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Defending the Earth Against Asteroids: The Case for a Global Response

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BACKGROUND

The Earth is immersed in a swarm of Near Earth Asteroids (NEAs) capable of colliding with our planet, a fact that has become widely recognized within the past decade. The role of crater-forming impacts in planetary history has been demonstrated through the exploration of the planets by spacecraft, and the face of our Moon provides an obvious lesson in the impact history of the Earth-Moon system. The ability of even relatively small impacts to perturb the environment and dramatically influence the biosphere has been apparent since the identification of the KT extinction with an impact 65 million years ago.[1] The data from astronomy, geology, and paleontology all converge to help define a significant contemporary impact hazard.[2]

The first comprehensive modern analysis of the impact hazard resulted from a NASA study requested by Congress and completed in 1992, chaired by David Morrison. This *Spaceguard Survey Report*[3] provided a quantitative estimate of the impact hazard as a function of impactor size (or energy) and advocated a strategy to deal with this threat.

Impacts represent the most extreme example of a hazard of very low probability but exceedingly grave consequences. Chapman and Morrison[4] concluded that the greatest hazard was associated with events large enough to risk a global environmental disaster, with loss of crops and mass starvation worldwide—an event that happens on average once or twice per million years. The NASA Spaceguard study[5] advocated focusing on these global-scale events,

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caused when asteroids larger than 1–2 km strike. The proposed Spaceguard Survey would discover these asteroids and determine their orbits long in advance of any actual impact. The relative orbital stability of even the Earth-crossing asteroids makes such discovery and cataloging a practical task. (Only in Hollywood do asteroids change orbits capriciously!)

A 1995 NASA study chaired by Gene Shoemaker[6] described a practical way to carry out such a Spaceguard Survey using modest-sized ground-based telescopes equipped with modern electronic detectors and computer systems. The Shoemaker team suggested a goal to discover and track 90 percent of the NEAs larger than 1 km within 10 years, a goal that was adopted by NASA in 1998. A government-sponsored study in the United Kingdom[7] confirmed the NASA conclusions and also raised the possibility of extending the survey to smaller NEAs, down to 500 m diameter, as a first step toward dealing with impacts below the threshold for global disaster.

A handful of telescopes in the United States are now used in the Spaceguard Survey. This survey has already found approximately 60 percent of the NEAs with diameter greater than 1 km, and it is well on the way to meeting the 90-percent goal by 2008.[8]

No asteroids have been discovered so far that threaten an impact over the next several centuries. Of course, we can say nothing about possible hits from the undiscovered fraction of the NEA population. These surveys are deemed to be worthwhile because we have the technology, at least in principle, to deflect a threatening asteroid, given decades of warning. The impact hazard is unique in that it is possible to avoid the damage entirely. In most natural hazard areas, “mitigation” consists of ways to plan for a disaster or to deal with the disaster after it happens. Only in the case of cosmic impacts can we develop mitigation plans with the objective of avoiding the disaster itself.

In 2003, NASA sponsored a third NEO study chaired by Grant Stokes[9] that focused on the role of impacts by sub-km asteroids, below the global hazard threshold. Such impacts are much more frequent, since there are many more small asteroids than large ones, but the damage would be local or at most regional in scale. As we retire the risk from the global hazard threats, it seems prudent to examine the options for defending against smaller impacts as well. This study raises (but does not settle) the issue of how much society should invest in protecting against impacts across the full range of energy and risk. As in so many other cases, we question how much protection we need and seek to strike the balance between cost and mitigation.

Comets as well as asteroids can strike the Earth. We do not know if the impact that killed the dinosaurs, for example, was from a comet or an asteroid. Statistically, however, asteroid hits are more frequent than comet hits. This disparity increases as the size declines, to the point where comets are virtually absent below 1 km diameter.[10] Therefore, the discussions in this article refer only to asteroids, which account for 99 percent or more of the risk in the sizes of primary interest.

This article summarizes the impact hazard issue from the current perspective, in which the Spaceguard Survey is steadily reducing the threat from global-scale impacts. The issues for asteroids larger than 1 km are how far to push the survey toward completeness and what plans should be made to develop technology to deflect an asteroid in the absence of a clear and present threat. For the smaller (sub-km) asteroids, the immediate question is how much should be invested in reducing the risk of these smaller impacts. There are broad international implications both in dealing with the globally threatening impacts (we might ask why other countries have not joined the United States in the Spaceguard Survey) and in the smaller impacts, which might target one country while leaving its neighbors relatively unscathed. Finally, there are issues of public perception (and misperception) that cut across all of these issues.

