THE COMET/ASTEROID IMPACT HAZARD:
A SYSTEMS APPROACH

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24 February 2001

EXECUTIVE SUMMARY

The threat of impact on Earth of an asteroid or comet, while of very low probability, has the potential to create public panic and – should an impact happen – be sufficiently destructive (perhaps on a global scale) that an integrated approach to the science, technology, and public policy aspects of the impact hazard is warranted. This report outlines the breadth of the issues that need to be addressed, in an integrated way, in order for society to deal with the impact hazard responsibly. At the present time, the hazard is often treated – if treated at all – in a haphazard and unbalanced way.

Most analysis so far has emphasized telescopic searches for large (>1 km diameter) near-Earth asteroids and space-operations approaches to deflecting any such body that threatens to impact. Comparatively little attention has been given to other essential elements of addressing and mitigating this hazard. For example, no formal linkages exist between the astronomers who would announce discovery of a threatening asteroid and the several national (civilian or military) agencies that might undertake deflection. Beyond that, comparatively little attention has been devoted to finding or dealing with other potential impactors, including asteroids smaller than 1 km or long-period comets. And essentially no analysis has been done of how to mitigate other repercussions from predictions of impacts (civil panic), how to plan for other kinds of mitigation besides deflection (e.g. evacuation of ground zero, storing up food in the case of a worldwide breakdown of agriculture, etc.), or how to coordinate responses to impact predictions among agencies within a single nation or among nations.

We outline the nature of the impact hazard and the existing ways that a predicted impact would be handled at the present time. We describe potential solutions to existing gaps in the required approaches and structures (both technical and governmental) for dealing with impacts, including the kinds of communications links that need to be established and responsibilities assigned.

We recommend crafting, adoption, and implementation of improved procedures for informing the broader society about the impact hazard, notifying the public and relevant officials/agencies about an impact prediction, and putting in place (in advance of such predictions) procedures for coordination among relevant agencies and countries. We recommend that pro-active steps be taken, perhaps through a high-visibility international conference and other types of communication, to educate the broader technical community and public policy makers about the impact hazard and the special aspects of mitigating this atypical hazard. For example, the most likely international disaster that would result from an impact is an unprecedentedly large tsunami; yet those entities and individuals responsible for warning, or heeding warnings, about tsunamis are generally unaware of impact-induced tsunamis. We also recommend that additional attention be given to certain technical features of the hazard that have not received priority so far, including the need to discover and plan mitigation for asteroids smaller than 1 km and for comets, study of the potential use of space-based technologies for detection of some kinds of Near-Earth Objects, study of chemical rockets as an approach to deflection that is intermediate between bombs and low-thrust propulsion, and further evaluation of the risks of disruption (rather than intended deflection) of an oncoming object.

Finally, we believe that international human society (and elements of it, like the U.S. government) needs to make an informed, formal judgement about the seriousness of the impact hazard and the degree to which resources should be spent toward taking steps to address, and plan for mitigation of, potential cosmic impacts. The existing unbalanced, haphazard responses to the impact hazard

represent an implicit judgement; but that judgement does not responsibly address the extraordinary and unusual consequences to nations, or even civilization, that could result from leaving this hazard unaddressed in such an arbitrary, off-hand way. For example, we believe it is appropriate, in the United States, that the National Research Council develop a technical assessment of the impact hazard that could serve as a basis for developing a broader consensus among the public, policy officials, and governmental agencies about how to proceed. The dinosaurs could not evaluate and mitigate the natural forces that exterminated them, but human beings have the intelligence to do so.

INTRODUCTION

The impact hazard from near-Earth asteroids and comets has evolved from a science fiction scenario to a serious societal issue during the past twenty-five years. The scientific community began to understand the implications for life on Earth of errant small bodies in the inner solar system in 1980 when Nobel Laureate Luis Alvarez and his colleagues published an epochal paper in *Science* (Alvarez *et al*. 1980) advocating asteroid impact as the cause of the great mass extinction 65 million years ago that led to the proliferation of mammal species. The same year, the NASA Advisory Council advocated study of a modern-day cosmic threat to civilization, leading to a formal study (The Spacewatch Workshop, chaired by Eugene Shoemaker) the following year.

A decade later, these scientific issues first received significant public consideration when lobbying efforts by the American Institute of Aeronautics and Astronautics (AIAA) and others resulted in action by the U.S. House of Representatives, which directed NASA to study the impact hazard. NASA responded by organizing an International Conference on Near-Earth Asteroids and two study workshops, one (chaired by David Morrison) leading to recommendations (Morrison 1992) for a telescopic "*Spaceguard Survey*" of the larger Near Earth Asteroids (NEAs) and the second (chaired by John Rather) evaluating a host of potential approaches to mitigation of an impending hazard should an asteroid be found to be on a collision course with Earth (Rather *et al*. 1992).

During the 1990s, numerous scientific and engineering conferences have been held worldwide concerning the impact hazard (including one held at United Nations headquarters, Remo 1997) and public interest groups were established in several nations, mostly associated with the Spaceguard Foundation[1] . Despite official notice being taken by several national and international entities (e.g. the Council of Europe), little serious attention has yet been given by governments to evaluation of the NEO hazard or preparations for dealing it (NEO = Near Earth Objects, including comets in addition to NEAs). NASA[2], in collaboration with the U.S. Air Force, is the major supporter of NEO research, with a few million dollars per year devoted almost solely to the use of existing telescopes to search for, and find by 2008, 90% of the NEAs larger than 1 km diameter. In late 2000, a task force recommended that the British government consider taking initial steps to support efforts to research the impact hazard (Atkinson 2000[3]); in late February 2001, however, the government responded not with concrete action but only promising to study the matter further and formulate an international approach to the issue.

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[1] Spaceguard Foundation (spaceguard.ias.rm.cnr.it/SGF/
[2] NASA NEO office (neo.jpl.nasa.gov)
[3] Atkinson 2000, (www.nearearthobjects.co.uk/index.cfm)

Other major elements of the impact hazard remain unaddressed. Searches for comets and for smaller NEAs are in their infancy. And little or no serious, official actions have been taken by governments to be prepared to respond to any announcement of a specific impact threatened in the years or decades ahead. For example, Dr. Brian Marsden, who directs the International Astronomical Union's Minor Planet Center[4] (where most astronomical data concerning NEOs is cataloged), recently said that he had no idea who in the United States government would be receptive to serious information he might have one day about an impending impact. Surely some agencies would be interested, but communication pathways, responsibilities, and implementation plans have yet to be established.

