PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2006) **364**, 2041–2054
doi:10.1098/rsta.2006.1812
Published online 26 June 2006

Asteroid and comet impacts: the ultimate environmental catastrophe

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Cosmic impacts represent the most extreme class of natural hazards, combining a very low probability of occurrence with a capability of killing hundreds of millions and destabilizing global civilization. Fortunately, these disasters are amenable to precise prediction and even (in principle) can be avoided entirely by appropriate application of space technology. However, impacts take place so rarely that they have only recently been recognized as a significant natural hazard. Concerted international action to deal with impacts depends on increased public awareness.

Keywords: cosmic impacts; natural hazards; asteroids; global catastrophes; risk perception; risk communication

1. Introduction

Although much less frequent than most natural hazards, cosmic impacts represent the most extreme known threat in terms of damage and casualties (for a recent review see Morrison *et al.* 2003). As we know from the end Cretaceous impact of 65 Ma, the global effects of such catastrophes can include mass extinction of species. Fortunately, events of this magnitude are exceedingly rare, and astronomers are confident that there are no asteroids in Earth-approaching orbits today as large as the one that ended the age of the dinosaurs. However, the population of cosmic impactors spans a vast size range, with many more small objects than large ones. There are more than a million near-Earth asteroids that are capable of causing severe local disasters when they strike. For perspective, note that even the smallest projectile that can reach the surface at cosmic speed has an explosive energy hundreds of times greater than the Hiroshima atom bomb.

It is of interest to compare the natural hazards discussed in this collection of papers. Although each acts in different ways, there are some points of commonality. An impact that releases a million megatons of energy (representing an asteroid approx. 2 km in diameter) excavates a crater with an initial volume of several thousand cubic kilometres. This produces some 10^{16} kg of ejecta, roughly equivalent to the ejecta from an M9 supervolcano, which is near the upper limit possible (both Toba and the largest past Yellowstone eruptions are

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One contribution of 20 to a Discussion Meeting Issue 'Extreme natural hazards'.

classed as M8, while Fish Creek was probably M9 (Lowenstern *et al.* 2006) this issue). A comparison of energy (but not, of course, ejected debris) indicates that the million–megaton impact of a 2 km asteroid is equivalent to an earthquake magnitude of 10, which is beyond the range considered possible. A magnitude 9 earthquake releases the same energy as an impact by a 600 m asteroid. Comparisons are more difficult for tsunamis, since the wavelength and propagation of an impact tsunami are different from that of a seismic tsunami. However, a deep-ocean impact by a 500 m class asteroid might produce an effect similar to the Indian Ocean tsunami of December 2004. In any such comparisons, of course, one must remember that different natural events have their own signatures in terms of damage and casualties, and these differences are not captured in the comparisons above.

The Earth's atmosphere provides protection against small impacts. Below about 40 m diameter, atmospheric friction and shear stress on a stony projectile cause it to decelerate and disintegrate at high altitudes, with little blast damage on the ground. These upper-atmosphere explosions are regularly monitored by military surveillance satellites. The debris that reach the surface typically consist of fist-sized rocks falling at terminal velocity—able to penetrate the roof of a house or a car, but unable to cause an impact explosion. The debris are called meteorites, and many tons fall on Earth every day. The risk they pose is miniscule—of order 1 reported fatality worldwide per century. The risk discussed in this paper is from impactors that retain their cosmic velocities down to the lower atmosphere or surface, where they explode with great destructive potential.

Impacts represent the extreme among natural disasters both in the large magnitude of the potential destruction and in the infrequency with which they occur (Morrison *et al.* 1994). These are not 10 or 100 year events, but events that take place on millennial or longer time-scales. In the modern world, no one has been killed by an impact explosion. Indeed, there are no reliable historical examples of mass mortality due to impacts. While we can calculate that the risk to an individual of death from impact is of order 1 in a million per year, it does not follow that one person in a million dies from this cause each year. The 'packaging' of this hazard concentrates most of the risk in the larger, very rare events.

