposed various schemes that could be used to shoot down incoming asteroids given a few days, or even a few hours, of warning (*e.g.*, papers from a Los Alamos workshop collected by *Canavan et al.*, 1993). However, there is no warning system in place or likely to be built that would focus on such a short-term threat. Almost any asteroid that is on an impact trajectory will repeatedly pass close to the Earth on previous orbits, with multiple opportunities for detection. An optical survey system has negligible probability of finding it on its final plunge to Earth, relative to discovery on some previous close pass. The Spaceguard Survey, discussed in detail later in this chapter, is just such a comprehensive optical search, with nearly continuous coverage of the space around the Earth to distances of order 10^8 kilometers. Already, we have found and calculated accurate orbits for more than half of the thousand-odd NEAs larger than 1 km. None of these poses any impact threat on the timescale of a human lifetime. On the other hand, it is still impossible to say anything about the orbits of the undiscovered ones. This Spaceguard Survey approach also has limited use against long-period comets. Fortunately, these comets constitute a rather small fraction of the total impact threat, and we generally omit them from consideration in this chapter.

While it is highly improbable that a large (diameter > 1 km) NEA will hit the Earth within our lifetimes, such an event is entirely possible. In the absence of specific information, such a catastrophe is equally likely at any time, including next year. Society needs to be prepared to deal with this eventuality. In the meantime, however, the search for possible impactors will inevitably

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lead to false positives, NEAs that appear for some time to be a real threat. We need to consider the effect of such reports on society. As we discuss in the final sections of this chapter, impact hazard studies can be considered an applied science; that is, science applied to tangible needs of society. In determining an optimum or even advisable hazard mitigation strategy, the reaction of society to scientific information on the hazard should be considered. The NEO community has a social responsibility to ensure that its message is not just heard but comprehended by society at large. Since the hazard knows no national boundaries, it also behooves us to seek solutions that recognize the international constituency with a stake in impact prediction and prevention.

2. IMPACT HISTORY OF THE EARTH AND MOON

The Earth and the Moon have shared a history of impact by asteroids and comets. The flux was high during accretionary epochs, but the course of general decline during the subsequent 0.5 Gyr is uncertain. A relatively short (~100 Myr long) period of high flux ended about 3.85 Gyr ago, forming a number of lunar basins (probably accompanied by smaller craters). Since this so-called Late Heavy Bombardment, the impact rate has been much lower and fairly constant, to within factors of a few (at least averaged over intervals of 10^8 yrs). The impactors are, by definition, Near Earth Objects (NEOs), which are currently dominated by asteroids derived from the main belt. The types of bodies responsible for impacts in the last ~3.5 Gyr have probably not changed appreciably (*Bottke et al.*, 2002). New analyses of lunar samples suggest variations in flux by up to a factor 4 (*Culler et al.*, 2000): basically a decrease followed by an increase in the last few hundred Myr. There is no reliable evidence concerning shorter, sharper spikes in the flux due to hypothesized comet showers or major asteroidal break-ups, except that they can have made at most a modest contribution to the cumulative impacts.

Modern recognition that the Earth is impacted by asteroids and comets is barely half-a-century old (*cf. Baldwin* 1949), and even Meteor Crater (Arizona) wasn't securely proven to be of impact origin until the work of *Shoemaker et al.* (1960). The fortunate fact that the atmosphere protects us from impacting bodies smaller than a few tens of meters diameter (except for the rare iron meteorites) has the consequence that we have almost no direct experience with cosmic impacts.

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The idea is still developing that impacts have dramatically shaped our planet's climate and the evolution of life. Whatever will eventually be found to be the comparative dominance of impacts versus other causes of climate change (*e.g.* exploding volcanoes, ice ages, snowball Earth instabilities), impacts necessarily make progressively less contribution to the forces shaping our environment on the shorter timescales relevant to humans. This is because impacts are instantaneous events rather than continuously operating processes, and the largest of those likely to have occurred during recorded human history are much smaller than the largest events expected over tens or hundreds of Myr.

Impacts large enough to affect dramatically the fragile climate and ecosystems of the whole planet can cause prominent changes in the geologic record of fossilizable species of life. Such mass extinctions, first recognized two centuries ago, are increasingly being explained as the consequences of impacts. Possible connections between impacts and extinctions had been suggested earlier (*e.g., Urey*, 1973), but the first solid evidence came from the work of *Alvarez et al*. (1980), who proposed that the dinosaur-killing K-T mass extinction was due to an impact, as inferred from the chemical signature of extraterrestrial material in the boundary layer at the end of the Cretaceous. This hypothesis was widely discussed and debated, but generally accepted only after identification of the Chicxulub crater (still among the largest identified on Earth) as the "smoking gun" (*Swisher et al.*, 1992; *Sharpton et al.*, 1992). Evidence is increasing that the very largest mass extinction (the Permian/Triassic) was also due to an impact (*Becker et al*. 2001). Nevertheless, the hypothesis of *Raup* (1990; 1991) that mass extinctions of all magnitudes are predominantly due to impacts has been resisted by many workers for at least two reasons. First, some paleontologists remain skeptical of what seems to astronomers as the inevitability of impacts and their enormous consequences (*Chapman*, 2002); many still consider impact to be an explanation of last resort. Second, the signature iridium-enriched layer found worldwide at the K-T boundary is generally lacking at other extinction boundaries. Possibly iridium-enriched material in large impactors is mainly ejected back into space, or their composition was less enriched in platinum-group metals than the K-T impactor was.

On the timescale of a human lifetime, the 1908 impact in the Tunguska River region of Siberia

stands out as the most remarkable. Estimated (from distant barographic records) as having an 10-15 megaton TNT equivalent energy (MT) when it exploded perhaps 8 km above the ground, the impactor affected an unusually remote part of the world; the first expedition to study Tunguska did not arrive until 1927. The early Russian investigators, failing to find a meteoritic fragments at the site, suggested that the culprit was a small comet. This assumption became the accepted wisdom, although *Sekanina* (1983) made an early case for an asteroidal impactor. Not until the 1990s did numerical modeling of the entry physics clearly indicate that a comet (low-density, friable material) with this kinetic energy could not penetrate into the troposphere, while a rocky (asteroidal) projectile would (*Chyba et al.*, 1993; *Hills & Goda*, 1993; *Chyba*, 1993). Note that by "asteroidal" we mean composed of solid materials of either stony or carbonaceous composition. While we prefer the traditional energy for Tunguska of 10-15 MT, this value is quite uncertain, and modeling by *Boslough and Crawford* (1997) suggests that the energy could have been as low as 3 MT.

A simple qualitative argument for the stony (asteroidal) nature of the Tunguska impactor has been given by *Zahnle* (1996). Consider the alternative. If an low-density icy (cometary) projectile in this energy range penetrates into the lower atmosphere, then a stronger rocky object will make it to the surface and produce a crater. Unless there are very few rocky objects in the small NEA population, we should see many of these fresh km-size craters. But they are clearly not evident on Earth; indeed most of the small young craters (like Meteor Crater) are associated with rare metallic impactors. Thus the common-sense observation that there are few small craters supports the numerical models that indicate that the Tunguska projectile was a rocky NEA and not a comet. If the energy is as low as 3 MT, this qualitative argument is even stronger. Although one still sees occasional statements in the literature that the Tunguska impactor was cometary, the asteroidal hypothesis is generally accepted; *e.g., Vasilyev* (1998), *Sekanina* (1998), *Farinella et al.* (2001).

