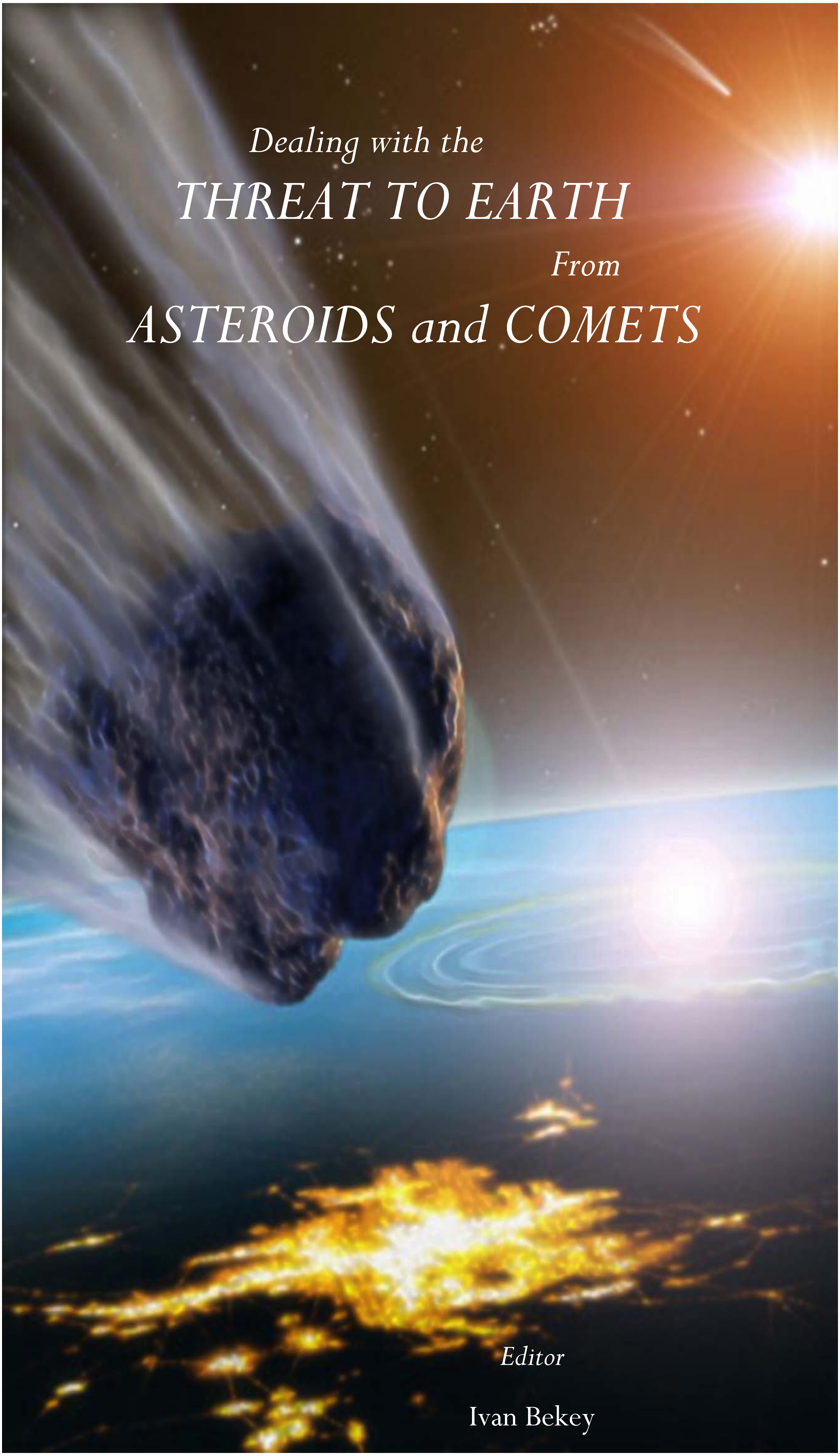


Dealing with the
THREAT TO EARTH
From
ASTEROIDS and COMETS

Editor

Ivan Bekey

Publisher

ACADEMIE INTERNATIONALE D'ASTRONAUTIQUE · IAA ·

Dealing with the
THREAT TO EARTH
From
ASTEROIDS and COMETS

The International Academy of Astronautics (IAA), a non governmental organization recognized by the United Nations, was founded in 1960. The purposes of the IAA are to foster the development of astronautics for peaceful purposes, to recognize individuals who have distinguished themselves in areas related to astronautics, and to provide a program through which the membership can contribute to international endeavors and cooperation in the advancement of aerospace activities.

Cosmic Study on

Edited by: Ivan Bekey

Published by

ISBN -

EAN

Cover Photo: Julian Baum / Take 27 Ltd

Printed by

Dealing with the
THREAT TO EARTH
From
ASTEROIDS and COMETS

Editor

Ivan Bekey

IAA · ACADEMIE INTERNATIONALE D'ASTRONAUTIQUE

Publisher

CONTENTS

Page

Abstract

The Earth has been struck by asteroids and comets (Near-Earth Objects, NEOs) many times throughout its history. The largest of these impacts have led to mass life extinctions, such as the one 65 million years ago which caused the disappearance of the dinosaurs. Humans are not dinosaurs and we possess technological tools that could deflect NEOs and avoid catastrophic impacts if we but develop the necessary plans and means. This report of the International Academy of Astronautics addresses the nature of the threat, expected future impacts, and the consequences of impacts from various size NEOs. It reviews current programs to detect, track, and characterize NEOs, and the future improvements required in order to take responsible and timely action. It identifies a number of techniques that could alter an incoming NEO's orbit so as to avoid an impact. It addresses the organizational aspects that will have to be dealt with if a serious international capability is to be developed and employed to mitigate the threat. It then addresses behavioral factors and the sociological and psychological aspects of the threat and attempts at its mitigation before, during, and after an intercept attempt, whether successful or not. Lastly the report examines some of the principal international policy implications that must be dealt with if the world is to act in a timely, unified, and effective way with the very real threat due to NEOs. The report presents a number of principal findings and recommendations in each of these areas to be considered by the world community in addressing this truly international threat in a truly international manner. The International Academy of Astronautics could facilitate this process, beyond the hoped-for contributions of this report, by supporting the international community's activities with international workshops; and through the technical, policy, social, and legal expertise of its members acting as consultants wherever beneficial.

Executive summary

Background and organization

This work was commissioned by the International Academy of Astronautics, a professional international association, as part of its focus on addressing space-related issues and potential programs via international Study Groups which allow an international perspective to be developed without requiring concurrence from individual nations or entities. A Study Group, comprised of 24 experts from seven countries, was organized by Mr. Ivan Bekey after a series of three international workshops he organized and led from 2001 through 2002 on the subject of NEOs which were sponsored by the AIAA. Further contributing information were the two Planetary Defense Workshops organized by the AIAA and Aerospace Corporation in 2004 and 2007.

Summary findings

The problem

The report analyzes the nature of the threat, which consists of a size spectrum of asteroids and comets whose orbits bring them to the vicinity of Earth and are thus called Near Earth Objects (NEOs). The Earth has been subjected to a bombardment by thousands of very large NEOs since its formation, extremely intensely initially, which has mostly dwindled to the current impact frequency since about 3.5 billion years ago. While the great majority of NEOs are small and pose little or no danger the most damaging ones are 6 km or more in diameter, and the effects of their impact on Earth would likely cause the extinction of most life on Earth

This has occurred several times, the most recent being the impact 65 million years ago which extinguished the dinosaurs and 60% of other species, but fortunately their average impact frequency is only every 100,000,000 years. The impact of NEOs 1-6 km in diameter would result in catastrophic damage regionally or globally. There are an estimated over 1,100 such NEAs (Near Earth Asteroids) and their estimated average impact frequency is every 1,000,000 years. NEOs about 300 m diameter would result in great local or regional damage and millions of deaths, and their average impact frequency is every 10,000 years. Smaller NEOs in the 45 m diameter class may not penetrate the atmosphere but could still create extensive local damage and deaths due to blast, and their average impact frequency is every 100 years.

The average NEO hazard is very important in the spectrum of hazards humanity faces, being greater than that from biological warfare and terrorism (to date), though smaller than that from major wars.

Detection, orbit determination, and impact warning

The report describes current and future means used to detect NEOs, determine their orbits, characterize them, and issue warnings of an Earth impact probability. Detection of NEOs is almost exclusively based on ground based telescopes, with sometimes crucial near-in data provided by ground radars. The current major effort, the Spaceguard survey, is an international effort with participation by Italy, the USA, Japan, Australia, ESA, and the Czech Republic. In 2008 it completed its initial task to catalog 90% of NEAs larger than 1 km. As of mid-2008 over 700 NEOs were catalogued, and about 1,100 total are estimated to exist. A follow-on effort to catalogue 90% of those NEAs that constitute potentially hazardous objects (PHAs) larger than 140 m diameter by 2020 is under consideration but as yet unfunded.

Two organizations provide independent orbit cataloging, confirm NEO close approach, and perform risk assessment. They are the Horizons ephemeris computation facility located at NASA’s Jet Propulsion Laboratory (JPL) in Pasadena, California, USA and the Near Earth Object Dynamics Site (NEODys) at the University of Pisa in Italy. The International Astronomical Union’s Minor Planet Center, operating at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, USA, is the organization that collects, computes, checks, and disseminates astrometric observations and orbit information for asteroids and comets from hundreds of observatories worldwide. A number of space flight missions have already been undertaken by several nations/consortia that demonstrated the ability to fly by and/or rendezvous with some asteroids and comets, perform proximity operations there, and begin to characterize the bodies.

The likely warning time available will be decades for known NEAs, years for newly discovered NEAs and short-period comets, and a few months to less than one year for Small Earth-Crossing Asteroids and Long-Period Comets in the absence of space-based telescopes. However, up to approximately 6 years of warning time of the potential impact of large Long-Period Comets would be possible if a large space-based telescope were developed.

Preventing or mitigating an impact

The report presents the physics of changing NEO orbits to cause them to miss Earth, and discusses a number of techniques already identified to effect such deflection. The orbit of an object far from Earth may be modified with the least expenditure of energy if its velocity along its orbital path is changed, causing it to arrive sooner or later than Earth at its orbit intersection. With warning times of many years or decades only centimeters per second change in the

NEO's orbital velocity will ensure that it arrives sufficiently earlier or later to completely miss the Earth. Some NEOs could well be in orbits that come near the Earth yet miss, passing through very small regions of space known as "keyholes", and enter a resonant orbit with repeating encounters and threats to Earth periodically over many years or decades. NEO velocity changes of only micrometers per second to millimeters per second may suffice to cause them to miss a keyhole and avoid a subsequent impact.

Changing the velocity of a NEO by centimeters per second may be accomplished "fast" or essentially instantaneously by imparting forces from an spacecraft impacted on the NEO or by a nearby explosion, or "slowly" by applying small forces from propulsive spacecraft or energy impingement whose integrated effects over much longer time cause the desired velocity change. A number of "slow" approaches have been identified. Some require contact and thus rendezvous and docking and use an electric propulsion-equipped spacecraft to push on the NEO or eject its rocks, to cause the desired reaction forces. A number of non-contact approaches have been also identified, including a gravitational tractor in which a spacecraft hovers near the NEO and its gravity results in a force being applied without contact with its surface; other techniques include laser ablation or reflected solar photons to effect a slow push.

All "slow" approaches develop small forces and technology limits their application to relatively small NEOs. While they have the advantage of precise control of the resultant velocity change, they all result in the instantaneous impact point of the NEO being slowly moved on the surface of the Earth until it eventually misses entirely. If there is an unrecoverable failure before its job is done the impact point could lie anywhere on the locus of possible impact points and the damage could be greater than had the deflection not been attempted.

There are only two options for "fast" deflection: non-nuclear and nuclear. The principal non-nuclear approach is kinetic impact--simply ramming a spacecraft into a NEO at high relative velocity to provide an instantaneous velocity change of the NEO due to energy and momentum exchange. The technologies and systems are essentially the same as already demonstrated for planetary and solar system exploration, and are well understood and developed. Kinetic impactors are best suited for deflecting relatively small NEOs with little warning time or larger ones when there is lots of warning time. There is only one option for deflecting a large NEO or one with little warning time, and that is to use nuclear devices because the energy requirements can be enormous, and the energy release of nuclear devices can be millions of times greater than that produced by kinetic impacts. Existing nuclear devices could be used with few, if any, modifications and launched by current launch vehicles and current technology upper stages, however current ICBMs are too small to reach the required velocities.

The probability of successfully deflecting a NEO with a single mission using any of the above techniques and current technologies is unacceptably low, given the status of technology and the likely scale of the consequences of a failure. Therefore the deflection of a NEO cannot be a mission but must rather be a campaign of multiple orchestrated missions deployed sequentially in increasingly capable stages using different technologies, with means emplaced to rapidly assess the status and effects of the missions as they unfold.

Organizing for the response

The impact threat is inherently international, and so must be the organization and resources to address it. The consequences of a NEO impact share many characteristics of natural disasters the world has experienced; however in contrast, the disaster date might be forecast years ahead, and most impacts could be prevented. The global nature of the threat introduces many challenges that must be addressed prior to impact, beyond the difficult decisions that must be made to embark on a deflection attempt. These challenges include the means and consequences of rapidly relocating or evacuating many millions of people across international borders.

A spectrum of organizational models, such as the US National Disaster Plan, could be used to model a national NEO response mechanism, however many disaster relief organizations and many nations/consortia need to participate in an international effort to develop a global coordinated response plan and means to carry it out. These could range from a UN managed effort through a non-UN international consortium to a number of coordinated national efforts commissioned by either.

During the impact event communications with the public will be paramount, including status of deflection attempts, evacuation activities, and instructions to the public. Post-event planning must take into account population return and/or relocation, rebuilding, and return to vigilance. Based on the experiences of the Indian Ocean tsunami and hurricane Katrina this will be a difficult and protracted period that only realistic planning and preparation can help to ameliorate.

Behavioral factors and planetary defense

Empirical studies of human response to threat and disaster provide sound underpinnings for NEO disaster management, however different cultures are known to respond differently to disasters and this must be taken into account in the planning. Even though the consequences could be terrible indeed, low probability or far future events generate little worry and little action, and thus planning for NEO impacts is an extraordinarily difficult undertaking. Proper planning requires moving beyond widespread but erroneous stereotypes regarding human behavior in catastrophic situations. These stereotypes are that panic will be widespread, civility/looting commonplace, and that a pervasive feeling of helplessness/passiveness will prevail. While to a degree they will occur, mutual assistance and support tends to be the rule rather than the exception.

Some of the likely chaos should be ameliorated by proper planning for these activities. In the pre-impact phase planning and rehearsals are crucial. The media must be involved, its workings understood, and an effective working relationship developed with it. Communications must either exist or be ready to be deployed, and must be adequate for the contemplated functions. An effective warning system must be in place, with different segments distributing coordinated messages. In the impact phase large numbers of direct casualties as well as anxiety disorders will be ubiquitous. Disaster workers will be affected as much as the people who they are trying to help. Acute stress reactions and several forms of trauma must be expected and psychological support prepared for addressing them, both for the injured and for the caregivers. In the recovery phase massive scale of triage, medical and psychological support and therapy, and long term post-traumatic effects should be expected. Five core values – empathy, trust, sensitivity to differences, openness and flexibility – will provide a firm basis for protecting human life and welfare should a NEO strike be in the offing.

Policy Implications

Several nations/consortia have active programs toward discovery, cataloguing, and characterizing the NEO threat, and their principal activities already have some international components. The existing international policy is limited to a number of instruments calling upon states to consider adopting a range of voluntary measures related to the NEO issue. In 1996 the Council of Europe recommended that ESA contribute to an international program to detect NEOs and development of a strategy for remedies against possible impacts. In 1999 Unispace III urged international coordination and harmonizing efforts aimed at detection and orbit prediction, and consider developing a common strategy for future activities. In 2003 the Organization for Economic Cooperation and Development recommended that governments explore strategies for mitigation of NEO threats, and established an advisory panel to work with ESA. In 2007 the UN COPUOUS Action Team 14 recommended addressing the threat from smaller asteroids, augmentation of the Minor Planet Center, and preparation of a draft NEO deflection protocol and international procedures. These efforts, though exemplary, are but a small start toward a truly international policy.

Principal recommendations

The report's recommendations are intended to improve understanding of the threat, refine estimates of the impact risk and consequences, develop well-defined options for mitigation, and prepare a framework for appropriate international political and social response. These are presented organized by report chapter. In addition a potential role for the IAA is identified.