Impacts are also unique among natural hazards in that they can be predicted with great precision and are amenable to elimination by the application of advanced space technology. In most natural hazards, preparation, response and mitigation all suppose that the event itself takes place, and the best we can do is take advanced action to minimize casualties and be prepared to provide assistance when the disaster occurs. In contrast, astronomers today are capable of predicting the motions of known asteroids with sufficient accuracy to identify specific potential impacts with a warning time of decades or even centuries.

Such prediction is possible because asteroids pass close to the Earth many times before they hit. A survey can pick them up decades or more before their final plunge toward impact, and asteroids do not (except in Hollywood) change orbits capriciously. We have neither the desire nor the capability to find them a few hours, or even a few weeks, before impact. A long-term warning of an impact can, however, permit relocation of the population and key infrastructure from the target area. Better yet, the threatening asteroid can, in principle, be diverted so that it misses the Earth entirely. While we have not yet developed this technology, I expect that several decades of warning of an impending global tragedy would provide sufficient motivation for the space-faring nations of the Earth to solve the technical problems of asteroid defence.

2. The impact hazard

In this section, I discuss the impact hazard the same way we often address other hazards, treating impacts as random or stochastic events and estimating impact probabilities and associated risk. Later in the paper I address its unique aspects as a predictable and preventable catastrophe.

Awareness of the impact hazard is a recent phenomenon, for the simple reason that no event of this kind has been directly observed in the course of human history (Chapman 2000). By the middle of the twentieth century, a few prescient scientists, such as Ernst Opik and Gene Shoemaker, began to realize the implications for Earth history of the cratered face of the Moon. Simultaneously, astronomical discoveries of numerous asteroids and comets having Earth-crossing orbits indicated that the crater-forming epoch of solar system history did not end millions of years ago. But widespread interest in impacts by both scientists and the public largely dates from the identification by Alvarez *et al.* (1980) of a cosmic impact as the cause of the K-T (end Cretaceous) mass extinction 65 Ma. Within a decade, the K-T impact crater had been identified and a substantial body of knowledge had accumulated on the killing effects of such an impact.

From the perspective of the current impact hazard, the most revolutionary insight of the Alvarez paper was that even small impacts (on a geological or astronomical scale) could severely damage the terrestrial ecosystem (Chapman & Morrison 1994). The K-T impactor had a mass one 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.

Figure 1 illustrates the average frequency of impacts on Earth by projectiles spanning 12 orders of magnitude in mass or impact energy, from the K-T impactor down to bright meteors or bolides. These estimates, which are accurate to roughly a factor of 3, are determined primarily from the observed numbers and orbital dynamics of current Earth-crossing asteroids and comets, but they are also consistent with the long-term cratering rates on the Earth and Moon (for recent reviews of the population of near-Earth asteroids see Bottke *et al.* 2004; Chesley & Spahr 2004; Harris 2004; Stuart 2001). Note that while comets undoubtedly contribute occasional large impacts, below a few kilometres in impactor size the population is greatly dominated by asteroids (Yeomans 2003). In the rest of this paper, we will generally neglect the small residual risk from comet impacts.

The threshold for atmospheric penetration of impacts, required for the blast effects to reach the ground, is generally at a few megatons of energy (MT; Chyba 1993; Chyba *et al.* 1993; Hills & Goda 1993). For impacts above this threshold, the primary effects of both airbursts and ground impacts are local blast and earthquake, together with setting of fires. The 1908 Tunguska explosion of an asteroid about 60 m in diameter provides a relatively small (15 MT) example that has received