Impacts or impact scars that most people can personally witness or study are unrepresentative of a big impact that could, with very low probability, present a significant hazard to modern life. We have no direct experience with the kind of impact by an object hundreds of meters or larger that could cause a regional or global catastrophe. However, there are current data from orbital surveillance systems on impact frequencies for objects a few meters in diameter, helping us to tie

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down the low-energy end of the population distribution. Although coverage is incomplete and there are substantial uncertainties in the luminous efficiency calibrations, *Tagliaferri et al.* (1994) estimated, from 136 reported atmospheric entries between 1975 and 1992, that the annual maximum impactor has an energy of roughly 10 kilotons, similar in energy to the Hiroshima atom bomb but about a factor of a thousand less than Tunguska. We have used data since 1992 in US Air Force press releases to derive similar fluxes. The single largest impact reported in the past 25 years, which is several tens of kilotons (*McCord et al.,* 1995), is also consistent with these estimates. Thus we know that collisions with Earth continue for small impactors, although we have little direct experience with the large events that dominate the overall impact risk.

3. PHYSICAL AND BIOLOGICAL EFFECTS OF IMPACTS

The most revolutionary insight of the *Alvarez et al.* (1980) paper was that even small impacts (on a geological or astronomical scale) could severely damage the fragile terrestrial ecosystem. The K-T impactor had a mass a billion times less than that of the Earth, yet the ensuing extinction fundamentally redirected the course of biological evolution. In the two decades since this discovery, considerable work has been done to understand the mechanisms of mass extinction and to evaluate the ways that environmental stress might depend on the energy of the impact. In this section, we summarize the discussion by *Toon et al.* (1997) of the environmental perturbations due to impacts.

The energy of the K-T impact is estimated at 10^8 MT from the size of the Chicxulub crater, and a consistent value of the size of the impactor (10-15 km diameter) is derived from the observed extraterrestrial component in the boundary layer. Immediate effects of the impact included blast and the generation of tsunami (since the impact occurred in a shallow sea). However, the primary agents of global stress appear to have been a short-lived firestorm from atmospheric heating of re-entering ejecta, followed by a persistent (months to years) blackout due to particulates suspended in the stratosphere. Other possibly important effects include chemical changes in the oceans and atmosphere and large climatic oscillations following the impact.

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Toon et al. (1997) reviewed all of these environmental effects and their dependence on impact energy. Their chief goal was to provide relatively simple prescriptions for evaluating the importance of impacting objects over a range of energies and compositions. Since mass extinction events such as the K-T impact are rare (intervals of tens to hundreds of million years), we are especially interested in down-scaling to determine the thresholds for damage on timescales more relevant to human history (*cf*. *Toon et al.*, 1994, *Covey et al.*, 1994, for earlier discussions).

The threshold for atmospheric penetration of impacts, required for the blast effects to reach the ground, is at a few MT (*Chyba et al.*, 1993; *Hills & Goda*, 1993; *Chyba*, 1993). Below this energy, the atmosphere protects us against all but the rare metallic projectiles. For impacts above this threshold, the primary effects of both airbursts and ground impacts are local blast and earthquake, together with setting of local fires. The Tunguska explosion of an NEA about 60 m in diameter provides a relatively small example. Such impacts cause little harm if they enter over the oceans. However, at sizes of hundreds of meters, oceanic impacts dominate the hazard calculations as a result of impact-induced tsunami (*Hills & Goda*, 1993; *Hills et al.*, 1994; *Hills & Mader*, 1997; *Toon et al.*, 1997; *Crawford*, 1998; *Ward & Asphaug*, 2000). Tsunami waves provide a relatively efficient way to carry the impact energy to large distances. This fact, coupled with concentration of human habitation near the shore, makes tsunami important for energies of tens of thousands of MT or greater (NEA diameters of hundreds of meters). While there is considerable uncertainty in both the height of the open-ocean wave and the run-up as it reaches the shore, Toon *et al.* conclude that large tsunami, occurring with average frequency of tens of thousands of years, contribute much more to the hazard than do terrestrial impacts in the same energy range.

The global environmental stress from the K-T event was dominated by a prompt firestorm followed by longer-lasting dust loading of the atmosphere. There is direct evidence in the boundary clay for the soot produced by burning a large fraction of the terrestrial biomass. In addition, analogous effects seen following the impacts of Comet Shoemaker-Levy 9 with Jupiter in July 1994 have been extensively modeled (*Boslough et al.*, 1994; *Zahnle & MacLow*, 1994, 1995). A global firestorm can be ignited by hot debris falling back into the atmosphere on ballistic trajectories from the ejecta plume, as first suggested by *Melosh et al.* (1990). Most of the energy is

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deposited in the mesosphere (where meteors shine), with radiative heating of the lower atmosphere and surface. Toon *et al.* conclude that while this mechanism was important in the K-T event, where it was the probable direct cause of the extinction of large land animals such as the dinosaurs, it does not produce surface temperatures high enough for ignition at impact energies below 10^7 MT.

Global darkness from the absorption of sunlight by ejected dust was the prime agent of the K-T extinction suggested by *Alvarez et al.* (1980). *Toon et al.* (1997), drawing in part on a large literature dealing with volcanic dust and with the stratospheric soot from a nuclear war, calculated the effects of dust loading on atmospheric circulation under various scenarios. GCMs (General Circulation Models) permitted them to follow the post-impact development of the suspended dust and calculate the resulting surface temperatures. As we might expect, the results depend in significant ways on the target material (land or ocean) and the season of impact, but less on exact geographic location, since the dust cloud quickly expands to global scales. Since these effects extend down to impacts as small as 10^5 MT, they dominate in determining the threshold for global disaster (defined by *Chapman and Morrison* (1994) as an environmental catastrophe capable of killing 25% of the world's population, primarily from the agricultural losses of an "impact winter"). Toon *et al.* concluded that the energy range between 10^5 and 10^6 MT is transitional between regional and global effects, with a mean value for the threshold of global catastrophe near 10^6 MT energy, corresponding to an NEA diameter of about 2 km.

Pope (2002) has recently questioned the assumptions made by Toon *et al.* (and others previously) concerning the quantity of submicrometer dust injected into the stratosphere. This fine dust has not been measured directly in the K-T boundary layer, and inferring its quantity indirectly introduces substantial uncertainty into the estimate of the threshold energy for a global catastrophe. This uncertainty could be as great as a factor of plus-or-minus ten in energy, corresponding to a diameter for an asteroid of between 1 and 4 km.

4. CONTEMPORARY HAZARD OF NEA IMPACTS

The hazard associated with NEA impacts -- that is, the probability for an individual of premature death as a consequence of an impact -- depends on the frequency of occurrence as well as the destructive effects. Quantitative estimates of this risk were presented in the *NASA Spaceguard Survey Report* (*Morrison*, 1992) and amplified by *Chapman and Morrison* (1994) and *Morrison et al*. (1994). Such estimates are substantially uncertain due to lack of precision (and possible time dependence) in the impact flux as a function of projectile energy, possibly wide variability in the environmental effects that depend on properties of the impactor and target, and especially ignorance of the response of society to disasters of a magnitude never experienced. However, we can estimate the order of magnitude of the risk and its approximate dependence on impact energy, as a guide to possible societal responses and efforts at mitigation.

For these order-of-magnitude estimates, it is sufficient to approximate the frequency distribution of the impactor flux by a simple, time-invariant power law not very different from the form proposed by *Shoemaker* (1983). In the subsequent section we illustrate such a curve (Figure 3) and examine this assumption in light of current NEA observations, but these considerations do not change the qualitative conclusions of the hazard analysis. This power law distribution, which is close to the expected mass distribution of an NEA population resulting from fragmentation, is essentially catastrophic in form, in that the rare large impacts dominate over the cumulative effects of more frequent smaller impacts. Coupled with the non-linear response of the environment to impact perturbations discussed above, we conclude (as did Chapman and Morrison) that the greatest risk is associated with large impacts, those that create a global ecological catastrophe.