Detection, orbit determination, and impact warning

An effective surveillance infrastructure should be emplaced to expand the Spaceguard survey to catalogue 90% of those potentially hazardous objects larger than 140 m diameter by 2020. Existing radars should be provided adequate resources to continue the search, while increasingly more capable ground based detection systems should be developed. Meter class space based sensors should be developed and orbited to accelerate the discovery and cataloguing of NEAs in the near term.

A serious effort should be begun to address detection, orbit determination, and impact warning for the long-period comet threat, which is much less well developed than for asteroids. To that end responsible definition of a large (10-20 m) new technology very lightweight and thus affordable optical space-based telescope should be performed.

Preventing or mitigating an impact

Detailed planning and mission design of both "slow" and "fast" deflection techniques must be undertaken. The mission designs should proceed using to the maximum extent existing vehicles and technologies. These mission designs must include all launches, sensors, communications, and command/control necessary to ensure deflection of a target NEO set with high probability. This probably means employing several different and/or redundant launchers, space vehicles, sensors, technologies, in campaigns designed to result in high confidence of mission success.

At least one non-nuclear kinetic mitigation and one slow deflection approach should be defined and designed so that a comparison of systems including complexity, life cycle cost, reliability, operations, and effectiveness can be made. The mission designs must include all systems and subsystems required to perform a mitigation mission after a threat has been identified, including precursor or follow-on missions for NEO characterization as required.

A separate system design of a nuclear interceptor should be made, with large NEOs or smaller NEOs with short warning time as intended targets. Non-nuclear laboratory and field experiments should be performed to fully understand the fragmentation issues involved in deflection attempts of various classes and compositions of NEOs.

Organizing the response

Response plans for a number of impact scenarios must be developed. This includes near-miss as well as actual impacts on various geographic locations around the globe, should deflection attempts either not materialize or fail. Disaster planning must also include the post-impact phases in which recovery and return to normalcy will be the goals. These response plans should be carried out by international planning groups with the support of national resources. The planning could proceed by several groups in parallel initially to benefit from differing viewpoints, but eventually a truly international organization should be created to take the global leadership role in NEO response planning, probably coordinated under the auspices of the UN.

While mindful that these are imperfect analogues of NEO impacts, it will be necessary to draw upon experience gained in the course of hurricanes, earthquakes, tsunami and other relatively common events, since evidence-based, policy-oriented research provides crucial building blocks for managing other disasters and will be useful for managing NEO threats as well. Such planning will require the coordination of organizations and agencies at many different levels: international, national, regional, and local. An important function of higher-level organizations will be to facilitate the efforts of regional, local, and “grass roots” efforts.

Behavioral factors and planetary defense

Pre-impact activities, including preparation and issuance of effective warnings, and the staging of personnel, equipment, and supplies, will require rehearsal. It will be important to recognize the role of religion, superstition and myth to effectively communicate risk, to encourage people to take protective action; and to effectively employ post-disaster relief. In all phases of mitigation planning, it will be important to be mindful that not everyone subscribes to the Western scientific viewpoint.

Mass casualties will require psychological as well as medical assistance, however, it will be very important to recognize and plan for the fact that disasters have adverse effects on the disaster workers and their families as well. Residents of the disaster area will need both immediate assistance and the tools to rebuild the infrastructure and regain independence. Recovery efforts should extend well into the post-disaster phase and remedy long standing local problems as well as the direct consequences of the impact.

Policy implications

An analogue of the Inter-Agency Space Debris Coordination Committee (IADC) would be an appropriate way to move forward toward a coordinated international plan for dealing with NEOs. A number of specific policy statements should be sought and activities undertaken, which include: establish the threshold of detection to NEOs which are equal to or greater than

140 m in size; establish a facility with complementary capabilities to the Minor Planets Center (MPC); establish common data management policy/protocols for the MPC "nodes" to include/address processes, calculations, data designation, data duration, data dissemination, data verification and validation, and data access/security; secure the long term operational status of an organization to coordinate NEO monitoring, including calculation of orbital elements and impact threat assessments; identify the criteria and thresholds associated with a potential impact event requiring active communication through official channels; and identify the communication channels, both at national and international levels, for communication of the NEO risk.

An international technical forum should be organized and recognized globally as an impartial focus of technical excellence to provide informed support to decision-makers worldwide. This forum should undertake the tasks of risk estimation, and the preparation of technically viable plans for mitigation and recovery options for a range of credible scenarios.

Among the support this forum could provide to international policy makers would be to: establish the risk threshold for conducting detailed assessment of the consequences of an impact threat; establish a methodology for assessing the consequences of a specific impact threat; develop a detailed protocol for the consideration of risk mitigation options and agree to criteria which will help to guide the choice and implementation of an appropriate response; develop a matrix of mitigation options and decision criteria to a level of maturation to permit reliable mission timelines to be mapped onto a decision timeline for the envisaged protocol; propose qualitative criteria to help to guide the choice and implementation of an appropriate response in situations where scientific evaluation of the consequences and likelihoods reveals such uncertainty that it is impossible to assess the risk with sufficient confidence to inform decision-making; and identify those aspects of existing legislation which require modification to permit agencies to mount a deflection mission, without fear of liability for the consequences when acting within agreed constraints.

Potential role of the IAA

The IAA could facilitate the process of dealing with the NEO threat, beyond the hoped-for contributions of this report, by supporting the international activities discussed above by organizing international workshops; and through the technical, policy, social, and legal expertise of its members serving on working groups and committees addressing the NEO threat.

Chapter 1:
INTRODUCTION/BACKGROUND

The topic of Earth-threatening asteroids and comets, collectively known as Near-Earth Objects (NEOs) is finally beginning to receive its due attention after languishing in scientific and professional circles for years as a “fringe subject”. If covered at all by the media it was usually in fanciful movies which often disregarded science, or in the press with a large helping of the “giggle factor”. The subject crept over the horizon of the public consciousness by Prof. Louis Alvarez’ theory that the extinction of the dinosaurs some 65 million years ago was caused by the impact of a large NEO, which has been since confirmed by discovery of an appropriately large crater (Chixchulub) in Yucatan. The general acceptance of that NEO impact as being an extinction-level event was followed by a number of uncomfortably close NEO apparitions and flybys of Earth which were not foreseen, and the spectacular impacts of comet Shoemaker-Levy into Jupiter which were captured by the Hubble Space Telescope and covered extensively by the media. All of these events demonstrated that such impacts can occur within our lifetime, and thus that NEOs must be taken more seriously.

This work was commissioned by the International Academy of Astronautics, a professional international association, as part of its focus on addressing space-related issues and potential programs via international groups, yet without personal or national attribution. This allows an international perspective to be developed without the usual international protocol problems and delays.

The genesis of this study followed a workshop which occurred in March of 2001 in Seville, Spain under the auspices of the AIAA as part of its International Cooperation workshop series. A session within the workshop was a broad overview that addressed detection, interception, and organizational issues surrounding asteroids and comets as potential impactors of Earth, organized and chaired by Mr. Ivan Bekey. At that time Mr. Bekey was asked by Dr. Michael Yarymovych, then president of the IAA, to follow up on the AIAA workshop and undertake a comprehensive IAA study which would result in a report which, if and when approved by the IAA Board of Trustees, would be issued by the IAA under its Cosmic Studies series of publications.

The report was envisioned as a comprehensive compendium of all aspects of the NEO problem compiled into one volume which could serve as a “table-top” publication, since none was known to exist at that time. It would thus aim at providing technically accurate material in enough detail to be comprehensive in its treatment of the diverse aspects of the problem, yet without too much technically arcane material. It would be compact and general enough that it would be read by non-technical management, political, or policy individuals as well as scientists and engineers.

It was decided at the outset that the study would focus on gathering existing material, placing into total context, and writing text chapters; and that if adequate sources were identified no additional research would be attempted. In order to gather sufficient information to enable that approach it was decided to hold two more workshops which were aimed at areas in which information was sparse in order to fill out the information base, and then to assemble a study group composed both of IAA members and non-members to undertake the study proper using the database and understandings developed in the workshops. Accordingly, the second workshop occurred in April of 2002 in Irvine, California under the auspices of the American Psychological Association, and addressed exclusively the generally overlooked sociological and psychological aspects of dealing with the threat, both before and after impact. It was co-chaired by Mr. Bekey and Dr. Harvey Wichman, professor of psychology emeritus of Claremont McKenna College. The third workshop took place in Houston in conjunction with the 2002 World Space Congress under the auspices of the IAA, and focused exclusively on interception and negation methods and issues. It was chaired by Dr. S. Peter Worden, then Brigadier General in the US Air Force.

These three workshops comprised a preliminary view of three vital but different aspects of the problem, and some of their potential solutions. A serendipitous event occurred in February 2004 when the AIAA and The Aerospace Corporation co-sponsored a very comprehensive conference on Planetary Defense from NEOs in the Los Angeles area (Orange County), organized and chaired by Dr. Bill Ailor. That conference addressed all the NEO issues with formal papers, keynote addresses, and extensive discussions, and added for the first time entire system and mission design for a number of example threats as well as overall response system considerations. Thus the formation and formal start of the IAA NEO Study group was delayed until after that conference in order to benefit from its material, and accordingly the IAA NEO Study Group was formally started in mid-2004. As the study proceeded from its first draft report to its second draft a second Planetary Defense conference took place in Washington, DC in March, 2007, also chaired by Bill Ailor, and the papers presented there further broadened and defined many aspects of the problem and issues. All the above workshops and conferences contributed much to the material of this report.

The IAA Study Group prepared this report using the above workshops and other information in the public record as a starting point, under the overall leadership and organization of Ivan Bekey. It was recognized that iterations would be needed to produce a report of the desired quality, and three generations of draft reports were thus prepared prior to finalizing the report's content.

It is the intent of these IAA Cosmic Studies to provide an international perspective of important space-related issues. The findings and recommendations of this report are intended to contribute to the understanding of national as well international organizations as to the issues raised by the asteroid and comet problem, and thus support the world community in its ability to address the problem and to facilitate international agreements and plans to deal with it.

The Study Group consisted of the following persons, each of which contributed to the preparation and/or review of the draft reports, in part or in whole. They are listed in alphabetical order:

Ivan Bekey, USA
Jonathan Campbell, USA
Clarke Chapman, USA
Eric Choi, CANADA
Mark Cintala, USA
Lee Clarke, USA
Bill Cooke, USA
Liara Covert, CANADA
Richard Crowther, UK
Dan Durda, USA
George Friedman, USA
Alan W. Harris, USA
Albert Harrison, USA
Syozu Isobe, Japan
Gregg Maryniak, USA
Dan Mazanek, USA

Allessandro Morbidelli, FRANCE
Volodymir Prisniakov, UKRAINE
Evan Seamone, USA
A. Taylor, USA
Richard Tremayne-Smith, UK
Ron Turner, USA
Harvey Wichman, USA
Makoto Yoshikawa, JAPAN
Anatoly Zaitsev, RUSSIA

In order to facilitate the preparation of the report each major chapter was prepared by a "Chapter Leader" or leaders, chosen from the larger Study Group, who wrote the chapter with inputs from others in the larger Study Group and their own contacts, lending their own experience and knowledge of the field. Thus the major burden of preparing the report chapters was carried by the Chapter Leaders, who were:

1. Introduction/Background. Executive summary - I. Bekey
2. The problem - A.W. Harris/C. Chapman/A. Morbidelli
3. Detection, impact prediction, and warning - D. Mazanek
4. Preventing or mitigating an impact - J. Campbell
5. Organizing for the task - R. Turner
6. Behavioral factors and planetary defense- A. Harrison/A. Taylor/H. Wichman
7. Policy implications - R. Crowther
8. Findings and conclusions - All
9. Recommendations - All

Each draft was reviewed by the larger Study Group in which all members had a chance to comment on every chapter as well as on the whole report. The entire report was envisioned, guided, assembled, and edited by Ivan Bekey.

Chapter 2:
THE PROBLEM

1. Brief history of the NEO population

Earth is in a "cosmic shooting gallery," as anyone looking up into clear, dark skies can witness: cometary and asteroidal dust grains disintegrating in the upper atmosphere as meteors or shooting stars. They are accompanied by a size spectrum[1] of ever larger, increasingly less common, bodies up to several tens of km in diameter. The vast majority of near-Earth objects (NEOs) are asteroids originally in the main belt, a small percentage are comets, plus, of course, their smaller fragments or disintegration products called “meteoroids” (which are called “meteors” while in the atmosphere and “meteorites” when on the ground).

There is scientific consensus that asteroids and comets are what remains today of the primordial building blocks of the planets, called “planetesimals”. Through mutual collisions, the planetesimals formed the cores of the giant planets and, in the terrestrial planets region, lunar- to Martian-mass bodies called planetary embryos[2]. The terrestrial planets formed on a timescale of several 10^7 years, mostly by collision among the embryos[3]. During that phase, the growing Earth must have experienced gigantic collisions, the most spectacular of which was probably that with the Mars-mass body that is believed to have created the Moon[4]. This body was most likely the largest NEO wit which the Earth has ever collided.

When the epoch of planetary accretion was over, numerous planetesimals remained in orbit around the Sun. Most of them were still on planet-crossing orbits, causing an intense bombardment of the young planets. How long this bombardment lasted is not well known. Computer models[5] show that the population of the planetesimals on planet-crossing orbits should have decayed with a half-life of at most ~100 My, being driven into the Sun or ejected in the interstellar space by the combination of planetary perturbations. If this is true, the bombardment rate of the terrestrial planets should have declined accordingly. However, the geological record on the Moon bears witness to an extremely intense bombardment between 3.9 and 3.8 Gy ago (i.e. 6 to 7 hundred My after planet formation), when about a dozen huge impact basins formed. This period is called the Late Heavy Bombardment (LHB) and erased most of the previous geological record. It is still controversial whether the LHB was a sudden spike in impact rate[6] -possibly due to an abrupt change in the planetary orbital configuration that destabilized a distant reservoir of planetesimals[7]- or instead the final phase of the intense bombardment discussed above[8], which for some reason declined much more slowly than the computer models predict. Whatever might have happened, the observed lunar LHB alone would have subjected the Earth, for ~50 Myr, to a bombardment rate *thousands* of times that of today, with pivotal implications for the origin and early evolution of life.

At the end of the LHB, the bombardment rate rapidly dropped by several orders of magnitude, as a consequence of the ultimate dynamical removal of the remnant primordial planet-crossing planetesimals. The bombardment rate, however, did not drop down to *zero*. This is because a small fraction of the planetesimals remained stocked in long-lasting reservoirs. By convention, those trapped in and inside of Jupiter's orbit are called "asteroids" and those farther out "comets", although each group is subdivided into specific orbital classes; comets are generally expected to have more volatiles than the more rocky or metallic asteroids, although primitive, carbonaceous asteroids could be volatile-rich at depth. The main asteroid reservoirs are a large torus called the main asteroid belt beyond the orbit of Mars and in two groups of "Trojans" averaging 60º ahead of and behind Jupiter in its orbit. The chief known comet reservoirs are the Kuiper Belt and associated scattered disk, beyond Neptune's orbit, and the much more distant spherical halo of comets, called the "Oort Cloud."

These small bodies slowly leak from these reservoirs, generally due to chaotic dynamics near planetary resonances (e.g. distances from the Sun where a small body has an orbital period that is a simple fraction of the orbital period of a planet), facilitated by collisions and other minor orbital perturbations (e.g. the Yarkovsky Effect, which is a force on a small, spinning body due to asymmetric re-radiation of absorbed sunlight on the body's warmer "afternoon" side[9]). Some dislodged bodies soon arrive in the terrestrial planet zone, becoming NEOs. The latter are in comparatively transient orbits, typically colliding with the Sun, or more unusually with a terrestrial body, or being ejected from the solar system on hyperbolic orbits, on timescales of a few million years; however, being continually replenished from the reservoirs, the NEO population remains in a sort of steady state. Indeed, over the past 3.5 Gy, the lunar and the terrestrial crater records show that the average Earth/Moon impact rate has varied little more than a factor of two during that time, although brief, moderate spikes in cratering rate must have happened [e.g.[10]].

At this low modern impact rate, impacts nevertheless happen often enough to affect profoundly the evolution of life (e.g. the Chixchulub impact 65 Myr ago, responsible for the K-T mass extinction). Because of the comparatively short time span of human lives and even of civilization, the importance of impacts as a modern hazard is debatable. The impact hazard is comparable, in terms of deaths and damage averaged over very long time periods, with other man-made and natural hazards that society takes seriously. On the positive side, NEOs and accompanying meteoroids bring samples from far-flung locations in the solar system to terrestrial laboratories for analysis and they leave traces in ancient impact craters and basins on the Earth and the Moon, permitting broad insights into primordial and recent Solar System processes. In the future, NEOs may provide way-stations for astronauts en route to Mars or elsewhere; they also may provide raw materials for utilization in space.