This White Paper has been supported primarily by a Presidential Discretionary Internal Research and Development grant from Southwest Research Institute. Its purpose is to outline elements of a systematic approach, with various options, for dealing with the full breadth of the impact hazard – starting with issues about discovery of potentially dangerous bodies, proceeding through societal issues about evaluating the hazard and taking appropriate advance measures, to actual mitigation of potentially threatening impactors. We conclude with some recommendations that might lead to a more comprehensive and balanced approach for twenty-first-century society to take toward a very real, if low probability, threat that could conceivably doom everyone we know and everything we care about.

DETECTION AND IMPACT EFFECTS

Detection

One major phase of impact hazard research is to identify and characterize potentially hazardous bodies and, in particular, to find any impactor long enough before it hits so that mitigation steps may be taken. This phase of research involves preliminary characterization of a potential impactor (perhaps even before there is any conclusive prediction that it will hit), as well as statistical characterization of physical properties of NEOs generally so that any future identified impactor may be quickly placed into an understood context. We address more detailed characterization of such a body under "Mitigation" below.

90% of Large NEAs

Current observational approaches to cataloging potentially threatening NEOs emphasize use of dedicated groundbased telescopes equipped with CCD detectors and automated routines for identifying possible NEOs. While telescopic search programs are underway, or gearing up, in several countries (though one program was stopped several years ago in Australia), most are located in the United States and are coordinated through the NASA NEO Program Office at the Jet Propulsion Laboratory (JPL). NASA's stated goal (Pilcher 1998) is to find 90% of the larger NEAs (>1 km diameter) by 2008. These are asteroids large enough to potentially cause a global climate disaster and threaten the continuation of human civilization (Chapman & Morrison 1994). The majority of such discoveries (~75%) are currently being made by the LINEAR project[5], operated by M.I.T. Lincoln Laboratory primarily with U.S. Air Force funding. The LONEOS program at Lowell Observatory is currently running a distant second, and other search efforts trail LONEOS.

It is estimated (D. Morrison, NEO News, 20 January 2001) that ~50% of the larger NEAs have been found, depending on how many there are >1 km

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[4] MPC (cfa-www.harvard.edu/cfa/ps/mpc.html)
[5] LINEAR project (www.ll.mit.edu/LINEAR/)

diameter (current estimates range from 700 to 1100). Since the more difficult-to-detect NEAs may take longer to find, it is not yet clear whether projected search programs will reach the 90% goal by 2008. It is nearly too late to begin building new telescopes in time to contribute meaningfully to meeting the deadline. An ancillary concern is whether the astrometric follow-up capabilities (largely undertaken by amateur astronomers and poorly-funded professionals in several nations) will ensure that reliable orbits can be established for newly found NEOs so that they will not be lost. Another ancillary issue is that physical observations of the discovered NEAs – for purposes of determining their sizes, shapes, spin rates, and composition – are proceeding very slowly. These are necessary for two reasons: (a) determination of size is required to ensure that discovery of NEOs of particular brightnesses actually are 1 km in diameter or larger; (b) an assessment of physical properties is ultimately the first step in developing a mitigation approach (see below).

Once 90% of large NEAs have been cataloged and found to be “safe” for the foreseeable future (as is very likely but not assured), then the risk to civilization will be known to be a factor of several (perhaps approaching an order-of-magnitude) lower than it was a decade ago when few NEAs had been found. However, several categories of potentially threatening NEOs remain mostly unaddressed by concentration on these larger asteroids: the remaining 10%, smaller NEAs, and long-period comets.

Last 10% of Large NEAs

The remaining NEAs >1 km diameter will include some that were just, by chance, missed. (During the last year, some surprisingly bright NEAs were discovered that somehow had escaped three decades of surveillance that would have been expected to have found them.) But many of the remaining NEAs will preferentially be those that are difficult to discover. Attributes of hard-to-find NEAs include very low albedo, location in orbits with periods commensurable with cloudy seasons where the chief search telescopes are located, those with very high inclinations, etc.

Perhaps the most difficult-to-find NEAs are Atens (NEAs with semi-major axes <1 AU [1 AU = mean distance between Earth and Sun] but which cross the Earth’s orbit and are seen for brief intervals at large angles from the Sun) and objects that orbit wholly within the Earth’s orbit (but may come nearly tangential to the Earth’s orbit). Historically, most search programs have concentrated on the “opposition point,” opposite the Sun in the sky, where NEAs are brightest (like the full Moon). In the last couple of years, this has been changing, and some search programs are now trying to search specifically for Atens. But appreciable inefficiencies exist in such groundbased efforts (often such NEAs are in a dark sky and above the horizon for short durations or are wholly lost in the Sun’s glare). So the question is raised about whether these objects – and their smaller cousins – might be better hunted for from locations in space, such as near the orbit of Venus where these bodies will be more fully illuminated by the Sun and are observable against a black sky away from the Sun for most of the time.

NEAs Smaller than 1 km

While NEAs <1 km diameter probably cannot threaten a global catastrophe, those between 200 m and 1 km in diameter also pose a significant threat. One could cause a tsunami of size and destructive power perhaps unprecedented in historical times, threatening everything near the coast of whatever ocean happens to be struck. Moreover, such objects are much more numerous than the larger ones and hence they strike Earth perhaps tens of times more frequently than the civilization-threatening asteroids. That means that there is a much higher chance (perhaps 1%) that we or our grandchildren will actually have to deal with such a disaster during this century.

While smaller NEAs are being found in great numbers (roughly twice as many have been found as those >1 km diameter), it would be very challenging to undertake a nearly-complete census of them, as is being done for the larger NEAs by Spaceguard. 200 m NEAs are 3 magnitudes fainter than 1 km asteroids. Suitable, dedicated groundbased telescopes (large [roughly 5 m] aperture, sensitive detectors) would have to be constructed in appropriate numbers. A recent recommendation by the American astronomical community (National Research Council 2001) is for construction of a single 8.4 m telescope, the Large-aperture Synoptic Survey Telescope (LSST), which would have as one of its major objectives, cataloging 90% of NEAs > 300 m diameter in one decade. There are difficulties in searching for small asteroids, such as problems with background objects (stars and galaxies) and the night sky background; infrared techniques could address some of the problems. The required astrometric follow-up programs would have to be developed as a separate, professional effort since the vast majority of these NEAs would be beyond the capabilities of the volunteers currently following up brighter discoveries. Physical characterization of small NEAs is, of course, correspondingly more difficult than for the larger ones.