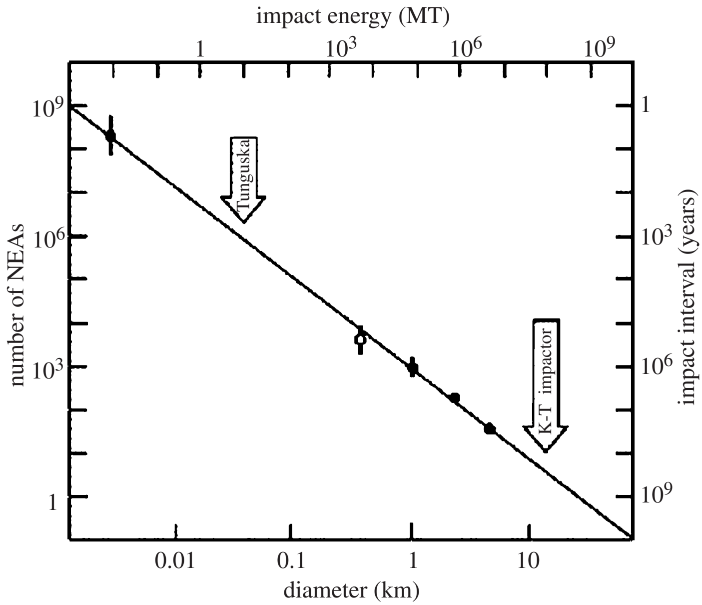

Figure 1. Power-law fit to the average impact frequency for the whole Earth as a function of impact energy in megatonnes of TNT. The scale at the bottom gives approximate equivalent diameters for an asteroid with nominal orbit and density. The four data points representing diameters from 30 m to 5 km (using the lower scale) are derived from current surveys of asteroids in near-Earth orbits. The data point at about 10 kilotonnes of energy is an estimate from observations of bright bolides in the upper atmosphere. Within the estimated uncertainties (perhaps as large as a factor of 3 in impact frequency), this curve is also consistent with historic average impact rates estimated from cratering on the Earth and Moon.

considerable attention from both scientists and the public. Some of the effects of larger impacts have also been derived from observations of the 1994 collision of Comet Shoemaker-Levy 9 with Jupiter. Toon *et al.* (1997) have estimated the environmental perturbations and potential mortality due to impacts from the limit of atmospheric penetration up to events of K-T (mass extinction) scale.

The risk to an individual is proportional to the expected casualties in a single event and inversely proportional to the frequency. As shown by Chapman & Morrison (1994) and utilized in the first NASA study of the impact hazard (Morrison 1992), the maximum statistical hazard is associated with impacts that have a global effect and can kill a substantial fraction of the Earth's human population. The models of Toon *et al.* (1997) suggest that atmospheric dust loading is the critical mechanism by which impacts generate a global hazard. While specific consequences depend on the nature of both the impactor and the target area, a nominal value for the threshold of global catastrophe is near one million MT, corresponding to an asteroid diameter of about 2 km. The associated annual risk of death to an individual is of order 1 in a million (or perhaps a factor of 2 or 3 less)—of roughly the same scale as the risk from the worst natural disasters such as earthquakes and severe storms. (For comparison, 1 in a million is about the risk of death in a round-trip commercial air flight). However, as further noted below, the risk of impact by an unknown asteroid is shrinking as surveys reduce the number of large undiscovered objects.

The energy threshold for global disaster is unlikely to be a sharp boundary, since the consequences of an impact must also depend in part on the nature of the impactor and the location of the strike. It is clear conceptually, however, that an impact that does not cause severe global effects must represent a far lower hazard, no matter how horrendous the destruction is locally. In this context, 'local' can include blasts large enough to destroy a modest-sized country and kill a large fraction of its inhabitants. Below the global threshold, impacts can be dealt with in ways that are analogous to our responses to wars or other severe disasters, with the undamaged parts of the planet able to assist the target region and contribute to reconstruction (Garshnek *et al.* 2000).

A recent NASA-sponsored study of impacts below the global threshold (Stokes 2003) focused on two classes of sub-kilometre impacts: land impacts yielding ground- or air-burst explosions, and ocean impacts that produce tsunami waves that endanger exposed coastlines. The effects of land impacts can be derived by extrapolation of our knowledge of large nuclear explosions. From about 50 to 150 m diameter, these are primarily airbursts; larger impactors reach the ground and produce craters. At 300 m diameter, the area of severe damage is as large as a US state or small European country. Owing to the highly uneven distribution of population on the Earth, most of sub-kilometre land impacts will produce few if any casualties, but much rarer impacts over heavily populated areas could kill tens of millions. Stokes and his team concluded that the greatest hazard for sub-kilometre land impacts is from asteroids 100–200 m diameter, with total expected equivalent annual deaths of a few dozen—approximately two orders of magnitude less than the similar metric for larger (global hazard) impacts.