The threshold impact of about 10^6 MT from Toon *et al*. is expected to take place roughly twice per million years. *Chapman and Morrison* (1994) defined the threshold as an event that would kill 25% of the Earth's population - far less than an "extinction level event", but large enough to rank as the worst catastrophe in human history. Adding the lesser casualties from smaller but more frequent impacts, we estimate very roughly that an average individual on Earth today runs a risk of the order of 1 part per million each year of death from an impact. For comparison, this is about the

same level of risk associated with one round-trip commercial air flight per year. Depending on where a person lives, this impact risk may be either higher or lower than the risk due to more familiar natural disasters such as earthquakes or flooding.

Although impacts below the threshold for global catastrophe are much more frequent, the total hazard from such impacts is less. At energies between 10^4 and 10^6 MT, the dominant risk is from tsunami created by deep ocean impacts, as discussed in the previous section. From 10 to 10^4 MT, the blast effects for land impacts dominate. Roughly, the average risk level from tsunami is about an order of magnitude lower than that of the threshold global catastrophe, and that of smaller (blast-dominated) land impacts is down another order of magnitude. However, such estimates depend critically on assumptions about human population distribution, warning time, and societal response (*e.g.*, discussions by *Canavan*, 1993; 1994; 1997).

The primary results from this hazard analysis are qualitative but robust. First, in spite of the substantial uncertainties, we have shown that the statistical impact risk is of the same order of magnitude as other more familiar hazards that are taken seriously by both individuals and governments. This conclusion motivates the quest to find out whether there is or is not an object presently on a trajectory that will hit the Earth. Second, we find that the larger impacts are more hazardous than the sum of all the smaller ones, thus focusing our attention on asteroids 1 km or larger.

Unlike more familiar hazards, the impact risk is primarily from extremely rare events - literally unprecedented in human history. Although there is a chance of order one in a million that each individual will die in any one year from an impact, it is not the case that one out of each million people dies each year from an impact. The impact hazard represents the extreme case of a calamity of low probability but high consequences - consequences that include the possible end of civilization as we know it. It is logical to concentrate first on mitigating the risk from global catastrophes, both because they dominate the risk and because catastrophes of this scale threaten global society, making them qualitatively different from any other known hazard. Later, it may be desirable to extend mitigation efforts to smaller impacts that, while they do not threaten society as a

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whole, are much more likely to happen within our lifetimes. This will be a political decision, of course, related to the value of mitigating the impact hazard relative to other natural hazards (such as earthquakes) that pose comparable local or regional threats.

5. THE SPACEGUARD SURVEY

The first formal proposal for a survey of potentially threatening NEOs was made by the U.S. Congress in 1990. At the request of the House of Representatives, NASA appointed a study group chaired by David Morrison that met during 1991 to evaluate the impact hazard and propose ways to dramatically increase the detection rate of Earth-crossing objects. That group proposed an international "Spaceguard Survey" to be carried out by ground-based optical telescopes equipped with state-of-the-art wide-field detectors and automated search capability (*Morrison*, 1992). The term "Spaceguard" was borrowed (with permission) from Arthur C. Clarke who had used it in his novel *Rendezvous with Rama* to describe a radar warning system designed to protect the Earth from impacts.

In 1994 the U.S. Congress asked the NASA Administrator to submit a Program Plan to locate all NEOs greater than 1 km diameter (roughly the lower limit to the threshold for global catastrophe). The resulting NASA study chaired by Gene Shoemaker articulated the "Spaceguard goal" to discover and catalog at least 90% of all NEAs larger than 1 km in diameter within ten years (*Shoemaker*, 1995). A strong rationale was presented that the NEAs with $D > 1$ km are the most dangerous and deserve the highest priority for detection, as discussed in the previous section (the probable range is from 1 to 4 km diameter). However, the 1-km objects specified in the goal can also be thought of as a convenient metric, since an optical survey does not distinguish between small nearby objects and large distant objects in the telescope field of view. While the largest (brightest) objects are the easiest to discover, at no point has anyone suggested "throwing the little ones back" as in fishing. The Spaceguard goal is a metric for assessing progress, not an end point after which we should cease surveying. As we approach the present goal (which is likely to be reached near 2008, assuming continuing incremental improvements in search systems), it might be well to switch to a new metric (smaller reference diameter for completeness), as has been suggested

(for example) in the recommendations of the UK NEO Task Force (*Atkinson et al*., 2000).

In order to design an optimum search system it is sensible to simulate discovery efficiency as a function of sky area covered, limiting magnitude, and various other parameters. This was done by Muinonen and Bowell as a part of the *Spaceguard Survey Report* (see also *Bowell & Muinonen, 1994*) and has been extended both for evaluating survey efficiency and for bias-correcting survey discoveries to estimate asteroid populations (*Muinonen*, 1998, *Jedicke et al*., this book). *Harris* (1998, 2001) has published the most thorough discussion of such a survey simulation, showing that it is generally better to sacrifice depth of coverage (limiting magnitude) in favor of sky coverage in order to maximize discovery rate. One gains breadth of coverage inversely proportional to integration time, but one gains depth of coverage only proportional to the square root of integration time. For example, by cutting integration time by one fourth, four times the area can be searched to half the depth (in units of intensity). This strategy is of course limited by cycle time (to move the telescope and process the image), and ultimately by the finite area of sky available.

Currently operating surveys cover most of the visible sky each month, with the exception of the southern sky below about –40 degree declination, so to a good approximation our evaluation can assume "all sky" coverage. In evaluating completeness of an all-sky survey vs. depth of coverage (limiting magnitude), *Harris* (1998) noted that the two magnitude parameters, the threshold limiting visual magnitude of detection (m_{lim}) of the putative survey system and the absolute magnitude (H) of the asteroid, are nearly 100% correlated with respect to detection probability. This is simply saying that a survey system with a limiting magnitude $m_{lim} = 20$ will achieve the same completeness of absolute magnitude H = 20 objects as a system with $m_{lim} = 19$ will achieve of H = 19 objects. This simple equivalence allows one to simulate detection efficiency using (m_{lim} - H) as the independent variable. A single calculation can thus be done to estimate fraction completeness as a function of (m_{lim} - H) and then scale the result for specific values of m_{lim} and/or H.

Figure 1 shows plots of completeness vs. diameter for a ten-year, all-sky survey with the same "universal completeness curve" scaled for specific values of survey limiting magnitude. These curves have been modified from those presented by Harris (1998) to represent integral

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completeness (fraction of objects *larger than* a give size, rather than fraction *at* a given size), and in units of diameter D rather than absolute magnitude H. An integral completeness curve depends on a population model, where we have assumed $N(>D)$ proportional to $D^{-2.5}$. The conversion from H to diameter requires and albedo model, where we have assumed a 50-50 mix of light and dark asteroids (albedos 0.20 and 0.05 respectively). From these plots it appears that achieving the Spaceguard goal should require a ten-year, all-sky survey to m_{lim} 20.2. This is about half a magnitude fainter than the detection limit of current surveys (*Stokes et al.*, this book), which are near visual magnitude 19.5 – 19.7.