Long-period comets Comets could be a significant part of the impact hazard, with estimates ranging from a few percent to nearly half the problem. And they pose great difficulties for both discovery and mitigation. Comets, until they “turn on”, are many magnitudes fainter than comparable asteroids (because of greater distance and sometimes lower albedo); if they are to be discovered before reaching Jupiter’s distance from the Sun, a survey might have to go 7 magnitudes fainter than Spaceguard. To discover incoming kilometer-scale comets before they reach Jupiter’s distance (and even that might give us inadequate warning – see below), a rough estimate is that we would need to deploy thirty 10 m aperture telescopes at Earth or 50 to 100 2.5 m telescopes at Jupiter’s distance. Such extravagant projects seem far beyond the realm of practicality, so innovation will be necessary to begin to address the comet hazard.

Search techniques There are three basic approaches to searching for potentially threatening objects: groundbased, spacebased near-Earth, and interplanetary. Groundbased searches have the enormous cost advantage of not having to be launched into space and maintained there. However, the duty cycle is restricted by daylight and cloudy weather, and the atmosphere degrades sensitivity in several ways. Earth-orbital observatories overcome some of these difficulties and might be of comparable cost if they could be piggy-backed onto some of the many other enterprises that operate Earth-orbiting satellites. Recently, there was reported to be a potential opportunity – for little more than the cost of building the instrument – to fly an NEA detector on a Canadian satellite (A. Hildebrand, 2000, personal communication). Interplanetary observatories are the most costly of all, but have the potential for enormous gains over Earthbased techniques in detectability of certain kinds of NEAs. Such gains are much more likely to be realized for objects like Atens, which are confined to the comparatively modest volume of the inner solar system and could be searched for advantageously from a location well inside the Earth’s orbit. The advantage of getting closer to outer solar system objects, like comets, is overwhelmed by the enormous volume of space that would have to be searched from a location like Jupiter’s orbit.

Search techniques currently operate at visible wavelengths, where the reflected sunlight is brightest and detectors are exceptionally efficient. However, background problems may be overcome by looking at other wavelengths where NEAs have signatures atypical of stellar objects (e.g. thermal infrared; cf. Tedesco *et al*. 2000). Radar is impractical for searching for objects of the sizes that pose regional or global danger, which need to be found long before striking Earth, generally at great distances.

Impact Effects

Little specific research has been funded to investigate the potential environmental and societal consequences of impact. Most of what is known has been derived (for smaller impacts) from extrapolations from nuclear weapons tests (cf. Glasstone & Dolan 1977), from numerical simulations, and (for larger impacts) from inferences from the geological record for the Cretaceous/Tertiary (K/T) impact 65 Myr ago. In addition, some consequences are analogous to effects studied in the 1980s in the context of Nuclear Winter. Global circulation and climate models have been used to simulate atmospheric perturbations due to dust and aerosols lofted by impacts. Larger impacts, especially, have diverse physical, chemical, and biological consequences, which dominate the fragile ecosphere of our planet and may be expected to act in synergistic ways that are difficult to imagine and model. Therefore, there is considerable uncertainty about the environmental consequences of larger impacts. The greatest danger from smaller impacts (impactors several hundred meters in diameter) are tsunamis, which very efficiently transfer the effects of a localized ocean impact into dangerous, breaking “tidal waves” on distant shores (Ward & Asphaug 2000).

Table 1 describes some of the more common immediate environmental consequences from impacts by NEAs in three size ranges: regional disasters due to impacts of multi-hundred meter objects that impact Earth every 10^4 years; civilization-ending impacts by multi-km objects that occur on a million-year timescale; and K/T-like cataclysms that yield mass extinctions on a 100 Myr timescale. Most of the listed consequences are derived from the recent review by Toon *et al*. (1997). Naturally, individual events may vary due to factors like angle-of-attack (oblique impacts are generally much more damaging than vertical impacts by the same size bodies), whether the impact is into land or ocean, and even the geology of the target region (e.g. it has been hypothesized that the K/T impact may have yielded especially large quantities of aerosols because the target region was rich in anhydrite). However, to first order, the consequences of impacts are simply in proportion to their explosive energy: impacts generate gigantic explosions by the virtually instantaneous conversion of the enormous kinetic energy of the asteroid or comet into other highly destructive forms of energy.

Impacts that are even smaller and more frequent impacts than those shown in Table 1 – like the 15 Megaton impact in Tunguska, Siberia, in 1908 – may have major consequences near ground zero. But other natural disasters, like earthquakes and floods, having the same damage potential (e.g. human fatalities), happen at least a hundred times more frequently than small impacts. Perhaps the most serious consequences of impacts similar to and smaller than Tunguska, which happen on timescales comparable to or shorter than a human lifetime, are unpredictable reactions by observers. A bolide ten times brighter than the Sun occurred in the Yukon in January 2000, yielding some meteorites. Such an event in an unstable location in the world could be misinterpreted as an enemy attack and precipitate war. Another possibility is that a small impact could generate political ramifications and fallout from the public, knowledgeable to some extent that NEA searches and mitigation efforts are underway, and angered at those who were ‘supposed’ to be on guard for such events (W. J. Cooke 2000, personal communication).

There has been essentially no modelling at all of the possible economic and social consequences of the kinds of environmental damage listed in Table 1.

Clearly, in cases of impactors >1 km in diameter, we enter a realm never previously encountered by modern civilization. Even the great World Wars of the twentieth century left many nations relatively undamaged, and they were thus able to serve as nuclei for recovery. An unexpected impact by a 2 km asteroid might well destroy agriculture in both hemispheres and around the world, leading to mass starvation from which no nation would be immune. Impacts may also precipitate catastrophic failures of modern communications and power infrastructures. Possible mass psychological reactions to such a devastating catastrophe, while portrayed in science fiction novels and movies, have also not been researched in an impact hazard context. Even a near-miss by a dusty comet could have serious ramifications, without even impacting: loss of many satellites in the geosynchronous constellation due to dust impacts and associated plasma arcing could severely disrupt global communications and associated economic and security infrastructures (P. Brown 2000, private communication).