Ocean impacts are less well understood, since we do not have any examples of impact tsunamis to provide 'ground truth'. Chesley & Ward (in press) have analysed the risk from impact tsunamis as a function of impactor sizes, based in part on an earlier study by Ward & Asphaug (2000). Since impact tsunamis have a smaller wavelength than seismic tsunamis, even large impact tsunamis are unlikely to flood more than a few kilometres inland. Chesley and Ward find that the highest risk of tsunamis from sub-kilometre impacts comes from small but more frequent events, as was the case with land impacts. However, since airbursts over water do not generate tsunamis, the peak tsunami hazard is shifted to impactor sizes 200–500 m. The total hazard is larger than that of sum-kilometre land impacts by roughly a factor of 5. However, since it should be possible to provide warning of an approaching wave in time to evacuate coastal populations, the actual casualties might be much smaller. Therefore the tsunami at-risk estimates are better understood as a surrogate for property damage rather than human fatalities.

The level of hazard from both global-threatening impacts and the more frequent sub-kilometre cases is sufficient to warrant public concern and justify possible government action. However, it has not been easy to make a convincing case for action to decision makers (Sommer 2005). Unlike more familiar hazards, the impact risk is primarily from extremely rare events with no historical precedent. The expectation value for impact casualties within any political term, or even within a single lifetime, is nearly zero. The most important consideration for society is not, therefore, either the expected frequency or average fatalities per year, numbers that mean little to most people, but rather the question of when and where the next impact will take place (Morrison *et al.* 2004).

3. Predicting impacts

Scientists do not need better estimates of statistical risk; instead they need to find potential impactors and thus predict specific future events. With such information, the impact hazard becomes deterministic, not stochastic. The primary potential impactors are near-Earth objects or asteroids, often called NEOs or NEAs. The search for such asteroids is called the Spaceguard Survey, after a suggestion by Arthur C. Clarke in his novel *Rendezvous with Rama*. The Spaceguard Survey was initially proposed by a NASA team at the request of the US Congress (Morrison 1992), with the official NASA Spaceguard Survey for asteroids larger than 1 km in operation since 1998.

Although they are quite faint, asteroids down to 1 km diameter can be detected by their motion using small ground-based telescopes (aperture about 1 m) with state-of-the-art imaging sensors. The search software picks out moving objects automatically, and a preliminary orbit can be obtained with data from even a single night. Much of the follow-up necessary to secure more robust orbits is carried out by dedicated amateur astronomers. Lists of new discoveries are posted every day on public websites, and this information is used to guide both the ongoing surveys and the follow-up support.

The most successful search systems are the Lincoln Laboratory Near Earth Asteroid Research project (LINEAR), which uses a pair of 1 m aperture Air Force telescopes in New Mexico, and (especially since 2003) the two similar-sized telescopes of the University of Arizona Catalina Survey. The surveys are discovering roughly two NEAs per day, about 10 per cent of them larger than 1 km and the rest smaller. (Initially the fraction of asteroids bigger than 1 km was larger, but it declines over time as asteroids are added to the known and subtracted from the unknown population.) For 2005, a total of 629 NEAs were found (with more than by the Catalina and LINEAR systems), 63 of them larger than 1 km (NEO Program Office 2006)

The Spaceguard Survey is intended to identify any potential threat to the Earth with a warning time of at least several decades. Current searches are optimized for finding asteroids near 1 km diameter, which embraces the lower limit in size for a global catastrophe. (The nominal threshold is at 2 km, with an uncertainty of a about factor of 2 in size, or an order of magnitude in energy). The specific 'Spaceguard Goal' is to find 90 per cent of the NEAs larger than 1 km within 10 years, or by the end of 2008. Out of an estimated total of 1000–1100 (Bottke *et al.* 2004; Chesley & Spahr 2004; Harris 2004), 75 per cent had been found by the end of 2005. This is not as positive a result as might seem, however, since the rate of new discoveries falls off as the survey nears completeness. This survey is being carried out with approximately $4 million per year from NASA, plus voluntary and in-kind contributions—a tiny sum compared to the ongoing cost of mitigation for numerically comparable but better-known hazards such as earthquakes, severe storms, airplane crashes and terrorist activities.