6. POPULATION AND SURVEY COMPLETENESS

To assess current progress toward achieving the Spaceguard goal, we begin with the number of presently discovered NEAs down to $H = 18$. As of January 28, 2002, using the discoveries and H magnitudes as listed by the Minor Planet Center, that number is $N(H<18) = 587$ (Figure 2). The total of NEAs of all sizes on this date was 1743. During 2001, more than 100 NEAs were discovered brighter than $H = 18$. The discoveries have been dominated by the LINEAR system of two telescopes (*Stokes et al.*, 2000), which have accounted for more than 75% of all discoveries since 1999. Because of the steady improvement in detection efficiency, the discovery rate of NEAs brighter than $H = 18$ has not yet shown the drop-off that would be expected as we pass the halfway mark in meeting the Spaceguard goal.

It is a more difficult task to determine the total population of NEAs in order to obtain a measure of the completeness of the present survey. Figure 3 is a plot of several estimates of the cumulative population $N(<H)$ vs. absolute magnitude (H), using three general methods to be described below. Also included in this figure is the present discovered population, which obviously forms a lower bound for the total population. Below the bottom of the plot is a scale of estimated NEA diameter, adjusted on the assumption that $H = 18.0$ is equivalent to $D = 1.0$ km, and representing typical impact velocities. The top and right-hand scales will be discussed in the next section.

D'Abramo et al. (2001) have estimated the total population by comparing the rate of new

detections of NEAs by LINEAR with the rate of redetections of known objects in the same sample interval. The total population is estimated as the ratio of all detections (new and already known) to redetections, times the previously known population. *D'Abramo et al.* find N(H<18) = 855±101, which because of various biases should be regarded as a lower bound.

Rabinowitz et al. (2000) and *Stuart* (2001) have utilized a different method to estimate the NEA population from discovered objects. They simulate the expected fraction to be discovered, in a manner similar to the method used by *Harris* (1998) for survey analysis, but using the actual sky coverage achieved by the survey in question. They normalize the numbers actually detected by the fraction of an assumed population that are detected by the simulation to derive a population estimate. Rabinowitz *et al.* use Spacewatch and NEAT discoveries to estimate N(H<18) = 689±184 and 708±161, respectively. Both of these estimates are based on very small-number statistics, only of order 100 of the more than 1,000 objects presently known. *Stuart* (2001) has applied similar methods to the much larger sample of LINEAR discoveries, obtaining an estimate of N(H<18) = 1227 (+150, -50). The method used by these investigators has biases that can work in either direction, so it is hard to know if the estimates are likely to be too high or too low. Finally, *Bottke et al.* (2000, 2002) have estimated a value of 960±120 NEAs brighter than H=18, based on a sample of 138 NEAs discovered or rediscovered by Spacewatch, and using a debiased orbital element distribution for the NEO population.

All of the population estimates above are derived from the currently known NEAs. In contrast, it is possible to estimate the average population over the past several billion years from lunar crater statistics (*Opik*, 1960; *Shoemaker*, 1983). Properly, this population will include both comets and asteroids, but several lines of evidence indicate that asteroids dominate the current impacts, as they may have done in the past. This is the approach taken recently by *Werner et al.* (2001), who used a relative size-frequency distribution (SFD) derived from the lunar mare crater SFD, scaled according to theoretical calculations of projectile-to-crater diameter ratio vs. crater size (*e.g.*, *Melosh*, 1989). Even without a detailed knowledge of the dynamics of the impacting population, this curve can be moved vertically to be tangent to the discovered population in the size range where it is presumably very near complete (*e.g.*, for NEAs larger than a few kilometers). Figure 3

shows the results from Werner *et al.* assuming, as customary, that H = 18 is equivalent to D = 1 km, which corresponds to an average albedo of 0.11. In addition we have shown in Figure 3 a curve corresponding to an assumed albedo 0.25. Werner *et al.* suggest that the albedo of smaller NEAs may be higher than those of larger NEAs such that the crater curve, transformed onto a scale of H, might be a smooth blend from the dashed curve on the left to the solid one on the right side of the plot.

In addition to the various estimates discussed above, we have included in Figure 3 a simple power law that is consistent with most estimates from current NEAs.

These estimates, using three different methods and a variety of data sets, span a rather wide range in values (from 689 to 1227 plus uncertainties) for the total NEA population to H = 18. The lowest values appear to be inconsistent with the current total numbers and the continuing high rate of discovery. A conservative lower bound is probably about 800. Considering all of these estimates, it appears that a reasonable summary value to use in evaluating survey completeness is N(H<18) = 1000±200. We will return to discussion of Figure 3 in the next section.

How are we doing with respect to the Spaceguard goal of 90% discovery, if the total population brighter than H = 18 is 1000±200? Consider the three cases of total population of NEAs (H < 18) of 800, 1000, and 1200, as of the beginning of 2002 when 587 had been discovered. Based on a model of completion vs. time of survey (*e.g.*, Figure 3 of *Harris*, 1998, or Figure 4 of *Harris*, 2001), we reach the following approximate conclusions. For a total population of 800, we are already 73% complete and have to find only 133 more to reach the 90% goal. This requires a current discovery rate of only 3/lunation to meet the goal by 2008. For our nominal population of 1000, there are 313 more that must be discovered, and the required rate is 9/lunation. For a total population of 1200, there are 493 more that must be discovered, and we need to be finding 15/lunation to be 90% complete in 2008. Since the discovery rate in 2000/2001 has averaged about 10/lunation, we are on target for the nominal populaiton of 1000, but the real answer to how the survey is progressing depends sensitively on the total population..

It is perhaps illuminating to compare these conclusions with our previous discussion of Figure 1. If the total population is 1200 (near our upper limit from Figure 3), then the conclusion from Fig. 1 that achieving the Spaceguard goal requires an all-sky survey to limiting visual magnitude $m_{lim} =$ 20.2 is consistent with the performance of the current survey at its limiting magnitude near 19.6, which yields a discovery rate (10/lunation) lower than that required for 90% completeness by 2008 (which is 15/lunation). If the population is about 1000, then there is a modest discrepancy between the model limiting magnitude and the current system performance. If the population is as low as 800, then this discrepancy becomes implausibly large. This contradiction, together with the fact that discoveries continue at a rapid pace even above the 600 mark, suggest that total population of NEAs to H = 18 is probably between 1000 and 1200. From a historical perspective, the most important recent change has been the drop in estimated total NEA population (H<18) from 1500-2000 to approximately 1000 –- a revision that has brought achievement of the Spaceguard goal within reach even though most of the survey telescopes are in the 1-m class and do not reach a limiting visual magnitude of 20.

The current telescopes in the Spaceguard Survey are not necessarily an optimum design, but they are doing the job. If we wish to augment the capability of the system, the primary requirement is to reach fainter magnitudes without giving up sky coverage. This could be achieved with larger apertures; today's survey telescopes are almost all in the 1-meter class, which is very small by current astronomical standards. It is also desirable to have at least one telescope in the Southern Hemisphere, since currently about 20% of the sky is not being covered. However, we note that while a southern telescope is desirable, it is not an absolute requirement. A NEA that is missed one year because it is too far south will likely be picked up on a subsequent pass. This gap (or "blind spot") in the south is not qualitatively different from, for example, the gap in coverage caused by the monsoon weather that typically closes down observatories in Arizona and New Mexico during the summer months. The primary effect of these gaps is simply to slow completion of the survey. Fortunately, a Southern Hemisphere survey telescope at a good site could go a long way toward filling both gaps.

Telescopes in space could also be used to augment the survey, but most of the systems that have

been proposed are not likely to be cost-effective compared with ground-based observatories. The cost-effectiveness would be greatly improved, of course, if the NEA survey activity were incorporated as a secondary goal into a spacecraft being launched for other purposes. There is no intrinsic advantage of Earth-orbiting observatories, other than continuously clear sky (in fact, some orbiting telescopes actually have lower duty cycles than ground-based telescopes at good sites). Telescopes looking from interior to the Earth's orbit have an advantage in discovering asteroids that spend most of their time inside the Earth's orbit, but we already know that there are relatively few of these. Any given survey system should be judged on its merits, of course, and there is no reason that a mix of space-based and ground-based instruments could not contribute to NEA surveys.