THE IMPACT HAZARD

Most scientific and public interest in the impact hazard dates from the widely reported identification by Alvarez and colleagues[11] of a cosmic impact as the cause of the KT mass extinction 65 million years ago. Within a decade, the KT impact crater had been identified and a substantial body of knowledge had accumulated on the possible killing effects of such an impact. From the perspective of the current impact hazard, the most revolutionary insight of Alvarez was that even small impacts (on a geological or astronomical scale) could severely damage the fragile terrestrial ecosystem. The KT 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.

The energy of the KT impact is estimated at 100 million (10^8) megatons (MT) from the size of the 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 waves (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 reentering ejecta, followed by a persistent (months to years) blackout due to particulates suspended in the stratosphere. Since mass extinction events such as the KT impact are rare (intervals of tens to hundreds of million years), we are interested in down-scaling to determine the thresholds for damage on timescales more relevant to human history.

The threshold for atmospheric penetration of impacts, required for the blast effects to reach the ground, is at a few megatons.[12] 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 1908 Tunguska explosion of an NEA about 60 m in diameter provides a relatively small (15 MT) example that has received considerable attention from both scientists and the public.[13] Some of the effects of larger impacts have been derived from observations of the 1994 impact of Comet Shoemaker-Levy 9 with Jupiter. Toon and colleagues[14] have estimated the environmental perturbations and potential mortality due to impacts from the limit of atmospheric penetration up to events of mass extinction scale.

To calculate the hazard, it is necessary to combine a "kill function" with the frequency of impact. The magnitude of the hazard is proportional to the product of expected casualties times impact frequency. As originally shown by Chapman and Morrison,[15] the maximum 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 and colleagues[16] suggest that atmospheric dust loading is the critical mechanism by which impacts generate a global hazard. 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, corresponding to an NEA diameter of about 2 km.[17] 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, one-in-a-million is about the risk of death in a round-trip commercial air flight).

The threshold for global disaster is unlikely to be a sharp boundary, as the consequences of an impact must also depend in part on 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 this 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. Numerically, these hazards are of order 1 in 100 million per individual per year. Thus even though these smaller impacts are much more frequent than the larger ones, their cumulative hazard over all impactor sizes (100 m to 2 km) is between one and two orders of magnitude less than those of the global or "civilization threatening" impact.

While the level of hazard is sufficient to warrant public concern and justify possible government action, its nature places it in a category by itself. Unlike more familiar hazards, the impact risk is primarily from extremely rare events—literally unprecedented in human history. Although there is a chance of the 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 expectation value for impact casualties within any single lifetime is nearly zero. The most important consideration for society is not, therefore, the average fatalities per year, a number that is meaningless to most people, but rather the question of *when and where the next impact will take place*. It is the purpose of the Spaceguard Survey to answer this question, not to improve our understanding of the impact frequency or the statistical risk. We must find each asteroid, one at a time, and calculate its orbit, in order to determine whether any are actually on a collision course. If there is such a threatening asteroid, we want to identify it, independent of the statistical frequency of impacts.

THE SPACEGUARD SURVEY

Although they are quite faint, asteroids down to 1 km diameter can be detected by their motion using modest-sized ground-based telescopes (aperture about 1 m) equipped with state-of-the-art electronic detectors. Moving objects are picked out automatically by the search software, 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 NEAs 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 survey system is the Lincoln Laboratory Near Earth Asteroid Research project (LINEAR), which uses a pair of 1-m aperture Air Force telescopes in New Mexico, operated with NASA funding.[18] LINEAR is discovering about one NEA per day, about one third of which are larger than 1 km and the rest smaller. Current catalogs of orbits[19] for all NEAs are maintained by the Minor Planet Center in Cambridge, MA, the NEO Program Office at JPL in Pasadena, and the NEODys system at the University of Pisa. Additional coordination comes from the Spaceguard Foundation in Italy, which daily prioritizes asteroids needing additional observations for orbital improvement.[20]

The Spaceguard Survey is intended to identify any potential threat to the Earth by detecting an asteroid on one of the many flybys that precede an actual impact. This approach should provide a warning time of at least several decades. The lower bound to the likely warning time is set by probabilities; it is more likely to find an impact with a long time horizon. The upper bound is determined by orbital stability; for NEAs that have close encounters with the Earth, it is not always possible to project an orbit forward with high accuracy beyond one or two centuries. The survey is optimized for finding asteroids near 1 km diameter, which embraces the lower limit in size for a global catastrophe. The ultimate objective is a complete catalogue of NEAs larger than 1 km.