EVALUATION AND WARNING

Recent history has provided several cases in which astronomers discovered potentially dangerous

asteroids and announced finite probabilities that they would crash into the Earth within the next few decades (cf. Chapman 2000, Chapman 2001). Even a very low probability of a devastating impact occurring on a precise day in our personal future lifetime generates great interest, news coverage, and fear. Given the unlikelihood of an actual catastrophic impact, the most likely realities that society may have to face are misunderstandings about such impact predictions, close approaches of NEOs, and actual small impacts that may be misinterpreted. Within the last few years, the astronomical community has made some progress in understanding and improving its own role, while there remains little awareness on the part of governmental entities about how to respond to potential NEO events.

Existing Structure

Formal approaches to handling NEO observations and orbital calculations, in a hazard context, are rather minimal but are more developed than they were prior to the March 1998 prediction, and subsequent retraction, of a close approach and possible impact by 1997 XF11. The nucleus of activity remains the Minor Planets Center (MPC) of the International Astronomical Union (IAU), located in Cambridge, Massachusetts. Through long tradition, observers (including the major telescopic NEO search programs that comprise Spaceguard) continue to send observations of NEO positions to the MPC. These positions are cataloged and, in an increasingly thorough and routine way, are used to calculate orbits and search for potential future impacts. Many of the data are made available to the larger astronomical community, and efforts are underway at several institutions (including University of Helsinki, Lowell Observatory, the University of Pisa, and Jet Propulsion Laboratory) to make independent orbital calculations and predictions.

Through a protocol developed at a 1999 workshop in Torino, Italy, and subsequently adopted as de facto procedure by the IAU’s Working Group on NEOs (WGNEO), astronomers decide if a future impact prediction is sufficiently important to warrant a careful independent check before public announcement. (There is an intention to be open, but it is recognized that errors and cries of “Wolf!” are much more likely to happen than actual impacts, so the desire is to weed out the mistakes before making an official public announcement.) If a predicted impact meets certain criteria (based on impact probability and size of impactor, as codified in the Torino Impact Hazard Scale [Binzel, 2000]), then a 72-hour process begins of peer-review by a subcommittee of the WGNEO. After that process is concluded, the IAU may post on its web-site an official confirmation that the prediction has been checked.

Because of a failure (at least in the public relations sense) of the system that happened in autumn 2000 (regarding the small object 2000 SG344), the 72-hour period may be changed in the near future and there is increasing emphasis on the need to avoid secrecy in the future. The hope is that the news media will wait, before publicizing a predicted impact possibility, for official confirmation that the prediction is valid, without astronomers being required to keep all information about the matter secret.

Various journalistic protocols, rapidly changing in the age of the Internet, then govern the public dissemination of information about potential impacts. In the past, various entities (including, for example, the Press Officer of the American Astronomical Society) have facilitated dissemination of news about NEOs, but no formal procedures exist. Neither do any formal procedures exist, that we know of, for information about potential impacts to be considered or acted upon by national or international governments or other entities. Informally, NASA’s NEO Program Office at JPL is kept “in the loop” and its personnel are, no doubt, expected to report matters of importance up the chain of command in NASA. Similar organizational reporting procedures presumably operate within other entities that are likely to discover NEOs or witness an actual impact, like the U.S. Air Force Space Command, which operates satellites that detect major bolides in the Earth’s atmosphere. However, there surely is an early disconnect in formal procedures when the IAU confirms an impact prediction by a posting on its web page.

Potential Structure

Given the widespread public interest in the impact hazard and the potential seriousness of an impact, there ought to be formal procedures for evaluating information about potential impacts, an outline of what should be done in various cases, and assignment of responsibilities to relevant agencies. Evaluation of potential impact predictions needs to go beyond the verification of orbital calculations, which is what the IAU WGNEO’s peer-review process currently focusses on. The 2000 SG344 event showed that there was an unexpectedly great uncertainty in estimating the size, hence potential dangerousness, of the potential impactor – it could have been quite serious (Tunguska-scale) or quite innocuous (if the object is a wayward booster rocket rather than an asteroid). Hazard evaluation and responsibility for making public announcements should be an activity expanded far beyond astronomers to the broader civilian and military communities of experts with experience in dealing with natural hazards and disasters.

We briefly consider this topic from both a U.S.-national and an international perspective.

U.S. National

Initial information about potential impacts will likely be developed within NASA or the Air Force. NASA’s NEO Program Office has responsibility within NASA, but it is a very small operation and is in the infancy of developing communications and response protocols for NASA as a whole. The Air Force Space Command and the Air Force-sponsored LINEAR search project (operated by M.I.T. Lincoln Laboratory) would be the first to handle NEO information obtained from Air Force programs. Other entities may have much more experience in dealing with analogous issues. For example, NOAA’s Space

Environment Center, in Boulder, Colorado, forecasts space weather (e.g. solar storms that may disturb the Earth's geomagnetic environment) and operates jointly with the Air Force the Space Weather Operations (SWO), which is the national and world warning center for space disturbances that can affect operations in space.

NEOs could be added to the SEC's duties. Alternatively, its joint operation of the SWO might serve as a model for creation of an interagency center that would deal with NEO issues. At the moment, there is no movement toward advancing beyond the ad hoc procedures currently in place. The next step would be to organize relevant national agencies that would be involved in mitigating an actual impact or dealing with issues arising from misunderstandings, "near-misses," etc. As a matter of policy, NASA has so far declined to accept any responsibility for mitigation. Other entities (many of them ultimately under the aegis of the National Security Advisor) that might be involved in consideration of preparation for mitigation include the Air Force, the Department of Energy (much interest and expertise in asteroid deflection, for example, already exists at Los Alamos, Sandia, and Livermore National Laboratories), the Federal Emergency Management Agency (FEMA), and tsunami warning entities (which are most thoroughly developed for the Pacific Rim region).

International

The United Nations Office for Outer Space Affairs has undertaken several activities (including sponsorship of some meetings and investigation of building a search telescope in Africa) but has not, to our knowledge, developed an approach for formal U.N. response to a potential crisis. Current efforts of the IAU (described above) might ultimately be combined with other scientific interests in the NEO hazard through the International Council for Science (ICSU), of which IAU is part. The ICSU has partnership relations with other relative entities (including the Council of Europe, which is formally on record as supporting NEO research, and elements of the United Nations, but not formally the U.N. Office for Outer Space Affairs).

Several countries support modest NEO observing programs and several governments with space programs have made statements about the NEO threat. The most substantive considerations at the moment are in the United Kingdom, where the government has recently responded to recommendations for addressing NEOs presented by a commission at the request of Parliament (Atkinson, 2000); while not committing to funding concrete actions (like building a new search telescope or establishing the recommended "British Centre for NEOs"), the government did promise to work within ESA toward coordinating substantive steps within Europe. International coordination of practical responses to a potentially hazardous impact might be initiated through the Inter-Agency Consultative Group for Space Sciences (IACG), which is the forum for interaction between NASA (USA), ESA (Europe), ISAS (Japan), and RASA (Russia). However, we are aware of no discussions about the NEO hazard within that forum.