Recent experience with the output of the NEA survey programs has led to more sophisticated treatments of impact probability (e.g., *Milani & Valsecchi*, 1999; *Chodas & Yeomans*, 1999; *Milani et al*., 2000a & 2000b; *Chesley et al*., 2002; *Milani et al*., this book). In particular, researchers have explored the dynamics of complex encounters. NEAs that might pose a future threat usually pass close to the Earth on previous orbits. On sufficiently close passes, the Earth's gravitational field substantially alters the NEA orbit. Typically, only a very few specific possibilities for resonant return will lead to an impact or even another close pass, at least on a scale of decades. "Keyholes" leading to a possible future impact may be found on the error ellipse of the NEA on the first encounter's target plane (passing through the Earth and normal to the asteroid orbit). These keyholes will initially be only a tiny fraction of the target error ellipse. There may be several keyholes corresponding to different resonances, thus to possible impacts on different future dates. The estimate of risk then depends on the probability that the actual trajectory will take the NEA through one of the keyholes. The rest of that specific target plane is safe, corresponding to the NEA being scattered back into the general population with an impact probability that is not substantially greater than that of typical newly discovered objects.

From a hazard perspective, the goal (for those error ellipses that are non-inclusive of the Earth) is to assure that the NEA does not pass through a keyhole. Follow-up observations or archival "precovery" may shrink the error ellipse away from the keyholes in the same manner that they can

shrink an Earth-inclusive ellipse off the Earth. In cases of short warning where a short arc of observation cannot eliminate the possibility of keyhole passage, it may be necessary to make negative observations along the virtual trajectories leading through the keyholes.

Of course, a specific NEA may impact the Earth without ever passing through a keyhole and experiencing a resonant return. Certain NEAs can impact in a non-resonant return (a return at the opposite node). There are also pathological cases of anomalously large keyholes resulting from "interrupted returns". These are all treated in *Milani et al*.(this book). In the case of one of the best-observed NEAs, 1950 DA (with a 50-year arc and radar range-doppler data), the uncertainty in evaluating a possible impact nearly a millennium in the future is actually dominated by the unknown influence of the Yarkovsky effect, which in turn depends on the albedo distribution, surface shape, and spin dynamics (*Giorgini et al.*, 2002)

One way to look at the Spaceguard Survey is as an effort to find each NEA and declare it safe. "Safe" can be defined as having a target plane error ellipse that is well clear of the Earth and of keyholes leading to the Earth. For this purpose, it is not necessary to calculate most orbits with extreme precision, although there may be good scientific reasons for doing so (such as identifying future targets for radar imaging). So far, nearly all the NEAs discovered by Spaceguard have been declared safe, and the very few exceptions (such as 1950 DA, *Giorgini et al.*, 2002) will remain under surveillance until we can sound the "all clear".

7. CURRENT NEA IMPACT FREQUENCY

While the long-term historic impact frequency can be estimated from lunar cratering, we must turn to the current NEA population to estimate current impact rates, since there is no assurance that such rates have remained constant over time. To relate energy to size of object, we need the average impact velocity, and to relate numbers of bodies to impact frequency requires some rather complicated considerations of the orbital distribution of the NEA population. One way to arrive at both of these quantities is to calculate the circumstances of close approaches to the Earth of the presently known population. Following approaches described in *Harris* (1998, 2001), we took

orbit elements and H magnitudes of all objects known as of July 3, 2001, from the ASTORB data file maintained by Bowell (ftp.lowell.edu/pub/elgb/astorb.dat). We selected only objects with H < 18.0 and perihelion q < 1.0 AU, that is Earth-crossing asteroids (ECAs) with estimated D > 1 km according to the usual assumed albedo of 0.11. The number of asteroids satisfying these criteria was 244, compared to a total of 488 NEAs (q < 1.3 AU) in the same size range. We then calculated all approaches to the Earth closer than 0.1 AU for a full century, from 2002 to 2102, choosing the dates to avoid the bias of discovery apparitions, using unperturbed osculating elements to provide a statistically valid measure of close approach frequency.

We found 273 close approaches (2.73/year) by a total of 100 different NEAs. For each close approach, we tabulated the encounter velocity so we could compute the mean squared impact velocity of the flux to relate that to energy. The radius of the Earth is 4.25×10^{-5} AU, so the frequency of actual impacts, not including the effect of gravitational focusing, should be $(4.25 \times 10^{-4})^2$ times less than the frequency of passes to within 0.1 AU. Since we kept track of encounter velocity for each event, we could correct for the effects of gravitational focusing, which enhanced the impact frequency by a factor of 1.66. Combining all these factors yields an impact frequency from the presently known population of $8.2 \times 10^{-7}\,y^{-1}$. The "per object" impact frequency for NEAs is thus $8.2 \times 10^{-7}/488 = 1.68 \times 10^{-9}\,y^{-1}$. The impact frequency implied for the ECA population is twice as high (but there are half as many of them). In Figure 3 we have taken this per object impact frequency to relate the expected impact interval, right hand scale, to the population N(>D), left hand scale.

An additional result that comes out of the close encounter calculation above is the RMS velocity to relate mass of impactor to energy. We have weighted the individual encounter velocities to account for the higher probability of slower impacts due to gravitational focusing and also added in the contribution of the Earth's gravity to obtain an RMS impact velocity of 20.2 km/s, in excellent agreement with a recent calculation by Bottke (private communication, 2001), in which he also included a bias correction for discovery selection effects. If we assume a mean density of asteroids of 2.5 gm/cm^3, the mass of a 1-km-diameter asteroid is 1.3×10^{12} kg and its kinetic energy at 20 km/sec is 2.6×10^{20} joules. In Figure 3, the impact energy (top) and diameter (bottom) are thus

scaled so that the impact energy is 6.25 x 10^4 MT for a 1-km-diameter NEA.

Steel (1998) carried out a similar derivation based on a sample of the 116 ECAs with H < 18.5 that were known in June 1996. He found an RMS impact speed of 19 km/s and an average terrestrial probability of impact of 5 x 10^{-9} yr^{-1}, about twice as large as the results from our work described above. Other earlier derivations also exist, going back to the work of *Shoemaker* (1983) and even *Opik* (1958, 1960), all giving generally consistent results.

To provide "ground truth" in terms of contemporary impact rates for relatively small NEAs, we plot in Figure 3 the estimated energy, 10 KT (with total uncertainty a factor of 10), of the largest event seen annually in the Earth's atmosphere, based on space surveillance data (*Tagliaferri et al*. 1994, and USAF press releases since 1992). This value is plotted as a horizontal bar in the upper left, representing the uncertainty in the average largest annual event. Note that the straight-line, power-law approximation to the NEA population in Figure 3 falls within a factor of 2 or so of almost all of the population and impact frequency estimates.

We can compare the expected impact frequencies in Figure 3 with the two well-known benchmarks, the Tunguska event (at about 10 MT) and the K-T impact (at about 10^8 MT). The range of uncertainties spans about a factor of 10 in energy for each, and of course we do not know the frequency for these singular events (except that it is not a great deal less than 100 years for Tunguska or 65 million years for K-T). From the plot, the expected frequency for Tunguska-class events ranges from about twice in a millennium for the power law to about once in 10,000 years for the lunar curves. Only if Tunguska was as small as 3-5 MT in energy does the expected frequency approach the century timescale even for the power-law size-frequency distribution. The K-T event frequency from the plot is generally consistent with an average interval of order 100 million years.