While asteroid searches had been underway for the previous decade, the formal beginnings of the NASA Spaceguard Survey were in 1998, the same year that LINEAR became fully operational. The specific objective is to find 90 percent of the NEAs larger than 1 km within 10 years, or by the end of 2008.[21] Halfway into this survey decade, nearly 60 percent of the estimated $1100^{+/-}$ 100 of these NEAs had already been found. This is not as positive a result as it might seem, however, since the rate of new discoveries falls off as the survey nears completeness. Estimates of when the 90 percent level will be met vary from 2008 to beyond 2010. This survey is being carried out with approximately $3 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.

If we focus on asteroids larger than 2 km, which is the nominal threshold size for a global catastrophe, then we are already more than 70 percent complete. For 5 km diameter, which may be near the threshold for an extinction event, we are complete today for asteroids (but at this size long period comets may represent a significant contribution to the hazard). Thus astronomers have already assured us that we are not due for an extinction level impact from an asteroid within the next century. Barring an unlikely strike by a large comet, we are not about to go the way of the dinosaurs.[22]

The field of impact studies is still too young to determine what society (and representative governments) seek in the way of protection. For those who mainly fear an extinction event that might end human life forever, we have already achieved a considerable level of reassurance. For those whose concern is a global, civilization-threatening disaster, we are more than halfway complete. But for those who are primarily concerned about the smaller but more frequent impacts by sub-km asteroids, the astronomers have not achieved even 1 percent completeness in our surveys.

Although it was not so perceived at the time it was proposed, it is now conventional wisdom that carrying out the Spaceguard Survey for asteroids large enough to threaten global disaster is a “no brainer.” The cost of this survey is much lower than the estimates of expected equivalent annual loses in lives and property for the U.S.A. alone, justifying the effort even if it is supported solely by the U.S. taxpayer. It is not equally obvious that the survey should be extended to smaller impacts, as discussed in the following section.

SUBKILOMETER IMPACTS

The term sub-km impacts is intended to include all potentially destructive impacts from asteroids with diameters between the threshold for global disaster (nominally 1–2 km) and the sizes where the Earth’s atmosphere offers protection (nominally 50–100 m). Below this size range, 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. The material that reaches the surface typically consists of fist-sized rocks falling at terminal velocity—able to penetrate the roof of a house or a car, but not to cause an impact explosion. These debris are called meteorites, and many tons fall on Earth every day. The risk they pose is miniscule—of the order 1 reported fatality worldwide per century.

Iron asteroids even smaller than 50–100 m diameter can penetrate the atmosphere and strike the surface with a substantial fraction of their cosmic velocities. There was one example of a large iron meteorite fall last century, in the Sikhote-Alin region of Siberia in 1948. Iron projectiles are sufficiently rare so that they also do not pose a major hazard.

Members of the NASA Science Definition Team (SDT)[23] focused on two classes of sub-km impacts by stony asteroids that do pose a substantial hazard: land impacts yielding massive 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. The SDT analysis uses estimates of blast damage as a function of impactor size by Hills and Goda.[24] From about 50 to 150 m diameter, these are primarily airbursts, and the impactor disintegrates explosively before reaching the ground. Impactors larger than 150 m produce craters. At 300 m diameter, the area of severe damage is as large as a U.S. state or small European country. Because of the highly uneven distribution of population on the Earth, most of these sub-km impacts, which are near the lower size limit, will produce few if any casualties, but much rarer impacts over heavily populated areas could kill tens of millions. Combining their explosion models with frequency-of-impact estimates and a model population distribution, the SDT concluded that the greatest hazard is from NEAs 100–200 m diameter, with total expected equivalent annual deaths from sub-km impacts at 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 and Ward have analyzed the risk from impact tsunamis as a function of impactor size, based in part on an earlier study by Ward and Asphaug.[25] They modeled the production and propagation of the waves and, with greater uncertainty, the run-up and run-in of the waves as they reach the coast. The impact tsunamis have an intermediate wavelength between seismic tsunamis (kilometer-scale) and familiar storm waves (tens of meters scale), leading to intermediate run-in. Even large impact tsunamis, with open ocean waves many meters high, are unlikely to flood more than a few kilometers inland. These wave penetration predictions are convolved with the distribution of coastal populations on the Earth. Chesley and Ward find that the highest risk 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 hazard is shifted to impactor sizes from about 200–500 m. The total impact tsunami hazard is larger than that of land impacts by roughly 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 properly understood as a surrogate for property damage rather than human fatalities. People living in the target region are likely to be wet and homeless, but not dead.