The survey results have already transformed our understanding of the impact threat. If we focus on asteroids larger than 2 km, which is the nominal size for a global catastrophe, then we are already nearly 90 per cent complete. For 5 km diameters, which may be near the threshold for an extinction event, we are complete today. Thus, astronomers have already assured us that we are not due for an extinction-level impact from an asteroid within the next century. Barring a very unlikely strike by a large comet, we are not about to go the way of the dinosaurs. Thus, the rest of this paper focuses on the more frequent impacts by sub-kilometre asteroids, which are still big enough to destroy a large city or a small country, or to devastate a coastline, with possibly world-altering economic and social consequences.

Although it was not so perceived at the time, it is now conventional wisdom that carrying out the Spaceguard Survey for asteroids large enough to threaten global disaster is a ‘no brainer’. The question whether we need a much larger survey for sub-kilometre asteroids is still being debated (Chapman 2000; Sommer 2005). When the Spaceguard Goal is reached, much of the residual hazard will still lie in the undiscovered 10 per cent of asteroids larger than 1 km. However, a comparable risk is associated with the still-sparsely sampled sub-kilometre asteroids. The largest hazard will be from tsunamis, but this is primarily a risk to property since fatalities can be greatly reduced by the application of tsunami warning systems. The most life-threatening hazard from sub-kilometre impacts is associated with airbursts over land.

Stokes (2003) and his team concluded that if we wish to make serious progress within the next decade in retiring the risk from sub-kilometre NEAs, we will need a much more ambitious survey using telescopes larger than the current 1 m systems. Such surveys have been proposed by two panels of the US National Academy of Sciences/National Research Council under the general name of LSST, or Large Synoptic Survey Telescope. One wide-field telescope of approximately 8 m aperture at a superior observing site could carry out a survey that is 90 per cent complete down to 200 m diameter within a decade while also accomplishing several other high-priority astronomy objectives that require all-sky surveys. Meanwhile, while the justification for an LSST is still being debated, the University of Hawaii, with support from the US Air Force, is constructing a \$60–80 million multiple telescope system called Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) with a primary objective of discovering sub-kilometre asteroids. When the first 1.8 m Pan-STARRS telescope begins operations in 2006, it is likely to double the rate of asteroid discovery, and the full system might increase the survey power by an order of magnitude beyond current capability.

We do not know how much political support exists for extending asteroid surveys to sub-kilometre impactors, perhaps down to the limit of penetration of the Earth’s atmosphere (at 50–100 m diameter). Such an undertaking is consistent with an imperative for governments to make an effort to identify and protect their populations from preventable disasters (Gerrard 1997; Seamone 2002). It may or may not be cost-effective, depending on political considerations and accounting assumptions (Sommer 2005). This effort would be considerably less cost-effective than the current Spaceguard Survey, since we would need to spend at least an order of magnitude more funds to protect against a risk that is at least an order of magnitude smaller than that of NEAs larger than 1 km. On the positive side, an impact from a roughly 100 m asteroid is unquestionably the most likely impact disaster, with a probability of several per cent of happening in the twenty-first century.

One by-product of the accelerated survey is discovery of asteroids that initially appear (with very low but non-zero probability) to threaten a future impact, even though these apparent threats usually evaporate as better orbits are determined.

Most asteroids can quickly be certified as 'safe', but at any one time some dozens exist for which the possibility of a future impact cannot be ruled out. Since the Spaceguard Survey and its associated orbital calculations are carried out openly, with results posted daily on the Internet by the two primary analysis teams (SENTRY at JPL in Pasadena, California and NEO-DYS at the University of Pisa, Italy), the press and the public are able to see the orbital status of NEAs in near real-time. One consequence has been a number of press scares, some generated by well-meaning scientists, others by an over-eager press (Morrison *et al.* 2004). When subsequent data (sometimes coming within just a day or two) show the chance of impact evaporating, the press often interprets this as a sign of failure. An irritating phrase that I have seen more than once is that the scientists 'got their sums wrong'. This is one of the penalties of moving from an abstract statistical hazard into the realm of predictions for real, known asteroids.