While most of the data are approximately consistent with a power law, the lunar-derived NEO population curve of *Werner et al*. (2002) shows an obvious departure, usually interpreted as a shortage of small (diameter less than a few hundred meters) impactors, although it might also

suggest an early excess of large asteroids or comets that are not currently represented in the NEA flux. Interpreted in the usual way, however, the lunar curve indicates that the frequency of Tunguska-size impactors is roughly one per 10,000 years, more than an order of magnitude below the usually quoted frequency of such impacts, and a surprising result given that we experienced such an event within the last century. We don't know where the problem lies, but we suggest that the NEA population derived by Werner *et al.* from the lunar cratering statistics warrants consideration of alternative interpretations of the data.

We conclude this section with a few words about uncertainties. The equivalence between population and impact frequency, and between diameter and impact energy, are probably quite well determined. However, since the observed NEA population curve is derived mainly from sky brightness of asteroids, the biggest uncertainty is the relation between absolute magnitude and diameter. The assumed mean albedo could be wrong by as much as about a factor of ±2 (range from 0.05 to 0.22), translating to a factor of ±1.4 in diameter, or ±4 in mass (energy). For the slope of the population line, this horizontal uncertainty is equal to a vertical (population at a given size) uncertainty of more than a factor of ±2. Note that the factor of two in each direction amounts to choosing mean albedos close to the high and low albedo peaks in the observed bimodal distribution, and ignoring the other fraction. Thus the total uncertainty, observation plus conversion from magnitude to diameter, leads to an uncertainty of perhaps a factor of 3 in our knowledge of the population vs. diameter. This is especially true at the very small end of the distribution where the observational basis is thin and we have almost no direct measure of albedos.

Finally, it is important to reiterate that the entire population of NEOs, or even of NEAs, does not contribute equally to the impact hazard. The NEOs include comets with very long periods. Obviously the individual impact risk for a comet is inversely proportional to its period. This is also true of NEAs in comet-like orbits, such as the recently discovered Earth-crosser 2001 OG18, which has a period of 50 years. Several large NEAs, including Eros, are currently in safe orbits and will not pose any threat for at least a million years. From the perspective of risk, fewer than half of the NEAs are important. Estimates of risk (and metrics of the performance of the Spaceguard Survey) should properly give higher weight to the subset of NEAs that are in the most

risky orbits (as is done, for example, in the file of possibly hazardous asteroids (PHAs) maintained by the Minor Planet Center). A corollary is that once a newly discovered NEA is shown not to belong to one of these hazardous subsets of the population, it can safely be ignored. Several such non-dangerous NEAs have been discovered and lost, but their orbits were determined with sufficient accuracy to ensure that they are not a threat.

8. SOCIETAL CONTEXT FOR NEO SURVEYS

While NEO research embodies classic scientific objectives, studies of impact hazards form an applied science that may be judged by different criteria. In determining an NEO hazard mitigation strategy, we must consider the reaction of society. Such considerations are familiar to specialists in other fields of natural hazard, such as meteorology (with respect to storm forecasts) and seismology. NEO hazard specialists have the added difficulty of explaining a science that is arcane (orbital dynamics) and beyond personal experience (no impact disaster within recorded history). As the NEO community has begun to realize, it has a social responsibility to ensure that its message is not just heard but comprehended by society at large. The adoption of the Torino Impact Scale (*Binzel,* 1997, 2000) was a notable first step toward public communication, although the unique aspects of NEO detection and warning (particularly the evolution of uncertainty) continue to cause communications difficulties (*Chapman,* 2000).

Once it is accepted that the impact hazard is a social and not just a scientific problem, it is a short step to allow that considerations of maximum social benefit may well constrain the scope and form of scientific investigation. That is, while the scientifically optimum level of uncertainty is zero, the socially optimum level is nonzero. It is neither possible nor affordable to remove risk and uncertainty entirely. This is not just a trite benefit-cost argument. Rather, scientific information can have marginal disutility. As an example, many might argue that society incurs a net cost for the science of nuclear physics, since nuclear proliferation is facilitated thereby. Nuclear test ban treaties rest upon a presumption of the disutility of the scientific and technical information derived from the tests. The inescapable conclusion is that if, despite its best intentions, the NEO community levies a perceived cost to society through mishandled or garbled communication, then society may well act

to remove that cost by choosing not to support NEO surveys and related work.

To date, international NEO survey programs have been conducted and coordinated by an eclectic mix of state and non-governmental organizations, operating within the scientific paradigm of openness. The emphasis has been on generating discoveries. Some of these discoveries indicate (initially at least) a non-zero possibility of a future impact, raising the issue of whether to issue a warning. In some cases (*e.g.,* 1997 XF11, 2000 BF19) individuals or organizations have made public warnings that were widely reported by the press, only to be quickly withdrawn when additional data or more refined calculations became available.

When and under what circumstances should public warnings be made? The trigger threshold for a "confirmed warning" is a key parameter for both NEO scientists and those (primarily science journalists) who make decisions about what information to disseminate to the public. The International Astronomical Union (IAU) NEO Working Group adopts as a threshold the "prediction of impacts with probability larger than one in a million (10^{-6}) in the near future (less than 100 years)." This accords with the Torino Scale threshold for a one-kilometer object to achieve Level 1 (that is, to rise out of the background risk). The Torino Scale "raises the bar" for smaller objects - for example, a 100 meter object requires a one-in-ten-thousand (10^{-4}) collision probability to reach Level 1. All of these guidelines are informal, and the IAU leaves any decision about public release to the discoverer of the threat. In practice, each case that has received wide publicity (1997 XF11, 1999 AN10, 2000 BF19, 2000 SG344, 1950 DA) has had its own unique nature, demonstrating both that guidelines must be flexible and that it is impossible to control the behavior of either astronomers or the media by fiat from above. Thus the recent historical average of approximately one warning (or rumor thereof) per year may continue.

Although much thought has been applied to modeling the discovery rate of survey programs (as discussed above), no researcher has attempted to model warning rates, yet that question is of paramount interest to policy makers. There have been no confirmed warnings to date that have survived for more than 24 hours (not counting 1950 DA, with a low-probability impact possibility nearly a millennium in the future), so when the first such occurs, society is in uncharted territory.

Of course, most confirmed warnings will become false alarms when new data are acquired, and it can be expected that major astronomical facilities can be quickly turned to NEO follow-up given sufficient priority to do so. It is an interesting situation: since most warnings will be false alarms, it would seem to make sense to raise the warning threshold, yet doing so might result in less effort to make new observations and thereby prolong the perception of a potential threat. The reason given for most announcements has been to stimulate additional observations, with warning to the public a secondary issue.