Chesley and Ward and the NASA Science Definition Team provide us the data to assemble a ranked estimate of the impact hazards remaining after 2008, on the assumption that the present Spaceguard Survey achieves its 90 percent goal. The largest hazard in terms of fatalities remains the residual 10 percent of undiscovered NEAs larger than 1 km, with an equivalent annual fatality rate of roughly 100, as well as the potential to destabilize global civilization. Even larger is the risk to property from impact tsunamis by sub-km NEAs (down to about 200 m diameter), but the fatalities can be easily reduced by the application of tsunami warning systems. Third in rank for both property damage and fatalities are the land impacts from sub-km NEAs (down to about 100 m diameter).

The present Spaceguard Survey will, if continued, eventually deal with the residual of undiscovered NEAs larger than 1 km, but it will require several decades of additional work to do so. However, the Science Definition Team concluded that if we wish to make serious progress within the next decade or two in retiring the risk from sub-km NEAs, we will need a much more ambitious survey using telescopes larger than the current 1-m systems. Such surveys have been supported by two panels of the National Academy of Sciences/National Research Council under the general name of LSST, or Large Synoptic Survey Telescope.[26] One wide-field telescope of approximately 8 m aperture at a superior observing site could carry out a survey that is 90 percent complete down to 200 m diameter within a decade while also accomplishing several other high-priority astronomy objectives that require all-sky surveys.[27] Alternatively, the NASA SDT propose that the task could be accomplished with 2 or more 4-m telescopes, or with a combination of ground-based and space-based survey telescopes. It is not clear whether these instruments can also push the survey limit down to 100-m NEAs, but they can certainly retire at least 80% of the risk that remains in 2008. The open questions, which I return to below, concern the cost-effectiveness of the LSST and other efforts to address the hazard from sub-km NEAs.

DEFENDING PLANET EARTH

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 options. At the minimum, the target area could be prepared or evacuated. But more important, 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 eight minutes. Thus, to avoid the hit, the arrival time of the asteroid at the collision point needs to be changed by only 8 minutes. A variety of ways have been suggested to achieve the corresponding small change in the asteroid's orbital period,[28] ranging from setting surface nuclear charges to pushing with an attached rocket motor. Recently, a 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.[29]

We do not have today the technology to deflect an asteroid, especially not one of the most dangerous class, which are larger than 1 km. However, it seems reasonable to expect that if such a large asteroid is discovered, one whose impact could kill more than 1 billion people and destabilize world civilization, the space-faring nations would find a way to accomplish the deflection and save the planet. One hopes that this could be accomplished through broadly based international collaboration, but it is also plausible that one nation, such as the United States, might take the lead or even go it alone. Given such a specific threat to our planet, 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-km NEAs, the defense 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. Because of 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 time less.

With these smaller impacts there are also other options in which no deflection is attempted. For example, a 200-m NEA striking the ocean would not produce a significant tsunami and might be ignored, with only 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. As a specific example, the Tunguska impact in Siberia in 1908 struck a wilderness region and killed only one person with its 15-magaton blast.[30] If today we discovered an asteroid of this size (about 60 m diameter) headed for the same location, which is still lightly populated, decision makers (whoever they are) would probably choose to evacuate the few residents and take the hit. The resulting ground zero area might then become a major tourist attraction—even more so in the case of a slightly larger impact that produced a crater a mile or two in diameter.

If an asteroid struck with no warning, which is the most likely case today,[31] mitigation would take a more conventional form. In cases where the impactor is of order 100 m in diameter, the situation would resemble the aftermath of a nuclear explosion (but without radioactivity) or major earthquake. In most cases the target would be a rural area of low population density, but it is possible that one or more urban centers might be severely damaged, just as with earthquakes. Response in this case would resemble current plans for civil defense, calling upon emergency medical care and other forms of disaster relief. However, there have been no serious studies of how best to respond to this particular kind of challenge, which might be of a magnitude far larger than any historic disaster.[32] Indeed, it seems probable that very few in the disaster-relief or civil defense communities are even aware of the possibility of an impact explosion of hundreds or thousands of megatons energy occurring anywhere on Earth without prior warning.