As we gain experience with asteroid orbital dynamics, we have uncovered some complex and interesting situations, exemplified by Apophis, a 350 m diameter NEA originally designated 2004 MN4. Apophis has a well-determined orbit, based on both optical and radar observations. At closest approach to the Earth on Friday, 13 April 2029, Apophis will be inside the geosynchronous belt of communications satellites, and it will be easily visible to the unaided eye for observers in Europe. After some initial concern, it is now clear that the chances of an impact in 2029 are effectively zero, but that is not the end of the story. Within the uncertainties on the position of Apophis at closest approach is a small region (called a 'keyhole') that leads to a return to Earth every seven years. Specifically, if the asteroid passes centrally through the keyhole it will collide with the Earth on 13 April 2036. We might not know whether it will miss the keyhole until 2029. We will return to Apophis later as an example of the challenges of defending against asteroid impacts.

Paradoxically, we can often predict the target area for an impact far better than we can answer the question whether an impact will happen. Thus we find ourselves saying that although a collision seems to have low probability (i.e. the asteroid is likely to miss us), if it does hit it will be at a specific date and time, and the target is along a well-defined geographic arc. This situation is taking place with Apophis, with respect both to its original possible impact in 2029 and its continuing small risk of hitting in 2036. Is it useful to publicize a map showing the possible impact trajectory? Should the people of London care that the original impact track for 2029 (now sure not to happen) passed through southeast England, while that of the 2036 impact (which is still possible though unlikely) does not? It is not clear whether such information enhances or obscures rational public debate about the impact hazard.

4. Preventing impacts

Surveys to discover threatening asteroids are the first, essential step toward protecting our planet from impacts. A several-decade warning of an impending impact, specifying magnitude, time and place, opens up a variety of mitigation and prevention options. At the minimum, the target area could be prepared or evacuated. But more importantly, such long warning times permit us to use space technology to deflect the object and avoid the collision entirely.

In its orbit, the Earth moves a distance equal to its own radius in just four minutes. Thus, to avoid the hit, the arrival time of the asteroid at the collision point needs to be changed by only four minutes. A variety of ways have been suggested to achieve the corresponding small change in the asteroid's orbital period, ranging from setting surface nuclear charges to pushing with an attached rocket motor. Recently, a public interest group called the B612 Foundation has proposed a specific near-term test in which a nuclear reactor powered ion thrust engine (a 'space tug') could be used to demonstrate the technology by making a very small, but measurable, change in the orbit of a 200 m asteroid (Schweickart *et al.* 2003; Conway 2004; Schwieckart & Chapman 2005).

In July 2005 the NASA mission Deep Impact (A'Hearn *et al.* 2005) demonstrated that a small near-Earth target can be hit by a ballistic projectile, but the change in the orbit of comet Tempel 1 was too small to be measured. Don Quijote is an asteroid-deflecting demonstration mission under study by the European Space Agency. The current scenario envisages two spacecraft in separate interplanetary trajectories. One spacecraft (Sancho) will orbit the target asteroid for several months, observing it before and after the impact by the second craft (Hidalgo). Of course, a major uncertainty in such missions concerns the nature of the target asteroid or comet (Belton 2004; Holsapple 2004). Even if a technique is tested on one kind of object, the information gained may not apply to others with different composition, internal structure, or spin dynamics.

Although these first small steps are being taken by space agencies, we are a long way from the technology to deflect an asteroid, especially not one of the most dangerous class, which are larger than 1 km (see AIAA 2004 for a current review of defence options). However, it seems reasonable to expect that if such a large asteroid is discovered, one whose impact could kill more than a billion people and destabilize world civilization, the space-faring nations would find a way to deflect it and save the planet. Given such a specific threat, almost any level of expense could be justified. This effort would represent the largest and most important technological challenge ever faced, and whether it is successful or not, world civilization would be forever changed.

For the sub-kilometre asteroids, the defence options are both less daunting and more varied. The orbits of these smaller asteroids can be determined with the same precision as the larger ones, and the lead time from discovery to impact is likely to be just as large. Owing to their smaller mass, however, they are easier to deflect. It would be much simpler to develop the space technology to deflect a 200 m asteroid than a 2 km one, since the mass and therefore the required thrust are a thousand times less.