As discussed previously, the Spaceguard Survey will shortly experience diminishing returns in its primary goal of discovering NEAs larger than 1 km, a natural consequence of population sampling without replacement. On the other hand, discoveries of smaller NEAs will continue in proportion to sky coverage and aperture, as their population has been barely sampled. There will be a natural incentive to shift the survey goal down in size to the region of highest return. There is already a "policy hook" for extending the search to smaller objects, in the form of the Council of Europe's Parliamentary Assembly Declaration 1080 "on the detection of asteroids and comets potentially dangerous to humankind". This document called for establishment of an "inventory of NEOs as complete as possible with an emphasis on objects larger than 0.5 km in size." More recently, the U.K. NEO Task Force (*Atkinson et al.,* 2000) called for a "new 3 meter-class survey telescope for surveying substantially smaller objects than those now systematically observed by other telescopes." In the US, the National Research Council has recommended the construction of a 6-8-meter Large-aperture Synoptic Survey Telescope (LSST), with one goal to "catalog 90% of the NEOs larger than 300 m" (*National Research Council*, 2001). Note that the smaller telescopes now used for follow-up will be unable to keep up with the newer, larger aperture survey telescopes in terms of limiting magnitude. This situation is recognized by the planners of the LSST, who expect that this telescope will carry out all its own follow-up observations, sufficient to yield a good orbit for each NEA discovered (*S.Wolff*, private communication, 2002)

9. MITIGATION PROGRAMS AND INSTITUTIONS

Mitigation of the NEA impact hazard can take three forms. The preferred but most technically

challenging option is to deflect the threatening NEA, changing its orbit so that it will miss the Earth (*Ahrens & Harris*, 1992, 1994; *Simonenko et al.*, 1994; *Melosh et al.*, 1994; *Morrison & Teller*, 1994; *Weissman*, 1994; *Asphaug et al.*, 1998; *Benz & Asphaug*, 1999). Alternatively, we can predict an impact and prepare the planet (or at least the target area) to survive the event as well as possible. Least desirable but perhaps most likely, we can follow the example of other natural hazards such as earthquakes and severe storms, focusing not on prevention but on dealing with the aftermath on an impact (*Garshnek et al.*, 2000). In practice, these options are complementary, depending primarily on whether or not there is a long-lead warning of the threat. Note that a short lead time for an NEA is extremely unlikely – we can expect either decades of warning or none at all. It is actually quite difficult to envision a system that provides only short warnings; a detection system that will find an incoming NEO 10 days before impact is also likely to find any impactor decades before it strikes. There are also legal implications of decisions to mitigate or not, as introduced by *Gerard* (1997) and *Seamone* (2002)

Consider the option of interception and deflection, which would require new and expensive defensive systems. Should such systems be developed now? From the standpoint of an allocator of society's resources, an uncertain threat calls for adaptive policies, delaying potentially costly action but informing later decision by investing in uncertainty-reduction measures. In the context of the NEO impact hazard, this means avoiding the costs of standing organizational structures and capital expenditures until a threat materializes, while continuing modest support for surveys and inexpensive studies of mitigation options. Measures to gather information about the hazard (such as space missions to NEOs) could also be supported, especially if they can be justified on other scientific grounds.

In an organizational sense, planning for adaptivity entails establishing a chain of responsibility prior to the materialization of an emergency - that is, a shadow institution. It is illustrative to examine a hypothetical NEO emergency organizational plan, using the U.S. government as an example. We need an office in the Executive Branch of government, and the National Science and Technology Council (NSTC, part of the White House Office of Science and Technology Policy or OSTP) seems to have natural purview over the impact hazard. NSTC has five multi-agency committees,

each of which pertains to an aspect of the impact hazard: Environment and Natural Resources; International Science, Engineering, and Technology; National Security; Science; and Technology. The formal assignment of the NEO impact hazard to an NSTC Committee would be accomplished by the drafting of a Presidential Decision Directive (PDD/NSTC) or Presidential Review Directive (PRD/NSTC). Little else would need to be done until there is confirmed warning of a threat. In all likelihood the draft PDD has remained in the desk drawer of an NSTC staffer. The President's signature would be sought only upon confirmation of the warning. In the unlikely event that lead-time is short, the issue will be moved out of the NSTC to the National Security Council (NSC). In that case, the PDD can be issued as a joint NSC/NSTC document, for which there is precedent in the National Space Policy of 19 September 1996 (PDD/NSTC 8 and PDD/NSC 49). Undoubtedly similar procedures exist in other countries, and it may be that multinational organizations (including the United Nations) would also wish to develop contingency plans.

The principles of adaptive planning in the face of uncertainty fundamentally affect mitigation investment decisions. Civil defense measures have the advantage that improvements can be gained due to synergism with more mundane natural hazards. To date, very little attention has been given to the demands that would be placed on governmental and private disaster-response systems by even a small (Tunguska-class) impact in a populated region (*Garshnek et al.*, 2000; *Chapman*, 2000)). However, consider the more challenging question of interception to deflect a threatening NEO, and the expenses of a standing force of anti-NEO launchers. It has been the position of most NEO researchers that these expenses are best deferred, since in all likelihood there will be sufficient warning time before impact to develop an interception system from scratch. To this, the advocates of interception systems reply that "in all likelihood" does not mean "always", and then play the trump card of the cometary threat. An example of a defense architecture oriented toward this most challenging case is found in *Gold* (1999).

The diverse nature of the NEO population (particularly with regard to mechanical strength and composition) has been used as an argument to defer investment in interception capability until a specific target object has been identified (*e.g.*, *Morrison et al.*, 1994; *Harris et al.*, 1994; *Sagan* 1992, 1994; *Sagan & Ostro*, 1994). On the other hand, in a survey regime characterized by many

false warnings, value can be gained from a system that has uncertain effect, to the degree that it reassures the population and prevents panic. For example, the US rushed Patriot antiaircraft missile batteries to Israel during the Desert Storm conflict with Iraq, for defense against ballistic missiles, despite the fact that they were not designed to intercept missiles. The Patriots proved militarily ineffective but politically very useful.

An adaptive planning approach could also accommodate the short warning scenario associated with long-period comets, requiring that a relatively low-cost generic interception system be built and tested, then shelved. In the event of emergency, the system would enter surge production, with industrial capacity commandeered from other programs. In this manner, there would be a tailored response to the threat, and operational flexibility would be enhanced. Salvoes could be launched, and in many cases, shoot-look-shoot would be possible.

It is facile but probably misleading to focus on a scenario where an NEO progresses in a step function from zero threat to Earth impactor. The threat that stays a threat will experience an overall rise in impact probability, as the error ellipse shrinks while the Earth stays within it. Many more threats than not, however, will suddenly see their impact probability go to zero as the error ellipse shrinks to exclude the Earth, or shrinks to exclude dangerous keyholes for the case of a resonant return. This feature of the evolution of impactor uncertainty will encourage those who wish to defer commitment to interception or who just want to keep the public purse closed. The net effect is that the system reaction time will need to be much shorter than the warning time from point of confirmed threat. This already challenging situation will only be worsened by failure to examine scenarios and develop appropriate contingency plans. To date the NEO community has not made much effort to pursue such options or enter into dialog with government organs that deal with security issues.

Many of these issues were discussed by *Parks et al*. (1994), who concluded that societies will not sustain indefinitely a defense against an infrequent and unpredictable threat. Governments often respond quickly to a crisis but are less well suited to remaining prepared for extended periods. But these conclusions reflect a history in which the less frequent threats are generally of less

consequence than those encountered more often. In contrast, the greatest NEA impact hazard is from the very rare large impacts. Put simply, each reader of this chapter has a greater chance of dying within the next month from a globally catastrophic impact than from any of the smaller more frequent impacts. It remains to be seen how governments and other institutions of society will respond to this unique problem.

10. INTERNATIONAL COOPERATION

While several governments have officially recognized the impact hazard and the value of surveying for NEAs, the bulk of the financial and material support for such surveys has come from the United States. With the support of the US Congress, NASA has taken the leading role in organizing and funding the Spaceguard Survey, while the US Air Force has supplied equipment and some key personnel. Current NEA discoveries are dominated by a few groups in the US, notably the LINEAR survey using two telescopes in New Mexico (Stokes *et al.*, 2000, Stokes *et al.*, this book). Other major programs are NEAT (a JPL-USAF partnership), Spacewatch (University of Arizona), LONEOS (Lowell Observatory), and the Catalina Survey (University of Arizona). However, discovery alone is not sufficient. To avoid losing newly discovered NEAs due to imprecise orbits, discovery must be followed by numerous follow-up observations, suitably distributed in time and aimed at collecting the data necessary to compute accurate orbits. These efforts are widely international in scope, and most depend on volunteer labor. As the number and size of survey telescopes increases, this follow-up becomes increasingly difficult.