CONCLUSIONS: PUBLIC POLICY ISSUES

The preceding sections of this article hint at a number of policy issues that are summarized in this concluding section. For this discussion, I assume that the current Spaceguard Survey will continue beyond its 2008 target of 90 percent discovery of NEAs larger than 1 km, and that other telescopes will probably reenforce this effort, thus retiring most of the risk of global-scale impacts from undiscovered asteroids. The following questions are all addressed to what steps we should undertake beyond Spaceguard.

1. Is it important to extend asteroid surveys to sub-km impactors, perhaps down to the limit of penetration of the Earth atmosphere? Such an undertaking is consistent with an imperative for governments to make an effort to identify and protect their populations from preventable disasters.[33] It may or may not be cost effective, depending on accounting assumptions. 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.
2. Should we begin to develop technologies for deflecting asteroids? To date, essentially no funds have been spent for this purpose.[34] 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 NEAs, including visits by spacecraft.[35] The knowledge gained by such scientific

exploration is also needed to make plans for future deflection efforts, if they are required.

3. Should we test asteroid deflection technologies? Edward Teller was an advocate during the final decade of his life for conducting such experiments. He argued not only that such experiments were needed to test deflection schemes, but also that the experience gained in planning such an international test project would be invaluable if and when we faced the real thing—especially if the options for defense included nuclear explosives.[36] The recent proposal by the B612 Foundation for a first test of a space tug represents such an experimental approach.

4. Who should be in charge of these efforts, from possible extensions of the Spaceguard Survey to potential testing of defensive systems? Is NASA the correct agency?[37] What should be the role of the Department of Defense? For that matter, are these topics the responsibility of the U. S. government? To date, there is no official position or plan that allocates responsibility within the government. This issue is sometimes raised among astronomers, who ask "Who should I call if I discover an asteroid on a collision course with the Earth?."[38]

5. Should civil defense and disaster relief agencies be planning to deal with the aftermath of an impact explosion that occurs without warning? Today, no warning would be expected for sub-km impacts. Who should assume responsibility in planning for mitigation if such a disaster should occur?[39]

6. How important is international participation? While the impact hazard has been discussed internationally by the United Nations, the Council of Europe, the Organisation for Economic Co-operation and Development, the International Astronomical Union, and the International Council of Scientific Unions, no concrete action has been taken. The most comprehensive study of the problem outside the U.S. was carried out in the UK. However, of the 14 recommendations in the *UK NEO Task Group Report*,[40] only one has been fully implemented—the establishment of a British National Center for public education on the impact hazard. The situation here is not dissimilar to that faced in defense policy, and perhaps it is the proper role of the only superpower to assume unilateral responsibility for the protection of our planet from cosmic impacts.

7. Which impacts (if any) do not require mitigation, and who will make the decision? Suppose the astronomers discover a 100 m NEA that will impact in the ocean—even if the science community concludes that there is no danger from tsunami, will that satisfy the public? Or suppose that a land impact is predicted; if the target area is deserted it may be easy to decide to let it hit, but suppose there are cities or other major infrastructure such as

dams in the target area. Who will decide whether a multi-tens-of-billions of dollars effort should be undertaken to deflect the asteroid? Who will pay for it? Will the decision depend on whether the target nation is a United States ally?[41]

8. If a sub-km 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. Who will the nations trust to carry out the deflection maneuver? And what if the maneuver is only partially successful and the asteroid ends up striking Nation C rather than missing the Earth? Who is responsible?

9. In any of these examples, will the population of the United States or any other country trust either scientific judgments or the decisions of public officials? If an asteroid is discovered with an initial well-publicized nonzero 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 40 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? (Many would find something suspect about the phrase "I'm from the (U.S.) government and am here to protect you from asteroids").

10. Is the public likely to support continued and perhaps accelerated government spending to protect the Earth from asteroids? It is difficult to sustain interest and support in the absence of known threats, and there has never been an asteroid impact in a populated area in all of recorded history.[42] In recent years, there have been a number of media-inspired scare stories, mostly based on very preliminary orbits, with the "threat" disappearing within a day or two. Such stories may sustain public interest, but they can also backfire if the public or the media conclude either that the astronomers don't know what they are doing or that they are "crying wolf" to attract public attention. Communicating the nature of this hazard, with no historical examples but possible fatalities of a billion or more people, is challenging. Yet if we are to create and sustain international programs for planetary defense, public understanding and support is required.[43]

We cannot today answer these questions. All would profit by a wider dialogue and the participation of individuals and groups who may never have been exposed to this unique natural hazard.