Apophis, the asteroid that passes very close in 2029, illustrates another defence option. It will pose a risk of impact in 2036 and subsequent years only if it passes through the keyhole in 2029. This keyhole is quite small, on the order of a kilometre across. If we knew the asteroid was headed for the keyhole, only a very small deflection would be required to save the Earth, since the target to be missed is four orders of magnitude smaller in linear dimensions than the Earth as a whole. Such a small deflection is within current capability and could even be achieved with a ballistic impact such as that used by the comet mission Deep Impact. However, this great leverage can be achieved only if the deflection mission takes place before 2029, and only if we are sure that there is a significant chance of Apophis passing through the keyhole. A current debate, therefore, concerns whether (and how) we can get the required information in a timely way. While Apophis seems unique today, there are surely other complex and unforeseen situations that we may encounter as a product of advanced asteroid surveys.

With small impacts there are also options in which no deflection is attempted. For example, a 200 m asteroid striking the ocean would not produce a significant tsunami and might be ignored, only requiring evacuation of the seaways and perhaps a few small islands near the impact point. The same logic could be applied to land impacts if the target area were relatively unpopulated, such as the Tunguska region of Siberia where the 1908 impact occurred. If today we discovered a similar asteroid (about 60 m diameter) headed for the same location, which is still lightly populated, we would probably choose to evacuate the few residents and take the hit. The resulting ground zero area might then become an economic asset as a tourist attraction.

If a sub-kilometre impactor is identified and a decision is made to change the orbit, there are a number of scenarios that could be complex and divisive. Suppose the initial target is identified as being in Country A. To change the asteroid orbit we must supply continuous thrust that gradually moves the impact point off the planet. But in this process the impact point crosses Nations B, C and D, which were originally not at risk. What country or organization can be trusted to carry out the deflection manoeuvre? And what if the manoeuvre is only partially successful and the asteroid ends up striking Nation C rather than missing the Earth? Who is responsible, and what are the liabilities?

If a sub-kilometre asteroid struck with no warning, which is the most likely case today, mitigation would take a more conventional form (Garshnek *et al.* 2000). In cases where the impactor is on the order of 100 m in diameter, the situation would resemble the aftermath of a nuclear explosion (but without radioactivity) or an earthquake. In most cases the target would be a rural area of low population density, but it is possible that one or more urban centres might be severely damaged, just as with earthquakes. Unfortunately, there have been no serious studies to date of how best to respond to this particular kind of challenge, which might be of a magnitude far larger than any historic disaster. Indeed, it seems likely that few in the disaster–relief or civil defence communities are aware of the possibility of an impact explosion of hundreds or thousands of megatons energy occurring anywhere on Earth without prior warning.

5. Communications and policy issues

Cosmic impacts are both quantitatively and qualitatively different from other hazards. The death toll from the impact of a comet or asteroid no larger than the City of London (1 mile across) could reach hundreds of millions. This is also an equal-opportunity hazard, with everyone on the planet at risk from impacts across the entire size range from Tunguska-class up to extinction-level events. The one exception is the risk from impact tsunamis, which is limited to the small fraction of the world's population that lives very close to unprotected coasts.

Realizing the challenge of explaining this unfamiliar hazard, the scientific community has worked to facilitate communications with the media and the public (Morrison *et al.* 2004). First, the nature of the hazard itself has been explained in a variety of public forums (for example, hearings in the US

Congress and documentaries produced for television broadcast). Second, the Internet has been widely used to answer public questions and provide up-to-date information on asteroid discoveries and orbits. The two NASA websites (the impact hazard website at http://impact.arc.nasa.gov and the NEO Program Office site at http://neo.jpl.nasa.gov) each receive roughly a million hits per month. In the UK, information can be accessed at Spaceguard UK at http://www.spaceguarduk.com, and until recently also at the government-sponsored NEO Information Centre www.nearearthobjects.co.uk. Third, the International Astronomical Union has attempted to provide authoritative information on NEOs and possible future impacts and to work with other science bodies to broaden the base of interest in the impact hazard. Finally, we have encouraged the use of a simple, one-dimensional hazard scale, called the Torino Scale, to provide a readily understood metric for use by the press and the public (Binzel 2000).