The coordination of these efforts is informal and voluntary. When an object is discovered, its position on the sky is computed and this measurement is transmitted to the Minor Planet Center (MPC, Cambridge, Mass.), which acts as a clearing-house on behalf of the International Astronomical Union (IAU). If the observations pertain to an NEO and can be verified by additional data, they are posted on a special web page, the NEO Confirmation Page (http://cfa-www.harvard.edu/cfa/ps/NEO/ToConfirm.html), where observers can get preliminary ephemerides. All these data are available to observers around the world, and follow-up observations are performed by more than 80 centers. However, the MPC has not the capability, nor

the purpose, to coordinate observations at a higher level. Consequently, there is overlap and inefficiency in both the original surveys and the astrometric follow-up. In this sense, there is no single Spaceguard Survey, but rather a group of individual teams who cooperate or compete (usually both) based on their own capabilities and priorities.

More specific coordination is the objective of the Spaceguard Central Node of The Spaceguard Foundation (SGF). This professional international organization, created in 1996, began its coordinating efforts in 1999 (http://spaceguard.ias.rm.cnr.it). There are at least two types of searches that are coordinated by the SGF: the "real" follow-up, consisting of repeated observations of known objects and aiming at an improved knowledge of their orbits, and the archival searches intended to identify pre-discoveries. In both cases a better coordination is extremely helpful, and is obtained by providing support to the interested people and teams. Additional support comes from the NEO Dynamic Site at the University of Pisa (Italy; NEODyS: http://newton.dm.unipi.it/neodys), the NASA NEO Program Office of JPL in Pasadena (USA; http://neo.jpl.nasa.gov), and the Asteroid Observing Service of the Lowell Observatory in Flagstaff, Arizona (http://asteroid.lowell.edu).

Apart from the interest demonstrated by the Office of Outer Space Affairs of the United Nations, which organized a meeting on this subject in 1995 at the UN headquarters in New York, the first international, non-scientific organization to examine the issue of the impact hazard was the Council of Europe, in 1996. In its Resolution 1080 "on the detection of asteroids and comets potentially dangerous to humankind", the Council of Europe underlined the relevance of the impact threat and invited all Member States (about 30) and the European Space Agency (ESA) to take steps in supporting and funding an international program of NEO studies. Unfortunately, no European nation has taken any initiative in this sense until recently.

In 1999 the United Nations' Committee for the Peaceful Uses of Outer Space (COPUOS) organized its third conference in Vienna (UNISPACE III). The impact hazard was discussed in an *ad hoc* Working Group, which produced a document asking for a deep involvement of all nations, and of the UN in particular, in NEO research. This document has moved the Assembly (composed

by representatives of the UN member states) to include a mention of the necessity of an internationally coordinated effort on this subject in the Declaration of Vienna, the final document of the Conference approved by the UN General Assembly later in the year.

In addition to the United States, two more nations have taken initiatives concerning NEOs: Japan and the United Kingdom. The Japanese government has funded an observational facility in Bisei that expects to be operational in 2002 (*Isobe*, 1999). This center is intended to perform simultaneously studies on space debris and NEOs. The most visible recent action has come from the United Kingdom, where the government nominated a Task Force on NEOs in 1999, chaired by Harry Atkinson. The main purpose of this group was to investigate the current status of the NEO issue and to suggest to the British government actions to be taken to cope with it. The report of the NEO Task Force (*Atkinson et al.,* 2000) contained 14 recommendations to the government. The position of the British government is that any initiative in this sense must be agreed internationally, and internationally funded. The British government has been the only European government, at this time, to make a public commitment to some kind of action.

As discussed in the previous section, we can expect greater governmental interest when the entire NEO impact problem is addressed, not just the astronomical search for NEAs. Scientific investigations alone are not sufficient, nor completely appropriate, for the solution of the problem. Other, non-scientific organizations must be involved, especially the civil defense organizations in different countries. Of particular interest is the decision in January 2002 that the Organization for the Economic Cooperation and Development (OECD) be directly involved in the elaboration of an action plan, owing to the authoritative influence that this organization has on scientific matters of global interest (through its Global Science Forum).

11. CONCLUSIONS

It is now evident that the impact problem has several peculiar characteristics that make it an issue of great scientific and social importance. Scientifically, the core of the problem is to understand the dynamical and physical processes that lead to impacts and that may affect the development and

evolution of life on Earth. Socially, we need to understand the effects of impacts (and warnings of impacts) on human society. This double character of the problem is one of the reasons for its confused status at a political level, and is the most urgent aspect that needs to be solved on an international basis.

NEO scientists, primarily astronomers, have succeeded in alerting the world to the existence of an impact hazard, and they have been very successful in undertaking the Spaceguard Survey, focused (so far) on the threat of global disaster from collision with a NEA of diameter greater than 1 km. It is fortunate that the greatest danger, in both quantitative and qualitative terms, arises from the larger NEAs, which are the most readily discovered by astronomical techniques. Our success is the product of synergy between the technology (wide-field CCD detectors and powerful computational tools) and a recognition of a societal desire to discover and track any projectiles large enough to threaten the survival of human civilization. Currently we have discovered more than half of the NEAs larger than 1 km, and perhaps more than 80% of those larger than 2 km. As a result, the present risk of being struck without warning by a large NEA has been cut by more than half. However, we should note that achieving the second half of the survey will be much more challenging than the first, and that there is still little formal coordination of observing teams (and follow-up) into a coherent international survey.

It is possible, however, that we will be a victim of our own success. As current surveys become more complete at sizes of 1 km or greater, the rate of discovery of 1-km NEAs will drop. There is as yet no consensus as to the next critical target. Do we want to find all NEAs down to 500 m, or 300 m, roughly the sizes at which the tsunami danger is greatest? Or should we ultimately anticipate a survey and warning system that is complete down to 50 m, so that we can with confidence predict the "next Tunguska"? How much is society willing to invest to reach these goals?

It is in this context that the NEO science community needs to engage in active dialog with other professionals with greater experience in disaster mitigation and national security. We need to consider the societal context of NEO searches and of approaches to mitigation. If the resources

required for NEO studies increase, these other considerations will play a critical role in determining what priority will be placed on protecting our planet from cosmic impacts.

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FIGURE CAPTIONS

Figure 1. Completeness vs. diameter for a ten-year, all-sky survey of NEAs; the model assumptions are described in the text. These plots suggest that achieving the Spaceguard goal of 90% completeness for NEAs larger than 1 km requires a ten-year survey to limiting visual magnitude of approximately 20.2.

Figure 2. Discovery history showing cumulative number for all NEAs and for those NEAs with absolute magnitude H = 18 or brighter (corresponding approximately to 1 km or larger diameter). The totals as of the end of January 2002 were 587 brighter than H = 18, and 1743 total.

Figure 3. Cumulative population of NEAs vs. absolute magnitude, with equivalent scales for diameter in km, impact energy in MT, and expected impact interval in years. See text for detailed discussion of scale equivalence factors and uncertainties of the various quantities plotted. The current observed rate of atmospheric impacts is plotted at the upper left, and the energies of the Tunguska and K-T (end-Cretaceous) impacts are also indicated. The straight line is a simple power law that approximates the data.

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