2. How the impact hazard was recognized

That comets might be dangerous is an idea that dates back at least to the 17th century, when Edmond Halley is said to have addressed the Royal Society and speculated that the Caspian Sea might be an impact scar[11]. The first NEO (Eros) wasn't discovered until 1898 and the first NEO that actually crosses Earth's orbit (Apollo) wasn't found until 1932. By the 1940s, three Earth-crossing NEOs were known, their basic rocky nature and relationship to meteorites was appreciated, and it was possible to crudely estimate their impact rate[12]. The actual damage that an NEO impact might cause on Earth was concretely described by Baldwin[13], a leading early advocate for the impact origin of lunar craters. Later, Öpik[14] (who understood both orbital dynamics and impact physics) proposed that NEO impacts might account for mass extinctions in the Earth's paleontological record. Around the same time, Shoemaker and his colleagues firmly established the impact origin of Meteor Crater in Arizona[15]. The first decade of planetary exploration revealed that Mars and Mercury were heavily cratered[16].

Not until 1980/1 did it begin to be realized in the scientific community that NEOs and impact craters carried major implications for the history of life on Earth, both in the past and possibly in our own times. Publication[17] of the Alvarez *et al.* hypothesis for the impact cause of the K-T extinctions was immediately followed by a NASA-sponsored workshop in Colorado entitled "Collision of Asteroids and Comets with the Earth: Physical and Human Consequences," chaired by Eugene

Shoemaker. Several dozen scientists and technologists identified the nature of the impact hazard and potential solutions in an unpublished but available report.

Even after discovery of the Chixchulub impact structure in Mexico and its temporal simultaneity with the Cretaceous-Tertiary (K-T) boundary and mass extinctions[18], it has taken some Earth scientists a while to recognize and accept the statistical inevitability that Earth is struck by asteroids and comets. Each impact, typically spaced 50 to 100 My, liberates tens of millions to billions of megatons (MT, TNT-equivalent) of energy into the fragile ecosphere, which *must* have had dramatic consequences every time. Some skeptics still consider the Chixchulub impact to be only one of several contributing factors to the K-T extinctions [e.g.[19]]. They also point out that direct evidence firmly linking other, older mass extinctions to impacts is so far either more equivocal than for the K-T, or altogether lacking – but this is a natural result of the ongoing tectonic resurfacing of our planet. If the great mass extinctions can somehow be explained by forces that are much less sudden and powerful than impacts (e.g. episodes of volcanism or sea regressions), one must ask how the huge impacts that must have occurred failed to leave dramatic evidence in the fossil record.

Public awareness of the modern impact hazard originated in the late 1980s when advanced telescopic search techniques identified NEOs passing by the Earth at distances comparable to that of the Moon. Such "near misses" made headlines and also inspired the AIAA to persuade the U.S. Congress to mandate that NASA examine the impact threat and methods for mitigating it. This led to the definition[20] (and redefinition[21] after the dramatic 1994 impacts of Comet Shoemaker-Levy 9 fragments into Jupiter) of the Spaceguard Survey, which NASA formally endorsed in 1998 by committing to discover 90% of NEOs >1 km diameter within one decade. (Spaceguard is a network of professional observatories, dominated by two 1 m aperture telescopes near Socorro, New Mexico, operated by M.I.T. Lincoln Laboratory [LINEAR], plus amateur and professional observers who follow up the discoveries in order to refine knowledge of orbits of the newly discovered NEOs.) As larger NEOs are discovered and their orbital paths extrapolated ahead one century and they are found to pose zero danger of impacting Earth, then we are safer: only the remaining, undiscovered asteroids pose a threat. In 2000, the British government established a Task Force on Potentially Hazardous NEOs, which led to a report (see ref. 11) and the establishment of the first governmental organization solely devoted to the impact hazard, the NEO Information Centre. More recently, NASA tasked a new group (NEO Science Definition Team, SDT) to advise on possibilities of extending NEO searches down to smaller sizes; it reported in August 2003[22].

There has been little actual funding for studies of the impact hazard and potential mitigation measures, so much of the thinking has taken place in the context of conferences and committee studies rather than comprehensive research programs; reports from these activities (often "grey literature") constitute the chief sources of information on the topic. An extensive literature exists on the role of impacts in Earth's geological and paleontological history; a recent compendium[23] is the fourth in a series of "Snowbird Conferences," which commenced in 1981 soon after the publication (see ref. 17) of the Alvarez *et al.* hypothesis. The dynamical and physical properties of NEOs were recently reviewed in several chapters of "Asteroids III"[24].

3. Orbital and size distributions of NEOs

NEOs are defined as bodies whose perihelia (closest orbital distance to the Sun) are <1.3 Astronomical Units (1 AU = the mean distance of Earth from the Sun). About 20% of NEOs are currently in orbits that can approach the Earth's orbit to within <0.05 AU; these are termed Potentially

Hazardous Objects (PHOs). PHOs are physically no different from other NEOs; they just happen to come close enough to Earth at the present time so that planetary perturbations could conceivably modify their orbits so as to permit an actual near-term collision, hence they warrant careful tracking. The Spaceguard search programs (chiefly LINEAR; Lowell Observatory's LONEOS in Flagstaff, Arizona; Jet Propulsion Laboratory's Near-Earth Asteroid Tracking [NEAT] in Maui and on MT. Palomar, California; and Spacewatch on Kitt Peak, Arizona[25]) continue to discover a new NEA every few days. As of July 2005, 3418 NEAs were known (of which 663 were PHOs), which compares with only 18 when the 1981 Snowmass conference met.

The observed distribution of the NEOs, concerning both orbits and sizes, is not representative of the true distribution. Each survey is affected by observational biases. Obviously, it is easier to find large NEOs than small NEOs, as the latter are detectable only when passing close to the Earth. Thus, the observed size distribution is strongly skewed towards large objects. But also, NEOs on moderate eccentricity, low inclination orbits with period longer than 1 year are more easily discovered than NEOs on orbits with short periods, high inclinations, or large eccentricities. In fact the former are much more likely to pass close to the opposition point in the sky, where most of the NEO surveys are concentrated, while the latter spend most of the time at small solar elongation or far from the ecliptic.

Nevertheless, taking advantage of the growing number of observations, it has been possible to build models of the true orbital and size distributions of the NEO population. The two most recent models have been developed in[26] and the previously cited reference 25. Despite the fact that different techniques were used and the observations on which the models were calibrated are disjoint, the two models are in very good agreement, which indicates that a satisfactory understanding of the NEO population has now been achieved.

According to these models, the estimated number of NEAs >1 km in diameter (the size for which NASA established Spaceguard's 90% completeness goal by 2008) is ~1100 ±200, of which about 70% have now been found. The differential size distribution is wavy, but can be approximated with a power law having an exponent between –3 and –2.75, for sizes between ~200 m and 5 km. At small sizes the size distribution becomes steeper. According to the impact record in the upper atmosphere, which shows of order of 1 collisions with impact energy ~5 kT per year, there should be about one billion NEOs with ≥4 m diameter[27], resulting in an average power law exponent of the NEO size distribution of –3.35.

About 94±4% of the NEOs with orbital period shorter than 20 years are of asteroidal origin (see ref. 26). The remaining 6±4% apparently are dormant Jupiter-family comets, most of which come from the trans-Neptunian region. The contribution to NEOs of long-period comets (e.g. from the Oort Cloud) is minimal. These comets disappear after a few orbits (the well known fading problem of long-period comets)[28]. It has been argued that they physically disintegrate[29], because if they became dormant, a significant number of objects with asteroidal appearance on long-period orbits should have been detected by the NEO surveys, which is not the case. Accordingly, the contribution of long-period comets to the threatening NEO population has recently (see ref. 22) been assessed to be very low (~1%). Nonetheless, there are many more comets of very large size, say greater than a few km, than asteroids, and since NEOs of such sizes are the "civilization killers" they need to be considered more seriously than has been done in the past.

Traditionally, the NEO population is subdivided into three groups: the Apollos (Earth crossing objects with orbital period larger than 1 year), the Amors (non Earth crossing NEOs, with perihelion distance between 1 and 1.3 AU) and the Atens (Earth crossing objects with orbital period shorter than one year). According to the NEO distribution model (see ref. 26), about 32% of the NEOs are Amors, 62% are Apollos, 6% are Atens. 49% of the NEOs should have orbital period shorter than 2.8 years, which is the minimal orbital period of main belt asteroids. This model also shows that, in addition to the NEO population, there is a population of non-Earth crossing objects with aphelion distance smaller than 1 AU, called IEOs. There are about 50 NEOs for every IEO.

The models of the NEO orbital and size distribution have been used to evaluate the effectiveness of the current surveys in discovering the remaining (i.e. not yet detected) NEO population[30]. It has been predicted that the discovery rate of new objects would have started to drop off in 2003 to lower and lower rates (this has indeed happened). The reason is not simply that it is statistically less probable to find one object, if fewer remain. It is also that the NEOs which are still to be discovered are the most difficult ones, as they are small (e.g. faint) and reside on orbits whose geometry relative to the Earth maximize the observational biases against discovery. Thus, according to [ref. 34], if there were no improvements to the current facilities the Spaceguard goal would not be reached before 2030, at best. Also, (see ref. 30) showed that the current surveys are completely inadequate to discover a large fraction of the population of NEOs smaller than 1 km in diameter. Despite their small size, these objects could still constitute a significant hazard for human civilization (see below). This has motivated NASA to mandate the SDT (see ref. 22) to study how the search for NEOs could be extended to smaller objects.

4. Frequency of impacts as a function of energy

Mineralogical compositions of NEAs are assessed from absorption bands and other spectral signatures in reflected visible and near-infrared sunlight, after accounting for modification of the optical properties of surface minerals by the solar wind and micrometeoroid bombardment ("space weathering," [31]). These spectra are summarized by a colorimetric taxonomy[32]; the majority are divided between low-albedo (<9%), low-density (~1.3 g/cm^3) types inferred to resemble carbonaceous chondritic meteorites and moderate-albedo (~15%), moderate density (2.5 g/cm^3) types inferred to resemble ordinary chondrites and other stony meteorites. There are some more exotic types, like nickel-iron (metallic) meteorites and basaltic chondrites. Such inferences have been augmented by radar reflection[33] (which is especially sensitive to metal content) and confirmed by more detailed close-up examination of the large NEA, Eros, by the NEAR Shoemaker spacecraft. Briefly, NEA colors and spectra, and inferred compositions, appear to be consistent with the calculations of the asteroidal and cometary source regions for NEAs summarized above [34],[35].

Models of the orbit-dependent distribution of taxonomic types among the NEO population have been recently developed[36],(see ref. 35). Coupled to the NEO orbital distribution models discussed above, the statistical knowledge of albedos and densities of NEOs has allowed the calculation of the frequency of impacts on Earth as a function of collision energy (Fig. 1). Ultimately, this is the information that we need in order to assess the real hazard represented by asteroid impacts and to decide the appropriate actions to counteract this menace. Again, the fact that models-despite being constructed in very different ways and calibrated on disjoint observation datasets- agree with each other at a very fine level, shows that NEO science has now reached a high degree of accuracy.

Figure 1 shows that collisions liberating an energy of 1,000 MT should happen on average only once every 65,000 years. They are due to NEOs of about 250-300 m in size. Such energies should produce consequences at a regional level, possibly with global implications on the world-wide economy (for comparison, the recent December 2004 disaster due to the tsunami in South Asia was caused by an earthquake liberating an energy of 10,000 MT). The UK Task Force on Potentially Hazardous NEOs (see ref. 11), defined 1,000 MT as a lower limit for "dangerous" impacts. Fig. 1 implies that there is only one chance out of 650 that such an impact will occur in the next century.

From these statistics, one might conclude that the NEO hazard is a non-problem. It is strange, therefore, that one recently discovered NEO (2004 MN4/Apophis) was calculated as having a better-than-5% chance of impacting the Earth on 13 April 2029 until pre-discovery images were found and radar detection of the object was accomplished, ruling out an impact in 2029. The pass will be very close, however, below the distance of geostationary Earth satellites, and there remains a 1-in-10,000 chance that the asteroid will pass through one of several "keyholes" and enter a near-resonant orbit resulting in an Earth impact in one of several years during the 2030s. As of the writing of this chapter (14 July 2005), there was yet another "dangerous" asteroid with an estimated diameter of 580 m (impact energy of 15,000 MT), that has a probability of 1-in-10,000 of colliding with Earth before the end of the 21st century. So it is not entirely clear that the statistics are giving us a complete understanding of the hazard from these "dangerous" NEOs.

Setting the threshold of "dangerous" at 1,000 MT is arbitrary. The Tunguska explosion in 1908 is widely estimated at 10-15 MT, and possibly less. It struck in a barren location and killed few people, maybe none at all. Yet the world population is increasing and it is increasingly likely that the impact of a small NEO would be genuinely harmful. As evidenced by the South Asia tsunami, there is explosive population growth along coastlines in countries around the world, and an NEO >150 m diameter might create a tsunami with disproportionate consequences. Natural hazard researchers regard disasters as "human constructs," in the sense that the definition of what constitutes a disaster arises from human fears and perceptions, as well as in the sense that human activities – such as building cities along coastlines and installing, or failing to install, tsunami warning systems – affects the magnitude of a disaster. Given that the deaths of "only" 3000 people from terrorist attacks in the US on 11 September 2001 or <100 people from terrorist attacks in London on 7 July 2005 resulted in some of the most consequential social, political, and economic reactions of recent decades, it is difficult to pre-judge the threshold of what constitutes a "dangerous" NEO impact or what level of priority should be given to trying to mitigate the potential consequences of a predicted close pass of an NEO with a specific (and ever-changing) probability of striking.

The odds are that, once all 250m NEOs are discovered and catalogued, none will turn out to be on a collisional trajectory with our planet during the next century. But, given the possibility that we can deflect an NEO in the unlikely event one *is* found to be on an impact trajectory, we are obliged to improve the current NEO survey capabilities in order to find all NEOs larger than 200m or so (see ref. 22). This will make us definitely sure (not only at a probabilistic level) that the Earth is "safe". Whether it makes sense to extend, at considerable additional expense, the search down to 150 m or even smaller remains a matter of discussion.

5. Structural properties of NEOs

In the unlikely case that it is necessary to deflect a NEO en route to the Earth, it is important to know the structural properties of such objects.

Our knowledge about the physical configurations of NEAs has undergone a revolution in the past decade. Although it was surmised several decades ago that some NEAs might be double (from double craters on the Earth and other terrestrial planets[37],[38]), only lately has it become clear that nearly 20% of NEAs have satellites or are double bodies. Definitive proof comes from radar delay-doppler mapping (see ref. 33). Other techniques (e.g. adaptive optics and analysis of "eclipsing binary" lightcurves) are also discovering duplicity among main-belt asteroids, Trojans, and Kuiper Belt objects[39]. Several independent modes of formation are required to explain all of the double or satellite-containing small-body systems. But break-up by tidal disruption during close passage to a planet (as exemplified by Comet Shoemaker-Levy 9's break-up in 1992[40]) seems to be the chief process accounting for the high fraction of NEO satellites and double bodies[41], (see ref. 39). Clearly, the potential for a threatening NEA to have one or more satellites may complicate a deflection operation.

Tidal break-up is facilitated by another geophysical attribute of NEAs. Long ago, it was proposed[42] that larger main-belt asteroids might be "rubble piles" because inter-asteroidal collisions sufficiently energetic to fragment them are insufficient to launch the fragments onto separate heliocentric orbits; instead, the pieces reaccumulate into a rubble pile. It is now clear that most asteroids, including those of sub-km sizes, should be rubble piles or at least battered and badly fractured (see ref. 41). Lightcurves confirm that most NEAs >200 m diameter are weak or cohesionless, while most smaller ones are monolithic "rocks". Few NEAs or main-belt asteroids >200 m rotate faster than ~2.2 h, at which a cohesionless, fragmental body would fly apart by centrifugal force. However, NEAs <200 m diameter with measured lightcurves have spin periods <2 h, ranging downward to just a couple minutes[43]. Clearly the latter are strong, monolithic rocks, while larger NEAs are rubble piles, susceptible to disaggregation by tidal forces during a close passage to Earth or another large planet. Numerical simulations (see ref. 41) show that some such tidal encounters result in double bodies or a dominant body with one or more satellites. During 2004 MN4 (Apophis)'s forthcoming close pass to Earth in 2029, tidal forces are likely to change its spin and rearrange its internal structure, but they are inadequate to break it apart.