Another international forum for discussion and coordination of NEO research is the an NGO called the Spaceguard Foundation (SGF), which is headquartered in Italy. For example, under sponsorship of ESA's European Space Operations Centre (ESOC), the SGF undertook a study of both groundbased and spacebased systems for identifying and characterizing NEOs (Carusi 2000). National chapters of the SGF exist in several countries.

Detection/Deflection/Mitigation

Most discussion of the NEO hazard has so far centered on technical discussion of systems for (a) detection of a potential impactor and (b) deflection of an oncoming body by means of space operations. An outline of how observations may be vetted among all relevant players and evaluated for potential mitigation steps has not yet been developed. We suggest that one or more of the national and international entities described above consider developing recommendations for the proper procedures that should be followed, once the IAU process identifies and confirms a potential future event.

A better understanding needs to be developed about how such information is disseminated to the public and to public officials (both through the unfettered activities of the news media and by official actions of government entities). Decision-making forums need to be identified in advance of a crisis, both national and international. While it is very unlikely that an actual impact will require urgent response (it is ten times more likely that an impact will be identified that is decades away rather than just years away), the public response to an identified future event may well require immediate action.

For starters, the IAU WGNEO procedures need to be critically evaluated. Is the 72-hour review time appropriate? Should the duration for review depend on the time until predicted impact? We suggest that an appropriate review period might be one day per year-to-impact, not to exceed two weeks. How much in the open should such reviews be conducted? How much urgency should be given to requests for confirmatory searches of past archives or new observations of a potentially hazardous object by existing telescopes? Beyond posting a confirmed prediction on its Web site, should the IAU actively inform other entities; if so, which ones? (At the moment, there is no formal way that predictions are sent up the chains-of-command.) And, then, which entities (in the United States, in the international arena) should be charged with formal responsibility for evaluating how to handle public evaluation of the potential crisis and implementing mitigation procedures? As a concrete example, from whom should high FEMA officials expect to receive reliable information that might cause them to set on-the-ground mitigation in motion?

Social/Political/Economic/Technological Issues

Numerous issues need to be addressed in appropriate forums in order to derive a consensus on how to address the wider NEO threat...beyond the narrow technical astronomical/space operations arenas in which most discussion has so far taken place.

- What is the appropriate level of public/governmental attention to the NEO Hazard that should be given? *Should* more telescopes be built? *Should* significant efforts be made by agencies that have so far given little or no attention to the NEO hazard, which necessarily might require a modest shift of emphasis from their current efforts? Has the NEO hazard actually been overblown by the naturally heightened public response engendered by Hollywood hype? How have the views of the public and of public officials been distorted by the “cries of ‘Wolf!’” which have occurred during the last few years?
- One element of addressing the question of how much attention, and how many resources, should be devoted to the NEO hazard would be an objective assessment of the anticipated economic and actuarial consequences of this hazard in the context of other natural hazards, diseases, and environmental concerns that compete for funds.
- There are strong political obstacles, in an era when governments are curtailing expenditures and considering massive tax cuts, to starting *new* programs. This may be one reason for footdragging by entities, like NASA, that might have otherwise been expected to adopt a more aggressive stance toward dealing with this hazard (especially since NASA’s Congressional oversight committee has several times asked it to do so). What are other

reasons for the disinclination to do more about the NEO hazard, and are they valid or should they be overcome?

- There have already been instances of interagency squabbling over who should take responsibility for projects related to the NEO hazard (e.g. creation of the cooperative arrangements between the Air Force and NASA over the Clementine mission were not smooth). How will responsibilities be assigned in a cooperative, non-redundant way, both nationally and internationally?
- What are the relative national and international responsibilities? In theory, until an impactor is discovered, all nations are at risk. A large enough impact would necessarily have global effects, and even a much more modest impact into the ocean might affect many nations. But by far the most likely actual impact in the near future (if one occurs at all) will be one of modest size that will have only local consequences, probably in a single nation.
- Procrastination is a serious issue. Already a dozen years have passed since major public discussion began about the NEO impact hazard, and some think that the failure of politicians to act has to do with the fact that an impact – or the need to mitigate one – is extremely unlikely to happen on a current politician's "watch". History is rife with cases where steps were put off into the future for dealing with seemingly unlikely disasters (perceived as going to happen in the distant future) like hundred-year floods. How do we ensure that the NEO hazard is dealt with soon enough in order that mitigation is reliably effective? What is an appropriate response to the claim that future technology will be much more capable of dealing with the hazard (e.g. deflecting an oncoming asteroid) than current technology, so we should wait until that technology has been invented and developed inasmuch as no imminent impact is known or likely to happen?
- Certain elements of the impact hazard can already be seen to be extremely difficult to address. Much of the hazard associated with NEAs >1 km diameter will be addressed within the next decade: most will be found by the telescopic search programs and we already have cogent ideas about how to investigate and deflect such NEAs. However, as discussed below, comets present a much more serious issue: it is unlikely that we will have sufficient warning to practically address the catastrophe threatened by an oncoming comet in time. Advance preparations of several sorts might help or give us a better chance to save ourselves. What are the advantages and disadvantages of taking preparatory steps to mitigate a comet impact, in advance of discovering that one is bearing down on us? For example, Carl Sagan argued that building deflection technologies in advance might be more dangerous than the threat they are designed to address (Ahrens & Harris 1994).
- Should response to the NEO hazard be considered "civil defense" to be undertaken by civilian agencies (e.g. FEMA in the United States) or as "planetary defense" to be undertaken by national or international military forces?
- We have little idea about the role that a civilian agency like FEMA might play in the NEO hazard (it has so far given essentially zero consideration to the issue at all). We know even less about the analogous entities in other countries as well as international entities that similarly need to be informed about this issue.