Although the impact hazard is clearly a matter that affects all nations (Remo 1996), to date only the US government has taken significant steps to tackle the problem directly through scientific research and astronomical observations, as previously described. In 2000, the UK government commissioned a report on the hazard, which was duly published later that year (Atkinson *et al.* 2000). In addition to an excellent analysis of the hazard itself, this report made 14 recommendations, including some highlighting the need for international cooperation and action, although there has been relatively little follow-up.

The UK encouraged formation of an NEO Working Group under the aegis of the Organization for Economic Cooperation and Development (OECD) Global Science Forum. In January 2003, an OECD workshop noted that 'Few governments have yet to make any specific office or administration responsible for assessing and dealing with the impact hazard, even though they may have a few scientists working on related scientific problems. Thus there is a need for each country to allocate responsibility to some specific branch of its government'. However, the OECD is not currently pursuing these issues.

The reluctance of governments to include impacts within their disaster planning and responsibility continues. When this issue does surface, it is likely to be in terms of the smaller impacts. Although as individuals we are more at risk from large impacts, a disaster manager or government official is more likely to be faced with a small impact within his or her jurisdiction, especially if this jurisdiction has a large area. In Australia, for example, with nearly 2% of the Earth's area, there are likely to be about 20 Tunguska-class impacts within the interval between global impact catastrophes.

Should we begin to develop technologies for deflecting asteroids? While several technical meetings have been held (e.g. Canavan *et al.* 1993; Melosh *et al.* 1994; Simonenko *et al.* 1994; AIAA 2004), essentially no funds have been spent for this purpose. Many would argue that it is prudent to begin such research before an actual threat is identified. Others argue that since these technologies are unlikely to be needed within the next few decades, it is a waste of resources to do any work at present. The most compelling case is probably to accelerate our study of the potential impactors (both comets and asteroids), including visits by spacecraft (Belton 2004). The knowledge gained by such scientific exploration is also needed to make plans for future deflection efforts, if they are required.

Eventually, it will be necessary to decide who, or what, agency should be in charge of efforts to deal with the impact hazard, from possible extensions of the Spaceguard Survey to potential testing of defensive systems. While NASA has taken the lead in supporting the Spaceguard Survey and the scientific study of asteroids and comets, there is no official plan that allocates responsibility for either prevention or emergency response if an impact takes place without warning. Astronomers sometimes ask, rhetorically, 'Who should I call if I discover an asteroid on a collision course with the Earth?'

In any action scenarios, it is not clear whether the population of the target area or of the Earth as a whole will trust either scientific judgments or the decisions of public officials. If an asteroid is discovered with an initial well-publicized non-zero chance of collision, and subsequent observations ultimately convince the scientific community that it will miss by a very small margin, will the public believe them? Or suppose an asteroid is found that is indeed on a collision course but the scientists estimate that it is only 30 m in diameter and thus will disintegrate harmlessly at high altitude. Will the people who live at ground zero trust this conclusion? What level of proof (or acceptance of responsibility) will be required?

Nor is it clear whether the public is likely to support continued and perhaps accelerated government spending to protect the Earth from impacts. It is difficult to sustain interest and support in the absence of known threats (Park *et al.* 1994). While an occasional media 'scare story' may stimulate public interest, they can also backfire if the public conclude either that the astronomers don't know what they are doing or that they are 'crying wolf' to attract public attention (Sommer 2005). Communicating the nature of this hazard, with no historical examples but possible fatalities of a billion or more people, is a continuing challenge (Slovik 1987; Posner 2004).

In conclusion, I note that we are interested in protecting people today, not far-future generations. The surveys we carry out and the mitigation strategies we develop are directed toward a possible impact within the next century. If it falls on our generation to defend the Earth, we need to be prepared. But what we do now will not protect generations centuries in the future. They will need their own surveys and their own protection plans, which will probably be much more advanced than what we are doing today.

I am grateful for continuing stimulating discussions with numerous colleagues studying asteroid impacts, including especially Clark Chapman, Alan Harris and Russell Schweickart, and to the organizers and speakers at this most interesting symposium on extreme natural hazards.

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