Small-scale surface properties of small, nearly gravitationless NEAs, below the resolution of radar delay-doppler mapping, remain conjectural, except for Eros, which was imaged down to cm-scales near NEAR Shoemaker's landing site. Pre-NEAR Shoemaker predictions about the small-scale structure of Eros' surface were dramatically incorrect[44],[45]: unlike the lunar regolith, small (<10 m diameter) craters are very rare on Eros, whereas boulders and rocks are extremely common. The character of surficial soils and regoliths on smaller NEAs is difficult to predict, but it is important, as all proposed deflection technologies (as well as future operations on asteroids, such as mining) would have to interact with the NEA's surface, whether to attach a device, burrow into the object, or affect the surface remotely (e.g. by neutron bomb detonation or laser ablation). Probably, the surfaces of rapidly-spinning small bodies <200 m diameter are composed of hard rock (or metal), with only an extremely thin layer of surficial particulates (e.g., bound by electrostatic forces). The surface properties of the small proportion of NEOs that are live or dead comets are even less certain. Deep Impact's dramatic cratering experiment on the nucleus of comet Tempel 1 in July 2005 was initially interpreted in terms of an unexpected deep surficial layer of fine powder.

6. Impacts during the Earth's geological history

We now consider the role impacts have played in the geological and biological history of our planet, which sets the stage for the modern impact hazard. About 170 impact craters have been recognized on Earth[46], and perhaps double that number according to private, commercial records. They range from recent, small (tens to hundreds of m diameter) impact craters to multi-hundred km structures expressed in the geologic record although no longer retaining crater-like morphology, which has been eroded away. Published ages for some craters are of varying reliability (raising doubts about alleged periodicities in impact rates). The Earth's stratigraphic history is increasingly incomplete for older epochs, but the virtual total loss of datable rocks back toward 4 Gy is consistent with the inferences from the lunar LHB that Earth was pummeled by a couple lunar-basin-forming projectiles every My for 50-100 My, which would have boiled away any oceans and completely transformed the atmospheric, oceanic, and crustal environment of the planet. Additionally, *thousands* of K-T boundary level events, one every 10,000 y, must have had profound repercussions.

The LHB must have "frustrated" the origin of life on Earth[47],[48] while some impacting projectiles might have contributed life-enhancing, volatile-rich substances to our planet. Any simple, extant life forms could conceivably survive cratering bombardment by being ejected into geocentric or heliocentric orbits, and subsequently "re-seed" life upon re-impacting Earth after terrestrial environments had relaxed from the violent aftereffects of such bombardment[49],[50]. As noted above, the Earth's impact environment became similar to today's by ~3.5 Gy. Dozens of K-T level impacts would have happened since that time, several of which were at least an order-of-magnitude even more devastating. Momentous events, like "Snowball Earth"[51],[52], have been hypothesized to have occurred in pre-Phanerozoic times (i.e. before 570 My ago); the inevitable cosmic impacts must be considered as plausible triggers for such dramatic climatic changes, or their cessation, during those aeons.

During the Phanerozoic, there must have been several K-T (or greater) impact events, roughly equaling the number of major mass extinctions recorded in the fossil record. Only the K-T boundary extinction is now accepted as being largely, or exclusively, due to impact (the formation of Chixchulub). Evidence accumulates that the greatest mass extinction of all, the Permian-Triassic event, was exceptionally sudden[53]; one recent study that argues for a gradual P-T extinction is invalidated by its faulty methodology. It is possible that the K-T impact was exceptionally efficient in causing extinction (e.g., because of the composition of the rocks where it hit, or if it were an oblique impact or augmented by accompanying impacts). However, straightforward evaluations of the expected physical[54] and biological[55] repercussions of massive impacts suggest that any such impact should result in such extreme environmental havoc that a mass extinction would be plausible, although conditions may cause consequences to vary among impacts of similar magnitude[56]. It is plausible that the difficulty of finding incontrovertible proof of the impact origin of earlier mass extinctions is because of the much poorer preservation and quality of the more ancient geological records.

One of us (Chapman) argues[57] that impacts must be exceptionally more lethal than any other proposed terrestrial causes for mass extinctions because of two unique features: (a) their environmental effects happen essentially instantaneously (on timescales of hours to months, during which species have little time to evolve or migrate to refuges) and (b) there are multiple environmental consequences (e.g., broiler-like skies as ejecta re-enter the atmosphere, global firestorm, ozone layer destroyed, earthquakes and tsunami, months of ensuing "impact winter", centuries of global warming, poisoning of the oceans). Not only the rapidity of changes, but also the cumulative and synergistic consequences of the compound effects, make asteroid impact overwhelmingly more difficult for species to survive than alternative, Earth-generated crises. Volcanism, sea regressions, and even sudden effects of hypothesized collapses of continental shelves or polar ice caps are far less abrupt than the immediate (within a couple of hours) worldwide consequences of impact; life forms have much better opportunities in longer-duration scenarios to hide, migrate, or evolve.

Other hypotheses for mass extinctions lack the diverse, compounding negative global effects of impacts. Only the artificial horror of global nuclear war or the consequences of a very tiny possibility of a stellar explosion near the Solar System could compete with impacts for immediate, species-threatening changes to Earth's ecosystem. Therefore, since NEA impacts inevitably happened, it is plausible that they -- and chiefly they alone -- caused the mass extinctions in Earth's history (as hypothesized by Raup[58]), even though proof is lacking for specific extinctions. What other process could possibly be so effective? And even if one or more extinctions *do* have other causes, the largest asteroid/comet impacts during the Phanerozoic cannot avoid having left traces in the fossil record. By analogy, in the modern world, the very tiny possibility of an impact by a large comet or asteroid, exceeding several km in diameter, is the largest conceivable natural disaster that humanity confronts.

7. Risks and consequences of impacts for society in the 21st century

The statistical frequency of impacts of various energies is quite well known, and is shown in Figure 2-1. Less well understood are the physical and environmental consequences of impacts of various energies. The most thorough evaluation of the environmental physics and chemistry of impacts is by Toon /et al./ (*See ref. 54);* later research has elucidated the previously poorly understood phenomena of impact-generated tsunami [59],[60]. There has also been recent argumentation [J.W. Birks, P.J. Crutzen, R.G. Roble 2007. "Frequent Ozone Depletion Resulting from Impacts of Asteroids and Comets," in "Comet/Asteroid Impacts and Human Society" (Eds. P. Bobrowsky, H. Rickman; Springer, Berlin) pp 225-245] that the ozone layer might be largely destroyed by NEOs as small as 0.5 km, smaller than previously estimated. Chapman has evaluated numerous impact scenarios[61], emphasizing their potential consequences on human society, which are even less well understood than environmental effects. The most comprehensive recent analysis of the risks of NEA impacts is that of the NASA NEO Science Definition Team (SDT) *(See ref.22).*

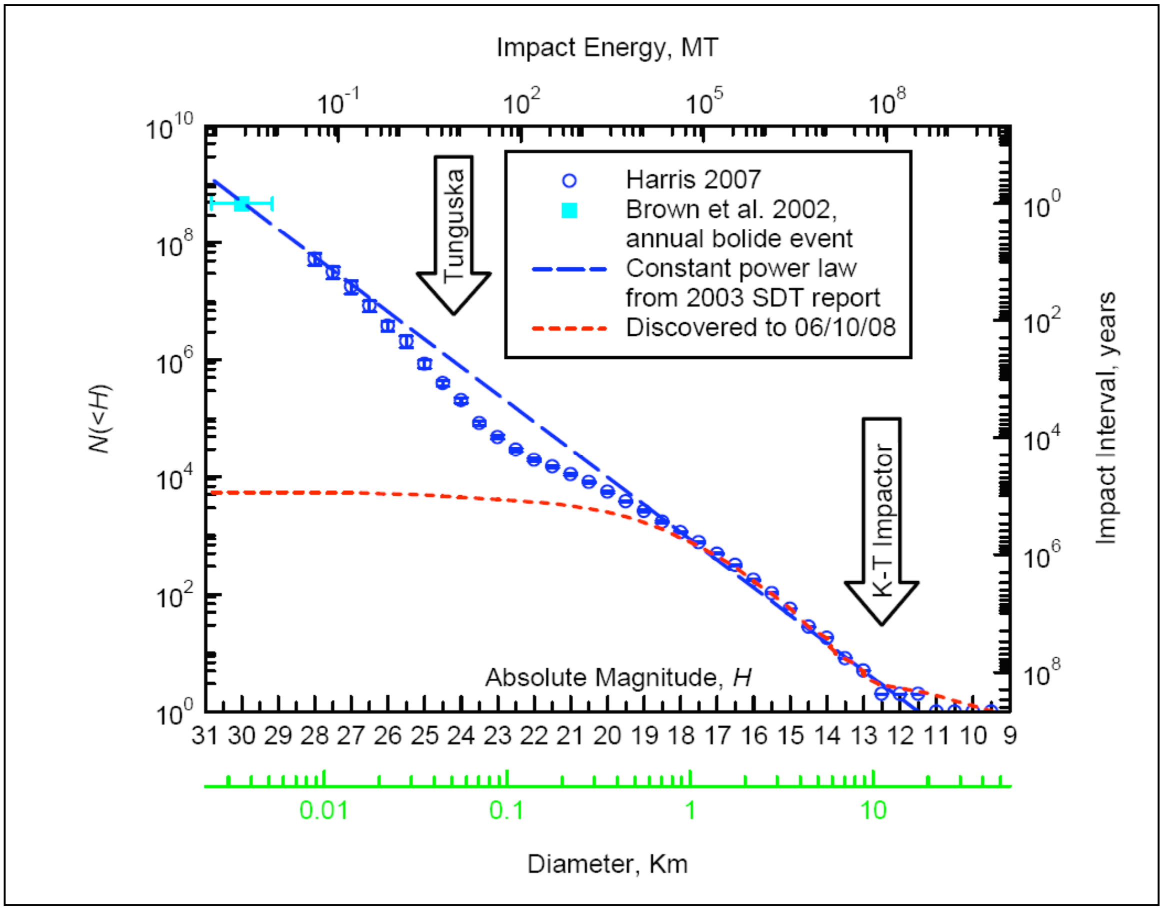


Figure 2-1: Size-frequency relationship for NEAs striking the Earth.

[The vertical axes of Figure 2-1 show the cumulative number of NEAs with absolute magnitudes less than H and the corresponding average interval between impacts of such NEAs. The horizontal scales convert H into NEA diameter and impact energies. The long-dashed line is the constant power law model of population adopted in the SDT report. The round symbols represent a 2007 updating of the SDT estimates; the short-dashed curve shows the total number of NEAs discovered as of mid-2008.]

The plot of Figure 2-1 summarizes both the results of and enlightens the agreement between the two models. The box `K-T' labels the energy uncertainty of the impact that caused the extinction of the dinosaurs, which happens on average every several hundred My. The box "1 km" labels the energy interval corresponding to impacts by NEOs of 1 km in diameter. These collisions happen every 1 My. The box "UK 2000" labels the impact energy that has been defined as a lower limit for "dangerous impacts" by the UK task force on NEO hazard. These dangerous collisions happen on average every 65,000 years. Finally, the box "Tunguska" marks the energy released by the Tunguska event, which, despite having occurred at the beginning of last century, should in reality happen only once every 2,000 years. (courtesy S. Stuart).

Before the Spaceguard Survey, the dominant mortality was expected to arise from those large NEAs (>1.5 – 3 km diameter) that exceed the threshold for globally destructive effects[62], thought at the time to be perhaps 3,000 deaths per year worldwide, comparable with mortality from other significant natural and accidental causes (e.g. fatalities in airliner crashes). The estimated intrinsic mortality is now somewhat lower, ~1200 annual deaths (Harris 2008; see ref. 22) mainly due to somewhat higher estimates of the threshold size for destructive global effects. Moreover, since none of the NEAs >1 km diameter that have been discovered as of 2008 (Fig. 2-1) will encounter Earth in the next century, the Spaceguard Survey has effectively "retired" most of the intrinsic risk so that the post-Spaceguard residual risk during the next 50 – 100 years is ~110 annual deaths, see Table 2-1 and Figs. 2-1 and 2-2, based on the SDT Report with 2008 updates (Harris 2008). Most of the remaining global threat is from the ~1/5 of large NEAs yet-undiscovered plus the minor threat from comets (comet impacts could be exceedingly destructive but are rare compared with NEA impacts).

The SDT also evaluated two other sources of mortality due to NEO impactors smaller than those that would cause global effects: (a) impacts onto land, with local and regional consequences analogous to the explosion of a large bomb and (b) impacts into an ocean, resulting in inundation of shores by the resulting tsunamis (see ref. 60). The SDT evaluated fatalities for land impacts using (a) a model for the radius of destruction by impactors >150 m diameter[63] that survive atmospheric penetration with most of their cosmic velocity (although 220 m may be more nearly correct[64]) and (b) a map of population distribution across the Earth, along coastlines, in particular. A thorough analysis of the tsunami hazard[65], based on reanalysis of wave and run-up physics, provided an estimated number of "people affected per year" by impact-generated tsunami. The SDT notes that, historically, only ~10% of people in an inundation zone die, thanks to advance warning and evacuation. Since a similar level of advance warning from an ocean impact could be expected, we suggest that the actual fatality fraction might be similar, although this was not taken into consideration in the SDT report. Hence, in Table 2-1, which summarizes mortality from land impacts, ocean impacts, and globally destructive impacts, we provide a second set of estimates, labeled F', in which we divide the SDT's estimated tsunami hazard by a factor of 10.

In Table 2-1, we separate out each of the general classes of hazard: land impacts, which are dominated by small impactors in the size range from 50 to 150 m diameter; ocean impacts causing tsunami, dominated by bodies in the 150-700 m size range; and the largest impactors, 1.5 km or larger that can cause global climatic catastrophes affecting people anywhere in the world, and hence more or less independent of the impact site. A last row lists the SDT estimate of comet impact risk, which is constant in all that follows. In the first pair of data columns, we list the intrinsic risk, before any NEAs were discovered, using the population model of the SDT report. In the next pair of columns, we use the same "kill curve" (F as in the SDT report and F' for the tsunami risk reduced a factor of ten), but apply it to the new population estimate of Harris (2008), shown in Fig. 2-1. The next pair of columns list the "residual" risk, reduced by the fraction of NEAs currently discovered and found to present no immediate impact risk in the next half century or so. The last two columns list the "residual" risk from each class that will remain after the Congressionally mandated "next generation" survey of 90% completion to a diameter of 140 m is achieved. None of these surveys will provide a meaningful warning of a comet impact, thus that risk remains unchanged. Figure 2-2 presents the risk versus size of impactor in histogram form, using the 2008 population model, for the intrinsic risk before any NEAs were discovered, and the residual risk at the current (mid-2008) level of completion. In both cases, we have used the SDT model of tsunami risk. If we had used that level divided by ten, the risk level in the mid-range from 150 m to 1.5 km diameter would be a factor of several times lower still.

		SDT Population		New Population		New Pop, current compl		New Pop, Next Gen	
Class	<D>, km	F	F’	F	F’	F	F’	F	F’
Land	0.05-0.15	61	61	23	23	11	11	4	4
Tsunami	0.15-0.70	182	18	59	6	35	4	3	0.3
Global	>1.5	1011	1011	1098	1098	54	54	11	11
Comets		10	10	10	10	10	10	10	10
Total		1264	1100	1191	1138	110	79	28	25

Table 2-1: Impact hazard by class of impactor.

[In Table 2-1 <D> is the size range of the most hazardous impactors of the class, i.e., the size associated with the highest “fatalities” per year. F is in principle the estimated fatalities per year, although for tsunami it is estimated that perhaps only 10% of the population in the inundation zone of a tsunami may actually die. For that reason, we tabulate also F’, in which we have reduced $F_{tsunami}$ by a factor of ten. We tabulate four sets of estimates. The first is essentially copied from the 2003 SDT report, using that population model and their calculated values of F. The next two columns use the same “kill curve” but impact rates derived from the more recent population model of Harris (2008), shown in Fig. 2-1. The next pair of columns show the “residual” impact risk, given that currently discovered (as of June, 2008) NEAs have been found to have essentially zero probability of impact in the next half century or so. Finally, the last two columns list the residual hazard that will remain when the Congressionally mandated goal of 90% of PHAs of D > 140 m is achieved.]