MITIGATION

Characterization of the Threatening Object

What we need to learn. The earliest information we will have, beyond knowing the orbit that determines that it will approach Earth, is a hint about the object's size (based on its brightness, which will specify its level of hazard on the Torino Scale). This might quickly be augmented by other data, if physical observations are obtained during the same apparition (more accurate size from radiometry and photometry, some information on shape and spin period from lightcurve photometry, and spectrophotometric indications of taxonomic association and mineralogy). In order to more accurately assess the danger and practicalities of mitigation, the most important additional information needed is:

- Detailed shape, configuration (e.g. double, bifurcated, spherical/irregular, presence/absence of satellites), and internal structure/cohesion/mass distribution.
- Detailed surface geology, including characterization of regolith.
- Good characterization of mineralogy (water, metal, rock/meteorite type, chemical composition).
- Specification of spin state, including pole orientation and precession (if any).

How do we learn it? Earth-based observations with the largest, most powerful telescopes and radars can provide improved estimates of size, shape, spin-state, and composition. These instruments could be employed rapidly, in most circumstances, if needed. Major advances in characterizing an asteroid require at least a spacecraft flyby. Unless the warning is very short or the threat is deemed to be marginal, one must expect that selection of spacecraft options will be determined by very different criteria than for the cost-constrained scientific asteroid missions of the past. So one would expect deployment of sophisticated orbiters and dockers/landers unless it were not feasible to match the object's trajectory, in which case only a flyby might be possible.

Flybys can yield the mass (hence density), geology (on a scale of tens of meters over much of the body), shape (e.g. with laser altimetry), distribution of compositional units (from a mapping IR spectrometer and perhaps a neutron spectrometer), magnetic field, etc. (Galileo's reconnaissance of Ida provides examples, cf. *Icarus*, Vol. 120, #1, March 1996.) By equipping the flyby with deployable surface penetrators, other measurements are possible (retro-reflectors, surface composition, assessment of regolith depth, geophones, measurements of thermal/electrical conductivity, testing surface character by setting off a grenade, etc.).

Still more can be learned from an orbiter (for which the NEAR Shoemaker investigations of Eros provides an inexpensive baseline: see Sept. 22, 2000, issue of *Science*, Vol. 289, No. 5487). NEAR's instruments can be augmented by carrying ground-penetrating radar sounders (most useful for C-type asteroids); using neutron beam/gamma-ray techniques to assess atomic composition in upper tens of cm of the surface; using laser ablation and other approaches to assess isotopic composition, volatility, etc.; and serving as an observation post for modules deployed to the surface (seismic net, dropped objects, etc.).

For investigating a small asteroid, there is not a very great jump from an orbiter to a lander/docker (even NEAR Shoemaker successfully "landed" on Eros and kept operating, although it was not designed to do so and lacked landing gear and "feet"). There are issues about how to establish firm contact and coupling with a small asteroid and one might expect an iterative approach to investigating the mechanical attributes of the surface (compressibility, strength, etc.) and making use of surface contact to study internal structure and other attributes that cannot be determined by remote sensing.

Logistics With no limitation on resources, it would still take ~18-24 months to get a flyby mission ready for launch. Arrival might take anywhere from a few additional months to quite a few years, with flyby speeds of a few to 20 km/sec or more. Solar electric propulsion might become an off-the-shelf capability in the future, and could be used to shorten durations to arrive at the target. More capability and time would generally be required to match trajectories in order to orbit/dock with the object. Studies should be done on what simplified fall-back strategies might be possible in the event of short notice or resource limitation.

Instead of waiting to characterize threatening objects only after they are discovered, consideration should be given to the advantages to building a capability in advance. For example, comets will be particularly difficult to characterize well in the short time likely to be available. Characterization of a generic, accessible comet in advance is one approach. Another is to deploy one or more spacecraft in high-energy orbits in advance, properly equipped to assess a comet when and if needed.

Deflection/Destruction of Threatening Body

The most direct approach to mitigating an impact is to ensure that the impact does not happen, by either deflecting or destroying the incoming body. In a wide range of cases, “destruction” of the body poses the potential risk of greatly augmenting the danger. Whether or not impact with a broken body, or parts of it, would be more dangerous than the impact of the original, intact body, the practical problems of dealing with the numerous, randomly deployed fragments of a disrupted body would be enormous. Nevertheless, there are some cases (e.g. very small body) where effective destruction can be assured; it is important to define what case/s are appropriate for considering destruction rather than deflection.

Roughly 3×10^{-3} joules/kg are required to change a body’s velocity by ~10 cm/sec, which is what would be generally required to change a predicted strike one year later into a miss. That is at least 1000 times less energy than what would generally be required to disrupt bodies 0.1 to 1 km in diameter according to our estimates, which are conservative by 1 to 2 orders of magnitude compared with other published estimates. So there is considerable margin available for deflecting a body rather than disrupting it, provided that the energy can be efficiently applied to deflection.

The most controlled approach to deflection would be by non-instantaneous (low-thrust) technologies, which don’t exist today in practical terms: solar-sail, powerful ion drives, mass drivers, etc. There are practical difficulties yet to be resolved in how to attach such devices to a small body. Moreover, the long durations of operation raise issues of maintenance.

If one could dock-and-push with the high impulse thrust of a chemical rocket, a variety of cases could be dealt with. The Space Shuttle main engine could just deflect a 1 km asteroid, given 30 years advance warning. A Delta 2 first stage, with a several-minute burn, could deflect a 100 m object given 6 months warning.

Far more energy can be delivered to an object by a bomb, and that is the only option available with current technology for dealing with the largest potential impactors on shorter time scales than just discussed. There are considerable uncertainties about coupling the energy of a bomb into the object, and doing it over a broad enough area to avoid disruption by the stresses of a very localized release of the energy (a stand-off explosion of a neutron bomb addresses this issue). If the coupling efficiency were as low as 1%, then one starts to challenge the margin of safety against disruption.

Another explosive approach to deflection would be by kinetic kill – maneuvering an object into the path of the object to be deflected and relying on the resulting hypervelocity collision to do the trick. Our preliminary assessment is that such an approach may be feasible for objects <100 m in size but would be generally impractical for 1 km bodies.

An issue illustrating the uncertainties of evaluating the dangers of break-up is the fact that comets are sometimes observed to spontaneously break up. It is unlikely that such break-ups result from especially energetic phenomena on comets. They probably say more about the fragile nature of comets than anything else. A relevant question is whether cometary fragments, then, might still be hazardous?

As with reconnaissance of a threatening object's nature, one may gain precious time by deploying planetary-defense "soldiers" in space located in orbits that may shorten the time it takes to arrive at the threatening object. Such a strategy, of course, involves advance commitments to very expensive hardware before a threat has been identified.