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9. G. Stokes, (editor). "Study to Determine the Feasibility of Extending the Search for Near Earth Objects to Smaller Limiting Diameters", Report of the NASA NEO Science

Definition Team (2003). Available at ⟨http://neo.jpl.nasa.gov/neo/report.html⟩ (1 April 2005). Unlike earlier discussions, in this report, most of the conclusions are based on the number of "Potentially Hazardous Asteroids" (PHAs), which represent the 20 percent (approximately) of NEAs with orbits that currently come closest to the Earth.

10. In the early 1990s, comets were thought to represent a substantial share of the hazard (up to tens of percent), based primarily on investigations of a few large long-period comets. For diameters of 10 km and larger (in the range of mass extinctions) this may be the case (P.R. Weissman, "The Cometary Impact flux at Earth," *Annals of the New York Academy of Sciences* 822:67–95 (1997)), but for the smaller sizes that dominate the current impact risk it is not. No comets have been discovered with diameters of less than 1 km, in spite of their high brightness relative to asteroids of the same size, and the comets imaged by spacecraft (Halley, Borrelly, and Wild 2) are all between 4 and 8 km in average dimension. Current arguments for the paucity of comets in the km and sub-km range are summarized by D. Yeomans in Chapter 2 "Population Estimates" of G. Stokes, "Feasibility of Extending Search" (see Note 9). Note that extinct comet nuclei (those no longer outgassing) in Earth-approaching orbits, if they exist, are counted with the population of near-Earth Asteroids (NEAs).

11. L. Alvarez, et al. "Extraterrestrial Cause," *Science* 208:1095–1108 (1980).

12. C. F. Chyba, "Explosions of Small Spacewatch Objects in the Earth's Atmosphere," *Nature* 363:701–702 (1993); C. F. Chyba, P. J. Thomas, and K. J. Zahnle, "The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid," *Nature* 361:40–44 (1993); J. G. Hills and M. P. Goda, "The Fragmentation of Small Asteroids in the Atmosphere," *Astronomical J.* 105:1114–1144 (1993).

13. Although often attributed in the past to a comet impact (or to weird phenomena such as a crashed UFO), it is now clear that the Tunguska impactor was probably a stony asteroid about 60 m in diameter that disintegrated and effectively exploded at an altitude of approximately 8 km, devastating more than 1000 hectares of Siberian forest. See, e.g.: C. F. Chyba, P. J. Thomas, and K. J. Zahnle. "The 1908 Tunguska explosion: Atmospheric disruption of a stony asteroid," *Nature* 361:40–44 (1993); N. V. Vasilyev, "The Tunguska meteorite problem today," *Planetary and Space Science* 46:129–150 (1998); Z. Sekanina, "Evidence for asteroidal origin of the Tunguska object," *Planetary and Space Science* 46:191–204 (1998); P. Farinella, L. Foschini, C. Froeschle, R. Gonczi, T. J. Jopek, G. Longo, and P. Michel, "Probable asteroidal origin of the Tunguska cosmic body," *Astronomy and Astrophysics* 377:1081–1097 (2001).

14. O. B. Toon, K. Zahnle, D. Morrison, R. P. Turco, and C. Covey, "Environmental perturbations caused by the impacts of asteroids and comets," *Reviews of Geophysics* 35:41–78 (1997).

15. See Note 4.

16. Toon, Zahnle, Morrison, Turco, and Covey. "Environmental perturbations," *Reviews of Geophysics* 35:41–78 (1997).

17. The analysis of the uncertainty in these estimates for the global threshold is beyond the scope of this article, but is dominated by uncertainties in estimating the amount of dust lofted into the stratosphere and its subsequent dispersion and lifetime, by modeling errors in assessing the global climate effects, by inadequate understanding of the response of world agriculture to this sort of environmental stress, and above all by uncertainties about the response of human civilization to such a catastrophe. (Societal amplification of the economic impact of the 9/11 terrorist attacks provides a cautionary example. See C. R. Chapman and A. W. Harris, "A skeptical look at September 11th," *Skeptical Inquirer* 26(5):29–34 (2002), or at ⟨http://www.csicop.org/si/2002-09/9-11.html⟩ (1 April 2005). Note that an order-of-magnitude uncertainty in energy corresponds approximately to a factor-of-two uncertainty in asteroid diameter.