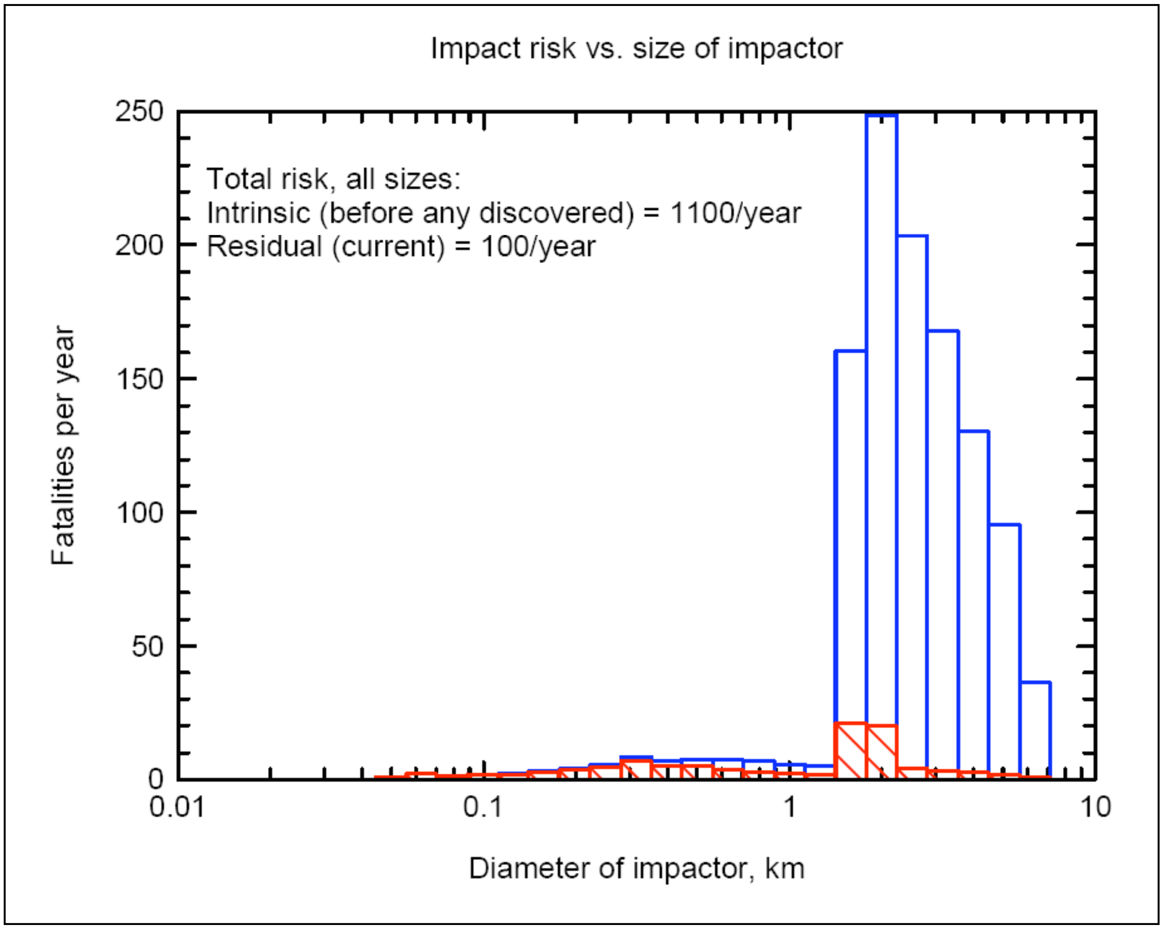


Figure 2-2. Number of annualized fatalities due to NEAs of various diameters.

[The open bars represent fatalities due to the intrinsic hazard from NEA impacts, as updated from the SDT estimates shown in Table 1 (see text). The cross-hatched bars represent the residual risk from the as yet (mid-2008) un-discovered fraction of the NEA population. Clearly, the dominant threat was from NEAs >1 km in diameter, but that threat has been greatly reduced by the Survey. The threat from small NEAs 50 m to 1 km in diameter has been reduced by a much smaller factor, but was intrinsically a minor part of the overall risk. This chart was updated from the SDT report and our Table 2-1.]

The SDT's main goal was to derive the cost-benefit ratio for building an augmented Spaceguard Survey, so they emphasized property damage rather than mortality, which gives greater weight to destruction by tsunamis compared with land impacts. On that basis, they calculated the costs of various ground- and space-based telescope systems that might retire 90% of the residual non-global impact hazard in the next decade or two. The SDT's final recommendation was to proceed, beginning in 2008 (the nominal date for completing the Survey, even though – as we've noted above—it won't be completed until well after that), with what they calculated would be a cost-effective 7-20 year program, costing between \$236 and \$397 million, designed to discover 90% of PHOs >140 m diameter.

Individual human beings and society itself reacts in subjective ways to comparisons of the impact hazard with other societal hazards, especially because of the inherent low-probability high-consequence character of the impact hazard. We consider mortality rather than property damage as being more central to fears of impacts. But neither mortality nor economic loss estimates provide a good forecast of how societies may respond in the future to different kinds of hazards. The ~3000 deaths from the terrorist attacks of September 11, 2001, had dramatic national and international consequences (involving economics, politics, war, etc.) while a similar number of U.S. highway fatalities during the same month were hardly noticed, except by family members and associates of the deceased. Risk perception expert Paul Slovic notes that asteroid impacts have many elements of a "dreadful" hazard (being perceived as being involuntary, fatal, uncontrollable, catastrophic, and increasing [increasing in news reports, anyway]), like terrorism or nuclear threats, in contrast with more mundane hazards that may be more serious as measured by objective criteria (see ref. 65). Society often spends much -- even orders of magnitude -- more per life saved to reduce "dreadful" hazards than mundane ones. For this reason, efforts to reduce the impact hazard and to plan for mitigation (e.g. evacuation of ground zero, storing food supplies in order to survive a global agricultural disaster, or developing capabilities to deflect a threatening NEO), may be perceived by many citizens as money well spent. On the other hand, Slovic's public opinion polls show that many others regard the impact hazard as being trivial.

8. Three examples of NEA consequences

We briefly summarize three scenarios (drawn from many more in ref. 61), which illustrate the breadth of issues that must be confronted in managing potential consequences of NEA impacts. For each impact disaster scenario, we consider the nature of the devastation, the probability that the event will happen, the likely warning time, the possibilities for post-warning mitigation, the nature of issues to be faced in after-event disaster management, and -- of most practical interest -- what can be done *now* to prepare in advance.

2-3 km Diameter Civilization Destroyer

A million MT impact, even though ~100 times less energetic than the K-T impact, would probably destroy civilization as we know it. The dominant immediate global effect would be sudden cooling, lasting many months, due to massive injection of dust into the stratosphere following impact. Moreover, the ozone layer would be destroyed. Agriculture would be largely lost, worldwide, for an entire growing season. Combined with other effects (e.g. a firestorm the size of India), it is plausible that billions might die from collapse of social and economic institutions and infrastructure. No nation could avoid direct, as well as indirect, consequences of unprecedented magnitude. Of course, because civilization has never witnessed such an apocalypse, predictions of consequences are fraught with uncertainty: is civilization inherently fragile or robust?

As discussed earlier, few NEAs >2 km remain undiscovered, so the chances of such an event are probably <1-in-100,000 during the next century. The warning time would almost certainly be long, in the case of an NEA, but with current technology telescopes might be only months in the case of a comet. With years or decades of advance warning, a technological mission might be mounted to deflect an NEA so that it would miss the Earth (and also possibly a comet should new technologies enable similar warning times for them). Moving such a massive NEA would be very challenging. In any case, given sufficient warning, many immediate fatalities could be avoided by evacuating ground zero and longer-term casualties could be minimized by storing food supplies to survive the agricultural catastrophe. Susceptible infrastructure (transportation, communications, medical services) could be strengthened in the years before impact. However, no preparation for mitigation is warranted for such a rare possibility until a specific impact prediction is made and certified. The only advance preparations that might make sense would be *at the margins* of disaster planning developed for other, “all-hazards” purposes: considering such an NEA apocalypse might foster "out-of-the-box" thinking about how to define the outer envelope of disaster contingencies, and thus prove serendipitously useful as humankind faces an uncertain future.

Once-in-a-Century Mini-Tunguska Atmospheric Explosion

Consider a 30-40 m office-building-sized object striking at 100 times the speed of a jetliner. It would explode ~15 km above ground, releasing the energy of ~100 Hiroshima-scale bombs. Some researchers consider that such an event would be spectacular to witness but would not have lethal consequences. Our review of the literature suggests, however, that weak structures might be damaged or destroyed by the overpressure of the blast wave out to 20 km. The death toll might be hundreds; although casualties would be far higher in a densely populated place, they would much more likely be zero (i.e., if the impact were in the ocean or in a desolate location). Such an event is likely to occur before or during our grandchildren's lifetimes, although most likely over the ocean rather than land. Even with the proposed augmented Spaceguard Survey, it is unlikely that such a small object would be discovered in advance; impact would occur without warning. Since it could occur literally anywhere, there are no location-specific kinds of advance measures that could or should be taken, other than educating people (perhaps especially military forces that might otherwise mistake the event as an intentional attack) about the possibilities for such atmospheric explosions. In the lucky circumstance that the object is discovered years in advance, a relatively modest space mission could deflect such a small body, preventing impact (see ref. 65).

Prediction (or Media Report) of a Near-Term Impact

This NEA scenario is the one most likely to become an urgent issue for public officials. Indeed, such events have already happened. The problem, which can develop within hours in the 24-hour global news media, is that something possibly real about an NEA is twisted by human fallibility and/or hyperbole. Hypothetical examples include: (a) a prediction, a few days in advance, of an actual near-miss ("just" 60,000 km from Earth) by a >100 m asteroid, which might be viewed with alarm by a distrustful public who would still fear an actual impact; (b) the reported (or mis-reported) prediction by a reputable (but mistaken or misquoted) astronomer that a huge impact will occur on a specific day in the future in a particular country, resulting in panic for several days until the report is withdrawn; or (c) a prediction, officially endorsed by an entity like the International Astronomical Union, of a few-percent chance of impact by a multi-hundred-meter NEA on a specific date decades in the future (Torino Scale = 4; see below), which because of circumstances cannot be refined for months. The last case actually happened around Christmas 2004, involving an asteroid then designated as 2004 MN4, except that fortuitous location of pre-discovery observations rendered the impact moot within a few days rather than months; because this prediction happened over the holidays and then overshadowed by the Indian Ocean tsunami, media hyperbole was muted.

Ways to eliminate instances of hype and misunderstanding involve public education about science, critical thinking, and risk; familiarizing science teachers, journalists, and other communicators with the impact hazard might be especially effective. Chapter 6 of this report treats the sociological and psychological aspects of planetary defense in much more depth. One approach that has evolved since a 1999 conference in Torino (Turin), Italy, is promulgation of the Torino Scale[66],[67] Figure 2-3, (see ref. 61), which attempts to place impact predictions into a sober, rational context (on a 10-point Richter-like scale, predicted impact possibilities usually rate a 0 or 1, and are unlikely to exceed 4 during our lifetimes).

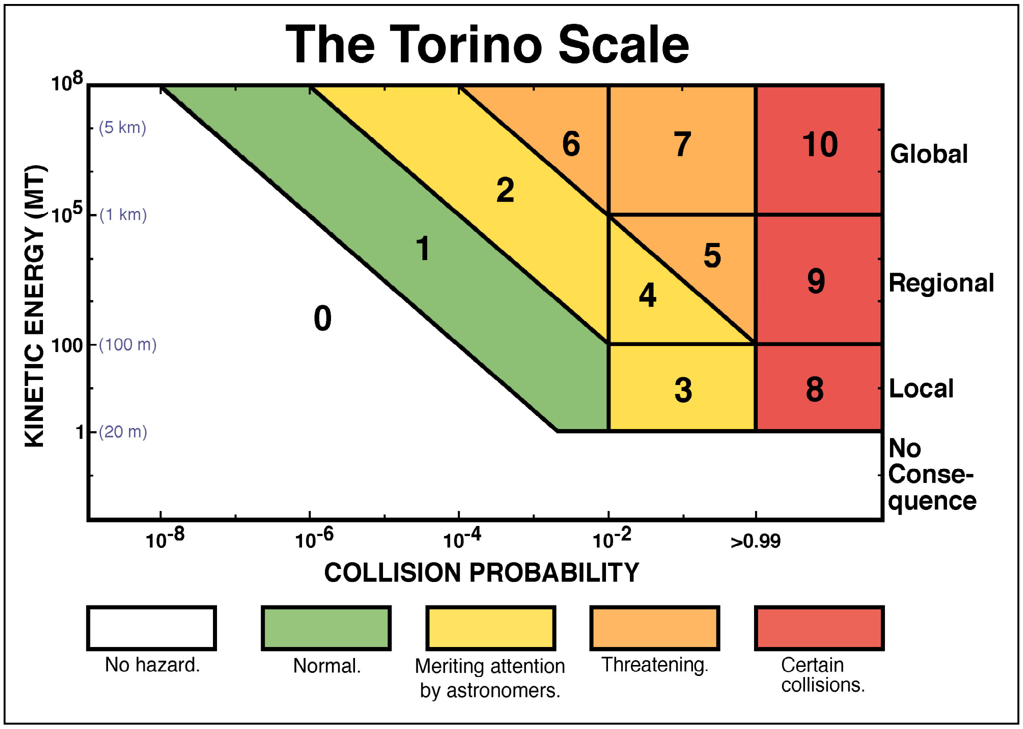


Figure 2-3: The Torino scale (NASA)

9. The modern impact hazard: Conclusions

Contrasting with most practical issues involving meteorology, geology, and geophysics, the impact hazard is both more extreme in potential consequences and yet so rare that it has not even been experienced in more than minor ways in historical times. It has similarities to natural hazards in that its practical manifestations mainly involve familiar destructive processes, such as fire, high winds, earthquakes, falling debris, and floods. Yet impacts differ from other natural disasters because the hazard is mainly not location-dependent (impacts happen anywhere, not just along faults, although ocean impact effects are amplified along coastlines) and there are no precursor or after-shock events.

There are also similarities and differences compared with terrorism and other human-caused calamities. Like terrorism, the impact hazard is "dreadful" (in Slovic's nomenclature), it seems to strike randomly (at least unexpectedly) in time and location, and few have been (or, in our estimation, are likely to be) killed, although in each case many *could* be killed. Dissimilar attributes include the essential "act of God" nature of impacts, whereas terrorism involves willful acts of evil, inspiring retribution. Also, we can probably *do something* about most impact threats, whereas terrorism and threats of nuclear war are dealt with by such imperfect human endeavors as diplomacy. Another disproportionate comparison involves past public expenditures: hundreds of billions of dollars are being allocated to the “war on terrorism” compared with a few million spent annually on the impact hazard (mostly supporting the Spaceguard Survey).

The impact hazard ranks with other natural and human-caused disasters in the mid-range of risks of death (see ref. 65): much less important than war, disease, famine, automobile accidents, or murder but much more important than shark attacks, botulism, fireworks accidents, or terrorism. The practical, public implications and requirements of the impact hazard are characterized by its *uncertainty* and "iffy" nature. Yet the chief scientific evaluations of the hazard, and thus (because of the subject's popularity) its public promulgation in the news, is skewed with respect to reality. In the last few years, many peer-reviewed papers have been published (often with popular commentaries and even CNN crawlers) about how many >1 km NEAs there are, ranging from lows of ~700[68] to highs approaching 1300. Yet far less attention is paid (although not quite none at all [e.g. [69]]) to the much greater uncertainties in environmental effects of impacts. And there is essentially no serious, funded research concerning the largest sources of uncertainty -- those concerning the psychology, sociology, and economics of such extreme disasters -- which truly determine whether this hazard is of academic interest only or, instead, might shape the course of history. Experts in the field of natural hazards regard natural hazards as “social constructs” in the sense that most aspects of disasters (predictions, perceived threat, warnings, actions taken in response to warnings, emergency response, recovery) are primarily, or heavily influenced by, social attitudes and societal structures. For example, many astronomers and geophysicists, who are amateurs in risk perception and disaster management, assume that "panic" is a probable consequence of predicted or actual major asteroid impacts. Yet most social scientists (e.g.[70]) have concluded that people rarely panic in disasters. Such issues, especially in a post-September 11th terrorism context, could be more central to prioritizing the impact hazard than anything that asteroid experts or “rocket scientists” can do.

We have noted the primacy of psychological perceptions in characterizing the impact hazard. Since the consequences of an impact (other than the spectacle of meteors, and occasional meteorite falls) have never been experienced by human beings now alive, we can relate to this hazard only theoretically. Since it involves very remote possibilities, the same irrationality applies that governs purchases of lottery tickets or re-building in 100-year floodplains just after a recent 100-year flood.