Whatever approach is taken to interacting with a threatening body, there are technical issues specific to impactor mitigation that need to be addressed. For example, there are difficulties involved with terminal navigation (e.g. how does one assuredly acquire small, non-reflective bodies prior to arrival?). While there has been preliminary thinking about many of these issues (cf. Gehrels, 1994; Canavan, Solem & Rather, 1993; Gold, 1999), no thorough, systematic evaluation of an NEO deflection system has yet been done.

Other Mitigation Approaches

Whether or not there is an opportunity to deflect an oncoming asteroid or comet and prevent a threatened impact from happening, there are many additional approaches to mitigating the hazard. These range from evacuation of ground-zero to taking advance action to prevent other social, economic, and environmental consequences from being as bad as they might otherwise be. Decisions on what steps to take should be based on the elements that define the Torino Scale (probability of an impact happening, magnitude of the impact) and on the duration until the impact and the location of the impact (when and if known).

Plans should be developed *now* to take the initial steps towards various kinds of mitigation, for different scenarios based on the matrix of possibilities described above. Even for cases of impact predictions that don't actually turn out to be true (say a near miss), much may have to be done to calm public fear and panic arising from the prediction itself. The same may be true for actual impacts that experts might think are too small to merit attention; consider the public's fear of the fall of Skylab in the 1970s [we are presently awaiting public reaction to the impending re-entry of the Mir space station]. Even the impact of a very small body, if the time and location are predicted with an hour's warning or more, might merit evacuation of people from ground zero. An impact of *any* scale is bound to do more damage near ground zero, or along the coasts of the body of water that is impacted, than elsewhere, so evacuation (and other localized mitigation steps, if there is time) can always help.

If, as would likely be the case, there is ample warning (years or more) of a large impact, even the effects of a potential civilization-destroyer could be minimized through proper advanced planning. For example, food supplies could be built up and stored safely, sufficient to carry the world's population through a year without agriculture. Since the outlines are known of the kinds of climatological changes that would be induced by an impact, measures could be taken to prepare for such changes. A predicted impact that might kill hundreds of millions of people, were they caught unawares, could be converted into a Y2K-like non-event – interesting but without serious damaging consequences.

Near ground zero, and elsewhere (perhaps even worldwide, depending on scale of impact), steps could be taken – in addition to evacuation – similar to precautions taken in earthquake zones (like enhancing the integrity of structures), in forested areas (lessening susceptibility to fire), and in protecting infrastructure assets during space weather events (since an impact could well induce electromagnetic disturbances). Along coasts, an understanding needs to be developed of how to predict, recognize, and track an impact-tsunami and perhaps prepare residents for events much larger than the tsunami events that have been predicted during their lives. Since it is most likely that a small impact would currently happen without advanced warning, there should be established within existing tsunami detection and warning systems a protocol for recognizing an impact-produced tsunami and understanding how its effects might differ from those produced by more usual causes (e.g. earthquakes).

Although there is little reason, in usual cases, to expect that a major impact will be preceded or followed by other impacts, there are several reasons why the public may expect such scenarios. First, earthquakes are generally followed by aftershocks, which may have the potential for causing major damage (and many other kinds of natural disasters occur over a longer period of time and/or occur in clusters). Second, fictional portrayals of cosmic impacts (e.g. in some blockbuster movies) have, for dramatic reasons, included both precursor impacts and multiple impacts, raising that probably-false possibility in the minds of many people. So consideration will have to be given to sounding an "all clear" after any predicted impact happens. The distinction regarding radiation between nuclear weapons and impacts also needs to be communicated; while there are various long-lasting consequences – some potentially hazardous – of an impact, exposure to radioactivity (at least due to the direct impact itself) is not one of them.

RECOMMENDATIONS

Our primary recommendation is that much broader groups of people need to be educated about impact hazard issues, beyond the superficial and often incorrect impressions they may have gotten from their chief exposures to these matters: exaggerated/retracted news stories about impact predictions and "near misses," and movies like "Armageddon." A much broader segment of the technical community, beyond astronomers and space engineers, needs to appreciate and become familiar with technical aspects of this hazard. These segments include the natural hazards community and experts in risk assessment, meteorological storms, seismicity, climate modelling, etc. In addition, public officials responsible for mitigation of (and response to) emergencies and disasters need to understand the basic attributes of the impact hazard. These include the chains-of-command in the military and in the law-enforcement/civil defense infrastructures.

Research, planning, and preparation need to commence now, although it remains to be determined how far such activities should go, given the low probabilities of having to address any real, major impacts in our lifetimes. We believe that several issues need to be addressed in the near future.

- The notification system (concerning a predicted potential impact) needs to be cleaned up, expanded, and officially adopted and implemented.
- Official clearinghouse/s for the best information need do be developed (potential nuclei for such functions, including fledgling web sites or analogous capabilities, already exist at Jet Propulsion Laboratory, NOAA, Spaceguard Foundation, and the IAU Minor Planet Center, among others).
- Serious connections need to be developed with the hazard mitigation community, including agencies like FEMA.
- More objective approaches to communications need to be developed to minimize misunderstanding of this hazard, which is so mismatched to our personal experience base (extreme rarity or low chances of happening vs. extreme potential consequences). In other words, the Torino Impact Hazard Scale needs to be further developed, extended, distributed, and explained.
- Official international channels for exchanging information about NEO hazard-related issues and events need to be developed.
- Within the United States, an interagency approach, and assignment of responsibilities, for dealing with the NEO hazard needs to be developed; the Global Change Program may provide a template. Analogous steps need to be developed in other nations and to coordinate among nations.
- Education about the NEO hazard would be facilitated by conducting a high-visibility, international conference on the NEO hazard, emphasizing the non-astronomical, non-NEO-deflection issues that have so far been treated as backwater concerns in previous NEO hazard conferences. Perhaps a newsletter should be instituted.
- Given widespread interest in extending the Spaceguard search down to bodies much smaller than the 1 km goal of the U.S. search efforts, a thorough evaluation of ground- vs space-based approaches needs to be made. Although spacebased efforts are usually vastly more expensive, they have advantages that may balance the costs in some cases; in other cases, the cost of spacebased efforts may not be relevant (e.g. the searches may be piggy-backed onto other endeavors that pay most of the costs).
- We consider the case of comets to be astonishingly intractable (they are difficult to detect, there is a short time between detection and impact so the object can’t be studied carefully, a comet may be difficult or time-consuming to get to so it may not be possible to “blast” it until it is almost here, a comet’s motion is difficult to predict, and the structural nature of comets is poorly known – they break-up independently and unpredictably). So we recommend more detailed study of the nature of comets and of cometary detection/mitigation strategies. At a minimum, we must quickly assess how large a part of the impact hazard comets are.
- Chemical rockets may have quite wide applicability to deflection scenarios; we recommend more study of that technology.
- In certain cases of attempted mitigation, disruption is more likely than deflection. More research needs to be done in this area, including studies of the potential consequences of disruption.
- All of these recommendations are predicated on a political decision about the importance of the NEO hazard and about the level-of-effort that should be expended in addressing it. The technical community needs to identify potential criteria (beyond simple comparisons of death rates from various hazards) for making this judgement. We recommend that official, objective

study/ies by bodies like the National Research Council be done for this purpose. Ultimately, society's decision about how seriously to address the impact hazard will have to involve broad segments of the public, beyond the technical community.