18. G. H. Stokes, J. B. Evans, H. E. M. Viggh F. C. Shelly, and E. C. Pearce, "Lincoln Near-Earth Asteroid Program (LINEAR)," *Icarus* 148:21–28 (2000). See also ⟨www.ll.mit.edu/LINEAR/⟩ (1 April 2005).

19. The following centers maintain open, on-line catalogs of known objects and information on recent discoveries: Minor Planet Center ⟨cfa-www.harvard.edu/iau/mpc.html⟩ (1 April 2005); NEO Program Office ⟨neo.jpl.nasa.gov⟩ (1 April 2005); and NEODys ⟨newton.dm.unipi.it⟩ (1 April 2005).

20. Spaceguard Foundation ⟨http://spaceguard.rm.iasf.cnr.it/SGF/INDEX.html⟩ (1 April 2005).

21. NASA formally adopted this "Spaceguard Goal" in a House hearing on "Asteroids: Perils and Opportunities," before the Subcommittee on Space and Aeronautics, Committee on Science, May 21, 1998. Transcript available at ⟨http://impact.arc.nasa.gov⟩ (1 April 2005). Note that the survey is not intended to search for incoming objects on their final approach to Earth (information that would not be of much value in any case), but rather to find any threatening object decades in advance.

22. For a summary of progress in the Spaceguard Survey and other asteroid studies, see D. Morrison, A. W. Harris, G. Sommer, C. R. Chapman, and A. Carusi, "Dealing with the impact hazard" in *Asteroids III* (W. Bottke, A. Cellino, P. Paolicchi, and R. P. Binzel, editors), Tucson: University of Arizona Press (2003) pp. 739–754.

23. G. Stokes (editor). "Feasibility of Extending the Search". Available at ⟨http://neo.jpl.nasa.gov/neo/report.html⟩ (1 April 2005).

24. J. G. Hills and M. P. Goda, The fragmentation of small asteroids in the atmosphere. *Astronomical J.* 105:1114–1144 (1993).

25. S. R. Chesley, and S. N. Ward "A quantitative assessment of the human and economic hazard from impact-generated tsunami," submitted to *J. Natural Hazards* (2004); S. N. Ward and E. Asphaug, "Asteroid impact tsunami: A probabilistic hazard assessment," *Icarus* 145:64–78 (2000).

26. The construction of a large telescope (LSST) to extend the survey to sub-km NEAs was recommended by the National Research Council in two studies: "Astronomy and Astrophysics in the New Millennium" (2001), and the similar recommendation for planetary exploration, published by the National Academy Press, Washington ⟨http://www.nas.edu⟩ (1 April 2005). The NRC did not recommend whether NASA or the NSF, or some other agency, should build and operate this facility.

27. Candidate specifications and observing protocols for the LSST are being developed by a Science Working Group organized by the National Optical Astronomy Observatories, ⟨http://www.noao.edu/lsst/⟩ (1 April 2005).

28. H. J. Melosh, I. V. Nemchinov, and Y. I. Zetzer "Non-nuclear strategies for deflecting comets and asteroids," In *Hazards Due to Comets and Asteroids* (T. Gehrels, editor), Tucson: University of Arizona Press (1994) pp. 1111–1134; V. A. Simonenko, V. N. Nogin, D. V. Petrov, O. N. Shubin, and J. C. Solem, "Defending the Earth against impacts from large comets and asteroids," In *Hazards Due to Comets and Asteroids* (T. Gehrels, editor), Tucson: University of Arizona Press (1994), pp. 929–954.

29. The B612 Foundation is described at ⟨http://www.b612foundation.org⟩ (1 April 2005). The proposal for changing the orbit of an asteroid is made by R. L. Schweickart, E. T. Lu, P. Hut, C. R. Chapman, "The asteroid tugboat," *Scientific American*, November 2003, pp. 54–61.

30. See Note 13.

31. There are no systems that could detect an incoming projectile with a few days, or even a few hours, of warning. Defense surveillance assets look down, not up; they record

the impacts of large meteors in the atmosphere but provide no warning. Thus the risk from the unknown NEA population can be treated as a statistical problem, but once an asteroid is found, its future path is deterministic and can be calculated with great precision and accuracy.

32. V. Garshnek, D. Morrison, and F. M. Burkle, "The mitigation, management, and survivability of asteroid/comet impact with the Earth," *Space Policy* 16:213–222 (2000).