Because society fails to apply objective standards to prioritizing hazard mitigation funding, it is plausible that the residual risks of this hazard might be altogether ignored (the Spaceguard Survey has been cheap, but it becomes increasingly costly to search for the remaining, smaller NEAs); or society may instead over-react and give "planetary defense" more priority than battling such clear-and-present dangers as influenza. Yet the impact hazard can be mitigated in much more concrete ways than is true for most hazards. An impact can be predicted in advance in ways that remain imperfect (see ref. 67) but are much more reliable than predictions of earthquakes or even storms, and the components of technology exist -- at affordable costs given the consequences of an actual impact -- to move any threatening object away and avoid the disaster altogether.

Chapter 3.
DETECTION, IMPACT PREDICTION, AND WARNING

Introduction

To successfully avert a future asteroid or comet impact with the Earth the impactor must first be discovered and the object's orbit and physical properties must be characterized sufficiently. Additionally, these functions must be successfully performed with enough lead time to provide sufficient warning time to avert the collision or mitigate the effects on the Earth and its inhabitants. Since we cannot predict with certainty the direction from which a threatening asteroid or comet will come, we must observe the entire sky. Finally, if a mission to deflect or disrupt an impacting Near-Earth Object (NEO) is accomplished, a reassessment of that object must be completed to access the effectiveness of that mission. Accomplishing these critical tasks inherently requires international cooperation. This chapter will describe the current capabilities to provide these functions as well as improvements that can be reasonably expected in the near future.

Survey and Discovery

Current Ground-based and Space-based Assets

In 1990, the United States House of Representatives directed the National Aeronautics and Space Administration (NASA) to study the impact problem. NASA organized an international conference and conducted two workshop studies. The first workshop (NASA International Near-Earth Object Detection Workshop), comprising three formal meetings in 1991, defined a program for dramatically increasing the detection rate of large Earth-orbit-crossing asteroids, and established the requirements for determining the orbits of such bodies. The second workshop (Near-Earth Object Interception Workshop), in January of 1992, focused on defining systems and technologies to alter the orbits of Earth threatening asteroids, or obliterate them. The 1992 report from the first workshop[1] recommended the establishment of a coordinated ground-based effort, known as the Spaceguard Survey, with the primary goal of searching for large Earth-crossing asteroids capable of global devastation. This logical first step has significantly reduced the chances that Earth will be impacted by a large near-Earth asteroid without significant warning time. In 1998, NASA formally commenced its contribution to the Spaceguard Survey and set as a goal the discovery and cataloging, by 2008, 90% of the all NEOs with diameters 1 km or larger capable of threatening the Earth. Since it is widely believed that the vast majority of NEOs are asteroids and inactive short-period comets, long-period comets are not included in the survey goal and it is generally accepted that the population of NEOs and near-Earth asteroids (NEAs) are nearly identical. Long-period comets represent an extremely difficult detection problem since the majority of their time is spent orbiting at great distances from the Sun effectively beyond the observational "reach" of current ground-based telescopes, and so are not generally addressed.

The total population of NEOs larger than one kilometer in diameter is currently estimated to be between 1000 and 1200. As of December 18, 2008, a total of 5901 NEOs have been discovered, with 761 of these approximately 1 kilometer or larger[2]. Figure 3-1 shows the cumulative total of known NEAs through July 17, 2008. Additionally, 1004 NEOs have been classified as Potentially Hazardous Asteroids (PHAs). A PHA is defined based on the asteroid's potential to make threatening close approaches to the Earth. Specifically, all asteroids with an Earth Minimum Orbit Intersection Distance

(MOID) of 0.05 AU or less and an absolute magnitude (H) of 22.0 or less with assumed albedo of 13% are considered PHAs (corresponding to an object approximately 150 m diameter).

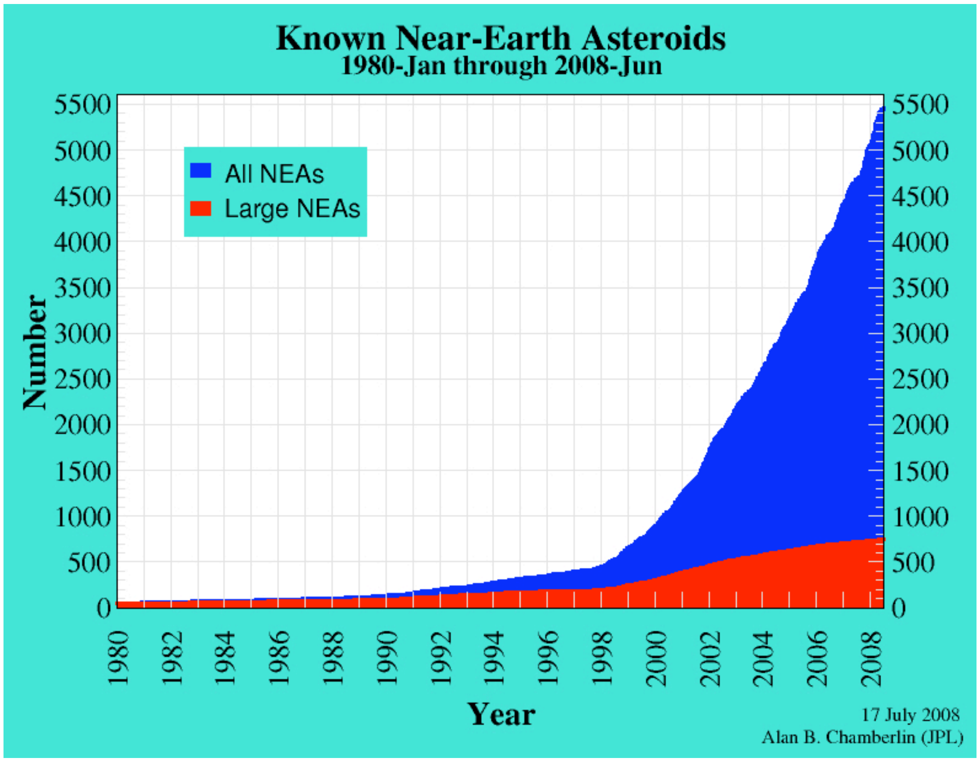


Figure 3-1: Cumulative total of known near-Earth asteroids since 1980 (Courtesy NASA/JPL-Caltech)

Several current NEO survey teams, involving fewer than 100 people worldwide, are focused on finding the largest objects. The current best estimate of the total number of NEOs larger than 1 km in diameter is approximately 1100. The population of objects between approximately 50 and 100 m in diameter is estimated to be about 500,000. This range represents the minimum size NEO capable of penetrating the Earth's atmosphere and impacting the surface. Although not efficient at searching for sub-kilometer size objects, these teams are finding far more NEOs smaller than 1 kilometer in diameter. The following is a list of the primary discovery teams currently participating in the Spaceguard Survey:

- Asiago-DLR (German Aerospace Center) Asteroid Survey (ADAS) near Asiago, Italy
- Campo Imperatore Astronomical Observatory near Rome, Italy
- Catalina Sky Survey – A consortium of three cooperating surveys: the original Catalina Sky Survey (CSS) and the Mt. Lemmon Survey (MLSS) in Tucson Arizona, USA, along with the Siding Springs Survey (SSS) near Coonabarabran, Australia
- Japanese Spaceguard Association (JSGA) observational facility near Bisei, Japan
- Lincoln Near-Earth Asteroid Research (LINEAR) in New Mexico, USA
- Lowell Observatory Near-Earth Object Search (LONEOS) in Flagstaff, Arizona, USA
- Near-Earth Asteroid Tracking (NEAT) at the Maui Space Surveillance Site in Hawaii, USA
- Spacewatch at the University of Arizona in Tucson, Arizona, USA
- Klet Observatory, Czech Republic

The discovery teams utilize charged couple device (CCD) image sensors typically 2096 x 2096 pixels in size. Three or more images are taken several minutes apart and then compared to the background object (stars, galaxies, etc.) to detect the more rapidly moving NEOs. The movement of the NEO is used to assist in determining the object's orbital characteristics and the brightness is used as an approximate indicator of its size based on an assumed geometric albedo (the ratio of a body's brightness at zero phase angle to the brightness of a perfectly diffusing disk with the same position and apparent size as the body). Figure 3-2 shows the yearly number of near-Earth asteroid discoveries by each team through July 15, 2008. Additionally, astronomers from around the world (many of them amateurs) provide follow-up observations critical for securing the orbit of a newly discovered NEO. Additional information on the survey teams and facilities can be found at the NASA NEO Program Office website[3]

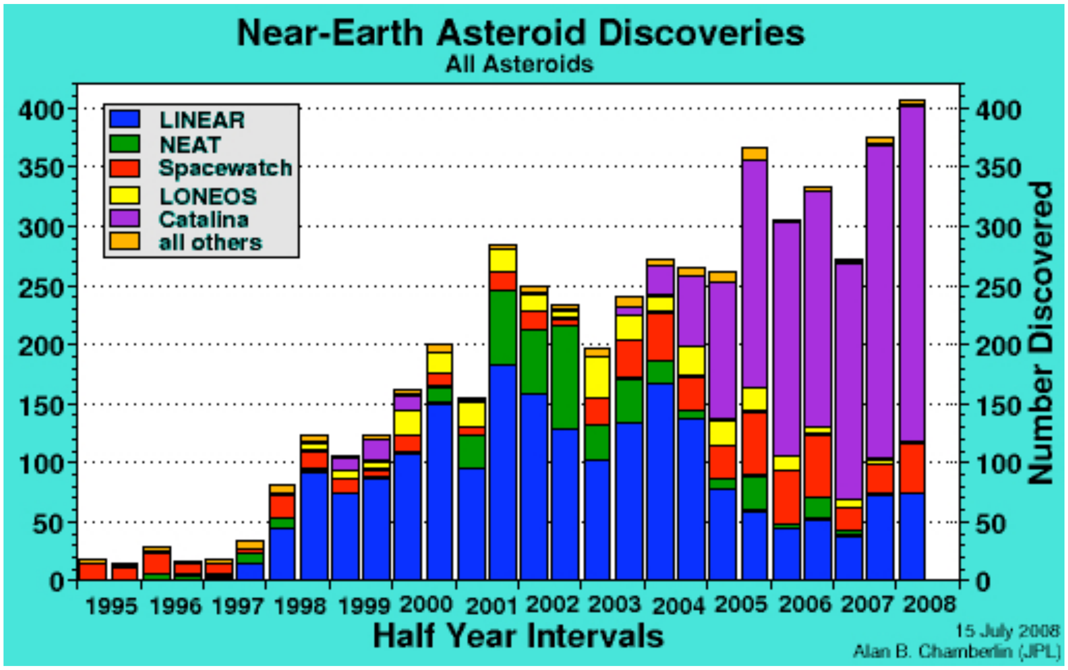


Figure 3-2: Yearly NEA discoveries by team (Courtesy NASA/JPL-Caltech)

At the present time, there are no dedicated space-based assets for NEO surveying and discovery. Space-based assets are limited to telescopes that can provide serendipitous discovery and limited support observations, particularly when higher resolution observations are required. A recent example of this is the set of observations provided by NASA's Spitzer and Hubble Space Telescopes during the break-up of Comet 73P/Schwassman-Wachmann 3 into over 60 fragments during April and May of 2006 (see Figure 3-3)[4]. The Canadian Space Agency (CSA) and Defense Research and Development Canada (DRDC) are currently developing the Near Earth Observation Surveillance Satellite (NEOSSat), which will use a 15 cm optical telescope to search for Atens and inner-Earth objects (IEOs) near the ecliptic within 45° of the Sun that may not be visible to ground-based observatories. This microsatellite will be the first space-based asset deployed specifically to search for NEOs and is currently scheduled for launch in 2009. The objective of the mission is to detect at least 50% of all IEOs having diameters greater than 1 km[5].

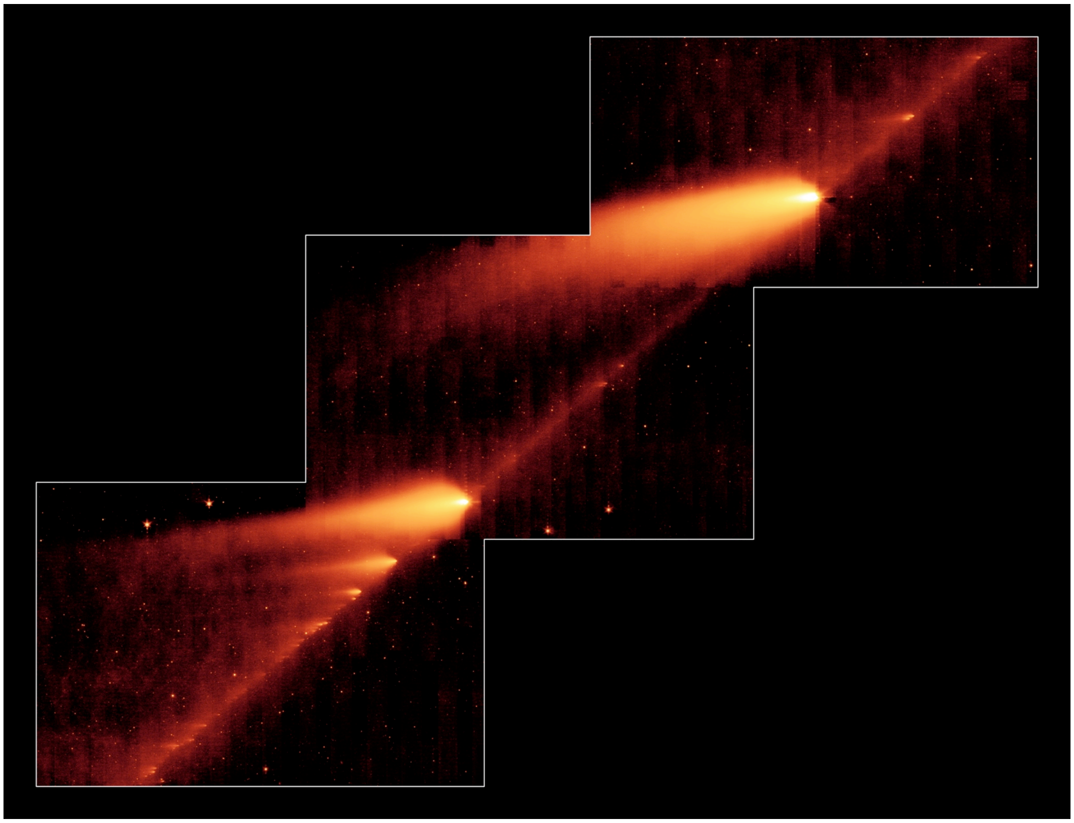


Figure 3-3: NASA's Spitzer Space Telescope image of Comet 73P/Schwassman-Wachmann 3 fragmentation (Courtesy NASA/JPL-Caltech)

Coordination of Observations and Dissemination of Information

The International Astronomical Union's Minor Planet Center (MPC)[6] operating at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, USA, is the organization that collects, computes, checks, and disseminates astrometric observations and orbit information for minor planets and comets from hundreds of observatories worldwide, both professional and amateur. This is performed via the Minor Planet Circulars (issued generally on a monthly basis), the Minor Planet Circulars Orbit Supplement (issued three or four times per year), the Minor Planet Circulars Supplement (issued three or four times a month) and the Minor Planet Electronic Circulars (issued as necessary, generally at least once per day). The MPC is also responsible for the designation of minor bodies in the solar system: minor planets; comets (in conjunction with CBAT [Central Bureau for Astronomical Telegrams]); and natural satellites (also in conjunction with CBAT). The MPC maintains an on-line NEO Confirmation Page (NEOCP)[7]. The NEOCP gives access to ephemerides for newly-discovered fast-moving (or other unusual) objects in need of confirmation. Most of the objects listed on the NEOCP have not received official provisional designations from the MPC, and follow-up observations are provided by international observatories on a daily basis. Additionally as the number of observations becomes larger it has become more difficult for the MPC staff to correlate an object detected at different times.

The *Horizons* ephemeris computation facility[8] maintained by the Solar System Dynamics Group located at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, USA and the Near Earth Object Dynamics Site (NEODyS)[9] at the University of Pisa in Italy provide independent orbit projections 100 or more years into the future and cataloging of confirmed NEO candidates. Both organizations provide NEO close approach and risk assessment information and offer convenient web-based services for observers, researchers, and the general public.

Capability Augmentation and Improvement

In 2003 NASA issued the Report of the Near-Earth Object Science Definition Team (SDT) titled "Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters."[10]. Motivated by the substantial progress being made toward the 2008 goal of discovering and cataloging 90% of the all NEOs with diameters 1 km or larger, this study specifically addressed what, if anything, should be done concerning the much more numerous smaller NEOs that pose a potential impact threat. The team recommended that a search system be constructed to discover and catalog 90% of the potentially hazardous objects (PHOs), which is a subset of the NEOs, larger than 140 m in diameter. PHOs approach the Earth's orbit within 0.05 AU (~7.5 million km).