ACKNOWLDGEMENTS

This white paper was primarily supported by a Presidential Discretionary Internal Research and Development Grant by Southwest Research Institute President Dan Bates. Some research reported here was also supported through NASA's NEO Program Office at the Jet Propulsion Laboratory. We appreciate the interest in this project of Walter Huebner and discussions with many colleagues.

REFERENCES

Ahrens, T.J. and Harris, A.W. 1992. Deflection and fragmentation of near-Earth asteroids, *Nature*, v. 360, pp. 429-433.

Alvarez, L., Alvarez, W., Asaro, F. and Michel, H.V., 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction, *Science*, v. 208, p. 1095-1108.

Atkinson, H.H. (Chairman), 2000. UK Government Report of Task Force on Potentially Hazardous Near Earth Objects: British National Space Centre, London (http://www.nearearthobjects.co.uk/index.cfm).

Binzel, R.P., 2000. The Torino Impact Hazard Scale, *Planetary and Space Science*, v. 48, p. 297?303.

Canavan, G.H., Solem, J.C., and Rather, J.D.G. (eds.) 1993. Proceedings of the Near-Earth-Object Interception Workshop, LA-12476-C (Los Alamos National Laboratory, Los Alamos), 296 pp.

Carusi, A. 2000. Spaceguard Integrated System for Potentially Hazardous Object Survey, final report to ESOC of Spaceguard Foundation, ESOC Contract No. 13265/98/D/IM, 94 pp.

Chapman, C.R. 2000. The asteroid/comet impact hazard: Homo sapiens as dinosaur? *In* Sarewitz, D., Pielke, R.A. Jr. and Byerly, R. Jr., eds., Prediction: Science, Decision Making, and the Future of Nature: Washington, D.C., Island Press, p. 107-134.

Chapman, C.R. 2001. Impact lethality and risks in today's world: Lessons for interpreting Earth history. *In* Koerberl, C., ed., Proceedings of the Conference on Catastrophic Events and Mass Extinctions: Impacts and Beyond, Geological Society of America Special Paper, in press.

Chapman, C.R. and Morrison, D., 1994. Impacts on the Earth by asteroids and comets: assessing the hazard, *Nature*, v. 367, p. 33-40.

Glasstone, S. and Dolan, P.J. 1977. The Effects of Nuclear Weapons (3rd ed.) (U.S. Government Printing Office, Washington D.C.).

Gold, R.E. 1999. SHIELD – A Comprehensive Earth Protection System, Phase I Report to the NASA Institute for Advanced Concepts, Johns Hopkins University Applied Physics Laboratory, 36 pp.

Gehrels, T. (ed.) 1994. Hazards Due to Comets & Asteroids, Univ. of Arizona Press, Tucson, 1300 pp.

Morrison, D. (ed.) 1992. The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop (Jet Propulsion Laboratory, Pasadena).

National Research Council 2001. Astronomy and Astrophysics in the New Millennium (National Academy Press, Washington D.C.).

Pilcher, C., 1998. Testimony before House Subcommittee on Space and Aeronautics, http://www.house.gov/science/pilcher_05?21.htm.

Rather, J., Canavan, G., and Solem, J. 1992. Summary Report of the Near-Earth Object Interception Workshop (Jet Propulsion Laboratory, Pasadena) 28 May 1992.

Tedesco, E.F., Muinonen, K. and Price, S.D. 2000. Space-based infrared near-Earth asteroid survey simulation, *Planetary and Space Science*, v. 48, p. 801-816.

Toon, O.B., Zahnle, K., Morrison, D., Turco, R.P. and Covey, C., 1997. Environmental perturbations caused by the impacts of asteroids and comets, *Reviews of Geophysics*, v. 35, p. 41-78.

Ward, S.N. and Asphaug, E., 2000. Asteroid impact tsunami: a probabilistic hazard assessment, *Icarus*, v. 145, p. 64-78.

Wolbach, W.S., Gilmour, I., Anders, E., Orth, C.J. and Brooks, R.R., 1988. Global fire at the Cretaceous-Tertiary boundary, *Nature*, v. 334, p. 665-669.

TABLE 1. CHIEF ENVIRONMENTAL CONSEQUENCES OF IMPACTS

Category: (Impactor Diameter) **Environmental Effect**	**Regional Disaster** (300 m)	**Civilization Ender** (2 km)	**K/T Extinctor** (10-15 km)
Fires ignited by fireball and/or re-entering ejecta	Localized fire at ground zero.	Fires ignited only within hundreds of km of ground zero.	Fires ignited globally; global firestorm assured (Wolbach *et al*., 1988).
Stratospheric dust obscures sunlight	Stratospheric dust below catastrophic levels.	Sunlight drops to "very cloudy day" (nearly globally); global agriculture threatened by summertime freezes.	Global night; vision is impossible. Severe, multi-year "impact winter."
Other atmospheric effects: sulfate aerosols, water injected into stratosphere, ozone destruction, nitric acid, smoke, etc.	None (except locally).	Sulfates and smoke augment effects of dust; ozone layer may be destroyed.	Synergy of all factors yields decade-long winter. Approaches level that would acidify oceans (more likely by sulfuric acid than nitric acid).
Earthquakes	Local ground shaking.	Significant damage within hundreds of km of ground zero.	Modest to moderate damage globally.
Tsunamis	Flooding of historic proportions along shores of proximate ocean.	Shorelines of proximate ocean flooded inland tens of km.	Primary and secondary tsunami flood most shorelines ~100 km inland, inundating low-lying areas worldwide.
Total destruction in crater zone	Crater zone ~5-10 km across.	Crater zone ~50 km across.	Crater zone several hundred km across.

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March 2001