33. Legal briefs discussing the responsibility of governments to protect against disasters are found in M. B. Gerrard, "Asteroids and comets: U.S. and international law and the lowest-probability, highest consequence risk," *New York University Environmental Law Journal* 6:1 (1997); and E. R. Seamone, "When wishing on a star just won't do: The legal basis for international mitigation of asteroid impacts and similar transboundary disasters," *Iowa Law Review* 87:1091–1139 (2002).

34. In the early 1990s a number of ideas were put forward (e.g., G. G. Canavan, J. Solem, and D. G. Rather (editors). *Proceedings of the Near-Earth-Object Interception Workshop*, Los Alamos Publication LANL 12476-C (1993). Follow-up workshops were held in 1994 at Lawrence Livermore National Laboratory and in 1995 in Snezinsk, Russia, but no significant funds were available to pursue these ideas.

35. M. J. S. Belton, "Toward a national program to remove the threat of hazardous *NEOs,"* in *Mitigation of Hazardous Comets and Asteroids* (M. J. S. Belton, T. H. Morgan, N. Samarasinha, and D. K. Yeomans, eds.) University Press, Cambridge, UK (2004), pp. 391–410.

36. Teller spoke out strongly for asteroid defenses at a series of forums in the early to mid 1990s, including all three of the defense technology workshops mentioned in Canavan et al. (see Note 34), plus addresses to the National Space Society, to an international workshop in Erice Italy, and to 1993 Tucson hazards meeting (see Note 2). The only one of these talks that led to a published paper is Morrison and Teller, "The impact hazard: Issues for the future," In *Hazards Due to Comets and Asteroids* (T. Gehrels, editor), Tucson: University of Arizona Press, (1994), pp. 1135–1144. Some of his other remarks are summarized in an entry for October 9, 2003, in the news archive at ⟨http://impact.arc.nasa.gov⟩ (1 April 2005).

37. While NASA supports the current Spaceguard Survey, no commitments have been made beyond 2008. At a NASA-sponsored impact mitigation workshop in September 2002, the NASA Associate Administrator for the Office of Space Science, Edward Weiler, asked rhetorically, "Who asked NASA to save the world?" For more general discussions of issues of communications and responsibility see C. R. Chapman, "The asteroid/comet impact hazard: Homo sapiens as dinosaur?" in *Prediction: Science, decision making, and the future of nature* (eds. D. Sarewitz, R. A. Pielke, Jr. and R. Byerly) Washington D.C.: Island Press, (2000) pp. 107–134.

38. This is not intended as a serious question, of course. Any such discovery would almost certainly be made by an international team of astronomers and orbital dynamicists and be reviewed by the International Astronomical Union. Undoubtedly it would be known via the Internet before any formal announcement could be made.

39. Garshnek, et al., "Mitigation, management, and survivability," *Space Policy* 16:213–222 (2000).

40. Atkinson et al. "Report of the Task Force," British National Space Center, London (2000); availbale at ⟨http//:www.nearthearthobject.co.uk⟩ (1 April 2005).

41. Some of the problems of attempting a controlled orbit change, which could also potentially be used to target an asteroid at an enemy nation, have been discussed in A. W. Harris, G. H. Canavan, C. Sagan, and S. J. Ostro, "The deflection dilemma: Use versus misuse of technologies for avoiding interplanetary collision hazards," in *Hazards*

Due to Comets and Asteroids (T. Gehrels, editor), Tucson: University of Arizona Press, (1994), pp. 1145–1156; C. Sagan, and S. Ostro, “Dangers of asteroid deflection,” *Nature* 369:501 (1994).

42. R. L. Park, L. B. Garver, and T. Dawson, “The lesson of Grand Forks: Can defense against asteroids be sustained?” In *Hazards Due to Comets and Asteroids* (T. Gehrels, editor), Tucson: University of Arizona Press (1994) pp. 1225–1232.

43. Some issues in communication with the media and public are discussed in R. P. Binzel, “The Torino Impact Hazard Scale,” *Planetary and Space Science* 48:297–303 (2000); D. Morrison, “Are Astronomers Crying Wolf?” *Mercury*, November–December 2003, p 15 (2003); D. Morrison, C. R. Chapman, D. Steel, and R. Binzel, ”Impacts and the public: Communicating the nature of the impact hazard,” in *Mitigation of Hazardous Comets and Asteroids* (M. J. S. Belton, T. H. Morgan, N. Samarasinha, and D. K. Yeomans, eds.) Cambridge, UK: University Press (2004) pp. 353–390.