The study evaluated a broad range of technology and search systems including ground-based and space-based optical and infrared systems across a credible range of optics and detector sizes. Ground-based telescopes with apertures of 1, 2, and 4 meters were considered along with space-based telescopes with apertures of 0.5, 1, and 2 meters. Various geographic locations were considered for the ground-based systems. Space-based telescopes in low-Earth orbit (LEO), the Earth-Sun L2 Lagrange point, and a Venus-trailing orbit (0.7 AU semi-major axis) were also assessed. According to the cost/benefit assessment performed for the study, the benefits associated with significantly reducing the risk of an impact with a smaller object justified substantial investment in PHO search systems. If the survey was to be completed within 10 years space-based systems were preferable, but at a higher cost than ground systems. If as many as 20 years were permitted to achieve the 90% complete goal, ground-based systems could perform the survey at a significantly reduced cost. Additionally, the ground-based systems could be repaired and upgraded more easily than the space-based systems.

In 2004, the European Space Agency (ESA) established an international panel called NEOMAP (Near-Earth Object Mission Advisory Panel) and the final NEOMAP report stated "The current consensus amongst the impact-hazard community is that future NEO search telescopes should be made sensitive enough to achieve near completion for objects significantly smaller than 1 km (the 'civilization-threatening' threshold in the original 'Spaceguard Goal' set by the US Congress in 1994). According to Harris (2004), systems such as the US Pan-STARRS (Panoramic Survey Telescope and Rapid Response System), the DCT (Discovery Channel Telescope) and LSST (Large Aperture Synoptic Survey Telescope) should be capable of discovering 90% of the population of NEAs with diameters of around 200 m or more after 10 years of operation. However, some of these facilities will serve general astrophysical research and will not be dedicated to NEO searches. It is not clear how much of their time will be made available for NEO searching or what operational constraints search programmes (sic) will be subject to." [11].

The future ground-based observatories identified in the NEOMAP report will greatly improve the search for NEOs and are currently at various stages of planning or implementation. The Panoramic Survey Telescope & Rapid Response System (Pan-STARRS) is an innovative wide-field imaging facility being developed at the University of Hawaii's Institute for Astronomy. Pan-STARRS will consist of four 1.8 meter telescopes and will have a 1.4 gigapixel CCD camera (38,400 x 38,400). The PS1 prototype telescope is essentially one quarter of Pan-STARRS, and "first light" occurred in June 2006.[12]. It will have the same optics design and camera design as anticipated for the full version of Pan-STARRS, which is currently in the site selection phase. The Discovery Channel Telescope (DCT) is Lowell Observatory's project to design and construct a powerful, 4.2-meter telescope. The DCT is being constructed 40 miles southeast of Flagstaff, Arizona and expected to fully operational in 2010.[13]. It is anticipated that the DCT, with its powerful wide field capability, will be able to discover 10-20 NEAs per hour, which is approximately ten times the discovery rate of all current survey programs combined. The Large Synoptic Survey Telescope is planned to be the world's most powerful survey telescope, consisting of an 8.4 meter aperture telescope with a 10 square-degree-field telescope. The LSST will be capable of scanning the entire visible night sky in a matter of days rather than years as is the case with current telescopes. A Chilean mountain peak has been chosen as the location of the telescope with construction to begin in 2009 and the facility to achieve "first light" in 2014.[14].

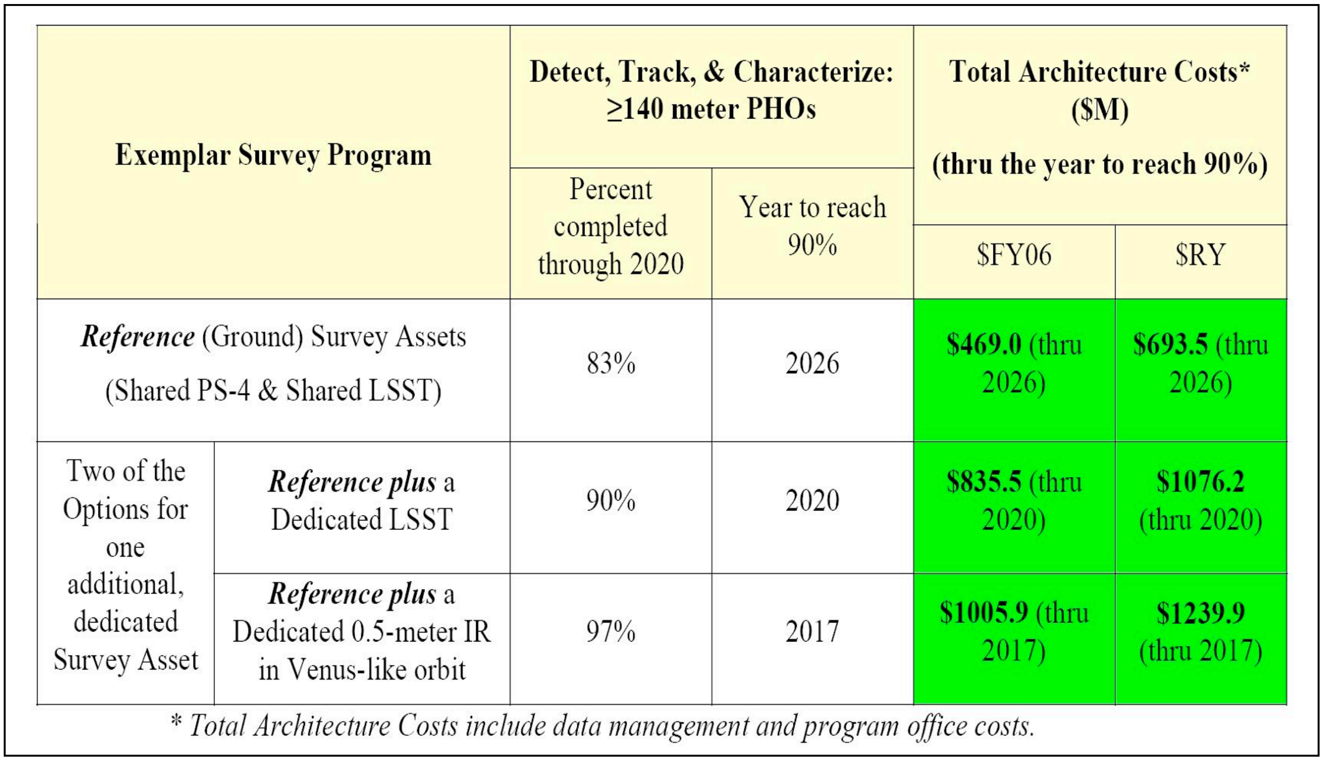
Future space-based observatories that are not dedicated to NEO detection will indirectly have a significant impact on the survey and cataloging of NEOs. For example, the European Space Agency's Global Astrometric Interferometer for Astrophysics (GAIA) mission is planned for launch by 2012. The GAIA spacecraft will observe the entire sky down to a visual magnitude of approximate V=20 and down to solar elongations of 35°. The GAIA spacecraft, which is anticipated to operate for five years, will be placed in orbit about the Earth-Sun L2 Lagrange Point. GAIA consists of two telescopes that will continually scan the sky and record every visible object that crosses its line of sight down to its limiting magnitude. Among its other astronomical objectives, GAIA will contribute to the search for NEOs due to its unprecedented sensitivity to faint, moving objects. The spacecraft is expected to detect tens of thousands of minor planets, many of which will be NEOs, main-belt asteroids, and Kuiper Belt objects.

On December 28, 2005, the United States Congress passed Section 321 of the NASA Authorization Act of 2005 (Public Law No. 109-155), also known as the George E. Brown, Jr. Near-Earth Object Survey Act. The objectives of the George E. Brown, Jr. NEO Survey Program are to detect, track, catalogue, and characterize the physical characteristics of NEOs equal to or larger than 140 meters in diameter with a perihelion distance of less than 1.3 AU (Astronomical Units) from the Sun, achieving 90 percent completion of the survey within 15 years after enactment of the NASA Authorization Act of 2005. The Act was signed into law by President Bush on December 30, 2005, and directed the NASA Administrator to transmit an initial report to Congress not later than one year after the date of enactment that provides: (1) an analysis of possible alternatives that NASA may employ to carry out the survey program of near-Earth Objects (NEO), including ground-based and space-based alternatives with technical descriptions; (2) a recommended option and proposed budget to carry out the survey program pursuant to the recommended option; and (3) an analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth.

The NASA report titled "Near-Earth Object Survey and Deflection Analysis of Alternatives - Report to Congress" was delivered to Congress in March of 2007.[15]. The report examined a large range of options including shared ground telescopes, dedicated ground telescopes, a number of space-based telescopes, and ground radar. Its principal findings were that the current Spaceguard system has little chance of meeting its goal of finding 90% of all NEOs with a diameter of 1 km or greater, even by 2030; that no single system examined completely accomplishes the goal; and that various solutions exist, including shared ground systems, dedicated ground systems, and ground systems augmented by one space-based telescope, whose performance increase is directly related to cost. A summary of the findings is shown in Figure 3-4, which indicates that the goal of 90% PHOs detected by 2020 can be met if a dedicated LSST system is added to the shared four-telescope Pan STARRS and a shared LSST system, for a total life cycle cost of $835 M. The addition of one 0.5 m space-based telescope gains 3 years at an increase in costs of $170 M.

In addition the NASA study concluded that ground-based radars were an extremely valuable tool for rapid and precise orbit determination of a few objects of potentially high interest when they approach Earth closely enough for the radar systems to be effective. As a particularly telling example, ground-based radars provided the definitive data when the orbit of the Apophis NEA was being intensely examined, and resulted in a lowering of the threat estimate to low enough probabilities that it is no longer considered an impact threat in the year 2029. The radars, principally Goldstone and Arecibo, would add another $100 M to the above life cycle cost estimates.

However the funding for continued operation of Arecibo radar, and thus its availability, is in grave doubt. The National Science Foundation is unwilling to continue its funding and absent a successful intervention effort in the US Congress the radar will soon be decommissioned. This would be a tragedy for the NEO community, and potentially for the world when, not if, another NEO with uncertain orbital parameters is found.



Exemplar Survey Program		**Detect, Track, & Characterize: ≥140 meter PHOs**		**Total Architecture Costs* ($M) (thru the year to reach 90%)**	
		Percent completed through 2020	Year to reach 90%	$FY06	$RY
Reference (Ground) Survey Assets (Shared PS-4 & Shared LSST)		83%	2026	**$469.0** (thru 2026)	**$693.5** (thru 2026)
Two of the Options for one additional, dedicated Survey Asset	***Reference plus*** a Dedicated LSST	90%	2020	**$835.5** (thru 2020)	**$1076.2** (thru 2020)
	Reference plus a Dedicated 0.5-meter IR in Venus-like orbit	97%	2017	**$1005.9** (thru 2017)	**$1239.9** (thru 2017)

** Total Architecture Costs include data management and program office costs.*

Figure 3-4: Program options recommended by NASA (Credit: NASA)

A number of other options were also studied and their performance and costs quantified. Overall the NASA study made clear that the goal was indeed achievable in a number of ways, that the addition of a modest space-based telescope shortened the time required by at least 3 years, and that the cost of all options that meet the goal would be in the vicinity of $1B. In addition the study made clear that the operation of any such system would generate 40 times more impact "warnings" than are currently experienced, up to 2-3 per week, by as early as 2010. The means to deal with such warnings and avoid an intolerable number of false alarms would stress the current operations center and systems. Clearly a major augmentation of these systems would be required to the handle the increased number of warnings.

2. Follow-up Observations for Orbit Determination and Object Characterization

Current Ground-based and Space-based Assets

Discovery of a new NEO is a necessary first step, but by itself is not sufficient. Securing a NEO's orbit is a critical aspect of the discovery and cataloging process, and refinement of the orbit sufficiently to determine if the object is probably on an impacting trajectory requires many highly accurate observations and sufficient observational arc lengths. This can be performed fairly well with the current NEO survey teams combined with the multitude of individuals (professional and amateurs) that provide follow-up observations to the Minor Planet Center. This effort is international in scope, but as the surveys become more numerous and more capable, follow-up observations become increasingly difficult, particularly for amateur observers.

Additionally, determining the physical characteristics of an asteroid or comet is crucial in the design of a mission to deflect or disrupt an Earth impactor as well as planning any robotic precursor missions. Of primary importance are the characterization of the object's mass, gravity field, spin state, surface topography and roughness, surface gravity field, and density distribution. Astrometric measurements (ground or space-based) can improve the accuracy of the orbit knowledge, estimate the body size, and potentially identify the existence of co-orbitals. Spectral imaging using filters can be used to determine asteroid type including composition, grain density, surface albedo, and size. Finally, intensity fluctuations can be used to estimate spin period, spin state, body shape, and rotation angular momentum. However, telescopic observations have their inherent limitations. Radar measurements provide a unique and highly capable source of information about a NEO's physical properties and orbit. The general methodology for a radar observation is to transmit a well characterized signal and compare it with the return echo to analyze the object's properties. Radar can be used to determine body shape, rotation state, co-orbitals, rotation angular momentum, improve heliocentric orbit prediction, and place constraints on surface density and roughness. Radar systems are limited in their range, but given sufficiently strong return signals they can permit two-dimensional spatial resolutions on the order of meters.

The accuracy of orbit determination can be improved greatly with measurements of range and range rate obtained from radar instruments. Radar measurements can determine the orbit well enough to prevent "loss" of a newly discovered asteroid and reduce the positional uncertainty by several orders of magnitude compared to optical astrometric observations only. Predictions based solely on optical data typically contain significant errors, even with long data arcs. Radar measurements can make the difference between estimating that an object will pass several Earth-Moon distances away from the Earth and realizing that the NEO will actually impact the Earth. However, because radar is an active technique it has very limited range capability compared to optical observations, and thus can only add to optical observations when the object passes relatively close to the Earth. This limits its ability to provide ephemeris-refining information, which could improve warning times when optical observations are not sufficiently accurate. Nonetheless radar is an extremely powerful detection tool and an indispensable observatory for detection and impact prediction of NEOs.

Radar has another vital capability, which is to help characterize the NEO. Given sufficient directional coverage of the object, the measurements can be combined to provide detailed three-dimensional models on the NEO and accurately define its rotation state. Detailed models of the object can provide tremendous insight into many of the areas critical to averting an impact with Earth. One critical area is the effect of the mass distribution on the stability of an orbit close to the NEO, which is required for any sort of rendezvous mission or landing. In addition radar observation can help to characterize the makeup of the object so that estimates can be made of its stability if it were subjected to various deflection or disruption techniques.

In-situ Space-based NEO Observations

Existing or future space-based assets to assist in NEO characterization in close proximity to the target body include robotic flyby, rendezvous, and landing missions using a variety of spacecraft such as orbiters, landers, and surface penetrators. Many instruments (visible cameras, synthetic aperture radar, lidar, mass spectrometers, seismographs, alpha particle x-ray spectrometers, etc.) currently exist and could be utilized to take extensive measurements of a particular asteroid or comet target. Many instruments have extensive flight heritage and have flown on various missions to asteroids and comets. Additionally, a radio transponder could be placed on a threatening NEO allowing for its orbit to be precisely determined. Robotic missions for the sole purpose of averting an Earth impact would only be possible if sufficient time existed before the impact and if the NEO's orbit was known well enough to be able to classify it as a probable threat. In general all scientific missions to investigate asteroids and comets provide valuable information and insight that can be useful in conjunction with principal means of observation in preventing an Earth impact by a NEO.

A small number of missions demonstrating the ability to flyby a NEO or rendezvous with the object and perform proximity operations have already been conducted by Japan and the United States. These missions demonstrated that the techniques are state-of-the-art and also provided invaluable data for the characterization of the NEAs. Of particular note is the Japan Aerospace Exploration Agency (JAXA) Hayabusa mission to the asteroid Itokawa. The Hayabusa spacecraft observed Itokawa with a suite of instruments including a multi-spectral telescopic imager, a laser altimeter, a near-IR spectrometer, and an X-ray fluorescence spectrometer. Hayabusa arrived at Itokawa on 12 September, 2005, made measurements of the NEA from an orbit around it, and actually landed on it (docked) twice on November 20 and 26, 2005. The probe is currently on a return trajectory to return to Earth and will arrive in June 2010. Spectacular images were returned from Hayabusa, some of which are shown in Figures 3-5 and 3-6. A number of smooth and rough areas were observed with high resolution instruments, as well as numerous boulders and 37 crater candidates, but no classic "bowl-shaped" craters were found.[16].

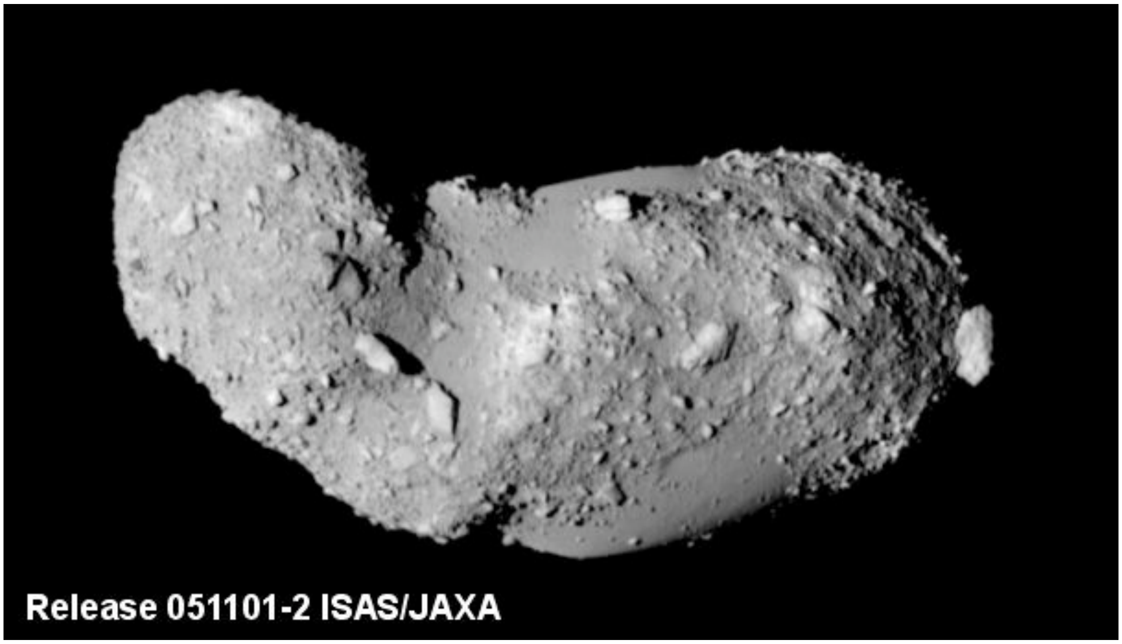


Figure 3-5: Asteroid Itokawa imaged by the Hayabusa spacecraft
(Credit and Copyright: ISAS/JAXA)

Figure 3-6: Close-up image of Itokawa prior to landing
(Credit and Copyright: ISAS/JAXA)

In addition to the data collected, the Hayabusa mission demonstrated the capability to characterize NEAs during rendezvous and docking missions. It is anticipated that the Hayabusa mission will return a sample of the asteroid Itokawa to Earth for laboratory analysis. Hayabusa determined that Itokawa is probably a small S-type asteroid, and that based on its surface material and bulk density, it is probably a loosely aggregated object, commonly referred to as a “rubble pile.” Its total mass was determined to be $(3.58 \pm 0.18) \times 10^{10}$ kg and its density was estimated at (1.95 ± 0.14) grams per cubic centimeter with a bulk porosity of approximately 40%.[17]. This type of information has primary application for the choice techniques that would be used to attempt the deflection or disruption of a future impactor.

The NASA Near Earth Asteroid Rendezvous - Shoemaker (NEAR Shoemaker) mission also demonstrated similar capabilities. NEAR Shoemaker rendezvoused with the asteroid Eros on February 14, 2000, and returned many images, some of which are shown in Figures 3-7 and 3-8. Combining digital images and data from the laser rangefinder, scientists built detailed maps and a three-dimensional model of an asteroid. Previously, many scientists had theorized that asteroids were either solid iron or cosmic rubble piles. The observations returned by NEAR Shoemaker indicated that Eros is neither. Data suggests that Eros is a cracked but solid rock, possibly a fractured chip off a larger body, made of some of the most primitive materials in the solar system. The regolith on Eros is nearly 91 meters deep in places. Data indicate that the regolith has moved downhill, smoothing over rough areas and spilling into craters. The cratering on Eros has surprised many scientists, with intriguing square-shaped ones and many fewer small craters than expected. More than 100,000 craters wider than 50 feet (15 meters) have been counted. Also, the large number of boulders was unexpected, with about one million house-sized or larger boulders. The last images returned showed clusters of boulders, a mysterious area where the surface appears to have collapsed, and extremely flat, sharply delineated areas in the bottoms of some craters, indicating the story of Eros’s composition is still incomplete

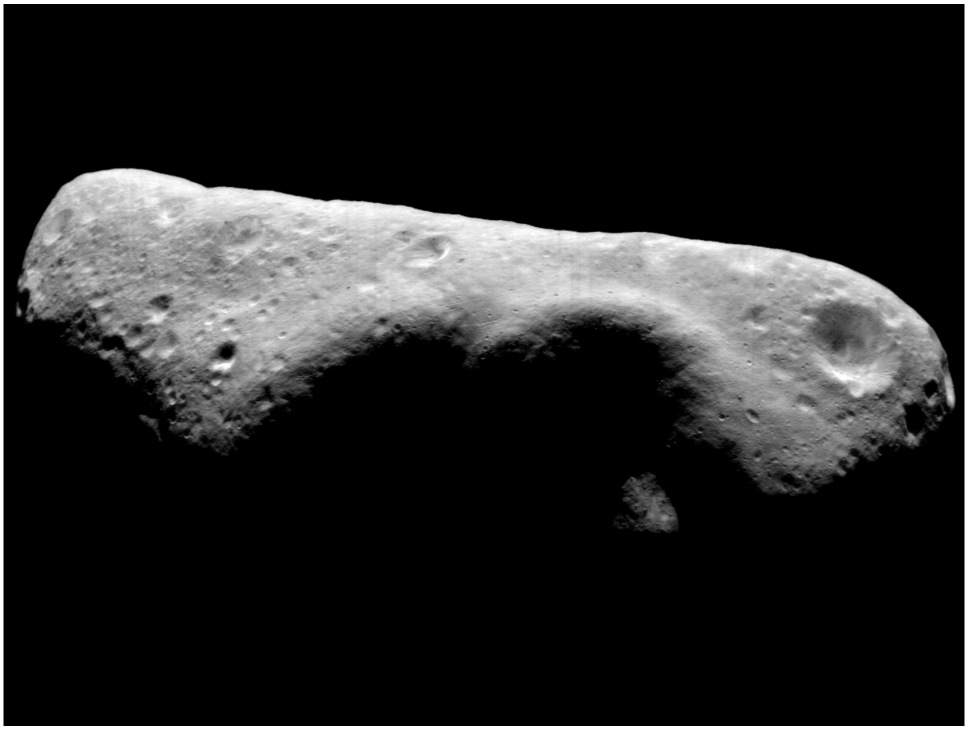


Figure 3-7: The asteroid Eros (Credit: NEAR Project, JHU APL, NASA)

Figure 3-8: Closeup of asteroid Eros (Credit: NEAR Project, JHU APL, NASA)

In addition to these missions, the European Space Agency (ESA) conducted a spectacularly successful, unprecedented flyby of the comet Halley (see Figure 3-9) with the spacecraft Giotto in 1986, and is directing the current Rosetta mission, which is due to orbit and land a probe on the comet 67P/Churyumov-Gerasimenko in 2014 for long term observations. Comet Halley was also visited by the Soviet Union by the spacecraft Vega 1 and 2, by Japan with the spacecraft Sakigake and Susei, and by the United States with the spacecraft ISEE/ICE. The conclusion from at least the Hayabusa and NEAR missions is that mankind does possess the tools at this time to mount missions to orbit NEAs, land spacecraft on their surfaces, and perform limited in-situ characterization. Future missions could well have augmented sensors including seismographic instruments to analyze and map their internal structure.

Figure 3-9: Comet Halley imaged by the ESA Giotto mission during flyby (Copyright: ESA. Courtesy of MPAe, Lindau)

Detection of Long-Period Comets

Long-period comets (LPCs) tend to be ignored in NEO studies at this time because the probability of an impact by a long-period comet is believed to be very much smaller than by an asteroid. However, virtually all NEOs larger than a few kilometers are comets rather than asteroids, and such large NEOs are the most destructive, and potentially the “civilization killers”. Additionally, the Earth regularly passes through the debris field of short-period comets giving us the annual meteoroid showers such as the Leonids and Taurids. These are very predictable but thankfully benign impact events. If the Earth were to encounter sizable objects within the debris field of a long-period comet, we would likely have very little warning time and would potentially be confronted with many impactors over a brief period of time. Although this type of event is currently speculative, this is a conceivable scenario which humanity could face. While the risk of a cometary impact is believed to be small, the destruction potential from a single large, high velocity LPC is much greater than from a NEA. Therefore, it is important to address their detection and potential methods for deflecting, disrupting, or mitigating the effects before one impacts the Earth.

Because of their high velocities (mean impact velocities of approximately 55 km/s)[1] and lack of a coma far from the Sun, as well as their generally low albedo, detection of long-period comets with ground-based telescopes is generally limited to distances of several AU, with resulting warning times of only a few months or at most half a year or so, which makes deflection or disruption extremely difficult compared to asteroids, for which decades of warning could be expected. Thus long-period comets are generally placed into the "too hard" category which, coupled with their much lower probability of occurrence, usually prevents their consideration as "serious" candidates for defensive actions among many scientists. This condition could change, however, if much greater warning time were obtainable for long-period comets. New technologies for space-based telescopes could make that a reality.

Ground-based telescopes cannot observe during local daytime or when there are clouds, and their sensitivity is seriously affected by moonlight and atmospheric effects. One or more dedicated robotic observatory telescopes of greater capability than the upcoming NEOSSat instrument could readily be placed into Earth orbit or in solar orbit near the Earth or at a Earth-Sun (E-S) Lagrangian point. Such telescopes would be able to observe nearly continuously, and their angular coverage would be almost spherical except for angles near the Sun. At the L2 point the telescope would also be continuously shielded from interference by sunlight. There would be no cloud or day-night effects either, and therefore a telescope in orbit could have 10-18 times the observing time on NEOs compared to any one ground observatory, and could be dedicated to NEO observation rather than be shared with other astronomical observations, as is typical with large ground telescope facilities.

The sensitivity obtained from a space-based observatory like this could be sufficient even with an aperture diameter of approximately one meter, which is easily achievable with today's technology. Future technology will support space telescopes whose primary mirrors consist of thin membranes, and thus will be orders of magnitude lighter and cheaper than space telescopes such as the Hubble or James Webb. Feasibility studies[2] have indicated that with 5-10 years of technology development such membrane mirror space telescopes could be developed to have apertures of at least 25 meters yet weigh under 700 kg. One such telescope placed into a solar orbit near Earth would extend the detection distance and sensitivity enormously so that a 1 km long-period new apparition comet could be detected well beyond 10 AU. Detection this far away could yield on the order of 5-6 years of warning time,[3] provided that the comet's orbital path could be calculated with sufficient accuracy. Since such instruments would rapidly detect asteroids and short period comets as well, those as small as 70 meters could be detected at 2.5 AU, and 140 m asteroids could be detected at 5 AU. These detection distances are far greater than can be rapidly accomplished with ground-based telescopes. Thus, large yet lightweight space-based telescopes would be extremely valuable as a principal means of detecting, tracking, and providing up to several years warning time on long-period comets, in the not too distant future.

3. Impact Prediction and Warning Time

Comparison of Impact Threats

Threatening near-Earth objects (NEOs) are typically divided among three classifications based on their orbital characteristics and telescopic appearances: near-Earth asteroids (NEAs), short-period comets (SPCs), and long-period comets (LPCs). Many publications also use the terms Earth-crossing asteroids (ECAs) and Earth-crossing comets (ECCs) to describe objects whose orbits can intersect the Earth. Although the primordial population of NEAs has long been cleaned out from the solar system by collisions and gravitational ejections, it is important to recognize that the population of NEOs is constantly being replenished through a variety of mechanisms.

There are believed to be two main sources of NEAs. The first is the main asteroid belt, which is believed to replenish the NEAs through collisions and chaotic orbital dynamics. The second source of asteroids is believed to be extinct comet nuclei. Short-period comets are thought to originate from the Kuiper belt, a vast population of small bodies orbiting the Sun beyond Neptune and extending 30 to 1,000 AU from the Sun. The Kuiper belt is estimated to contain 10^8 to 10^9 cometary bodies, with between 35,000 to 70,000 objects larger than 100 km residing in the region between 30 and 50 AU[4]. SPCs may also originate as LPCs with planetary interactions (primarily with Jupiter) perturbing them into short-period orbits. LPCs are believed to originate from the vast reservoir of comets known as the Oort cloud[5]. There is no direct evidence of the Oort cloud because no comet has ever been observed at this great distance. Although the number and mass estimates are not precisely known, the cloud may contain 10^{12} to 10^{13} comets with a total mass of approximately 30 Earth masses. It is believed that the inner Oort cloud begins approximately 1,000 AU from the Sun and may extend out to 100,000 AU (almost halfway to the Sun's nearest stellar neighbor). Although comets and asteroids have become the typical classifications applied to NEOs, there are asteroids that exhibit some amount of comet-like behavior, and some extinct comet nuclei may be classified currently as asteroids.

The size and structural integrity of the NEO are important when considering whether or not is should be considered an impact threat. Objects between 50 and 100 m in diameter are capable of penetrating the Earth's atmosphere. Precise orbit knowledge is the paramount factor for identifying a near-Earth object as an impactor. More rapidly determining an impacting object's orbit allows more warning time and opportunity to divert the object or mitigate against impact effects. Assuming that the NEO is of sufficient size and composition to pose a hazard, the following three categories generally define the impact threat from a warning time standpoint using the above classifications:

1. **Well-defined Orbits:** ***Warning time = Decades***
    Detected Earth-Crossing Asteroids

2. **Uncertain Orbits:** ***Warning time = Years***
    Newly discovered Earth-Crossing Asteroids and Short-Period Comets
    Long-Period Comets (detection likely requires large aperture space-based telescopes)

3. **Immediate Threat or No Warning:** ***Warning time = Months to none***
    Small Earth-Crossing Asteroids
    Long-Period Comets (if no large aperture space-based telescopes exist)
    Previously undiscovered Earth-Crossing Asteroids

Impact Probability Assessment and Warning Time

In order to provide sufficient warning time to avert an impact, or at the very least mitigate the effects of the impact, precise orbit determination calculations must be made. For the vast majority of NEOs whose initial orbit calculations indicate a high impact probability, the probability will reduce to zero as additional observations are included. In the unlikely event that a high probability of an Earth impact is confirmed, the next step would be to define the likely location of impact, along with an estimate of the object's size and physical properties, to determine the likely consequences. The accuracy of an impact prediction is a function of both the observational data and the computational methods. Classical methods of orbit determination have been largely replaced with statistical techniques due to the ever increasing processing capabilities of modern computers.

The JPL Sentry System and NEODyS are independent systems which utilize different software and theoretical approaches to provide impact risk assessments. The two systems employ different approaches for computing impact probability, but have demonstrated excellent agreement particularly for the higher probability potential impacts. Additionally, the two systems use different sampling strategies and one system may identify low probability events not detected by the other. Both sites make use of the Palermo Scale to quantify in more detail the level of concern warranted for a future potential impact possibility. The Palermo Scale compares the likelihood of the detected potential impact with the average risk posed by objects of the same size or larger over the years until the date of the potential impact. The Palermo Scale was developed to enable NEO specialists to categorize and prioritize potential impact risks spanning a wide range of impact dates, energies and probabilities[6]. Computing Earth impact probabilities for NEOs is a complex process and requires sophisticated mathematical techniques. The following description provides a brief overview of the Sentry risk analysis process as an example of the technique. A more detailed explanation of the techniques utilized can be found on the JPL Sentry website[7]

The Sentry risk analysis uses sophisticated non-linear methods, which are required when the uncertainties associated with close approach predictions are large. The uncertainty in the position of a NEO increases as the object's position is predicted into the future. The term virtual asteroids (VAs) is used to describe the set of slightly different orbits that all fit the astrometric observations to within their expected accuracies. The number of VAs estimated can number in the thousands or tens of thousands. The nominal (or central) orbit is most likely to be the actual orbit, and the farther that a VA is from the nominal position within this "swarm" of VAs the less likely it is to be the real orbit. This swarm of virtual asteroids is propagated forward in time using numerical integration techniques and the uncertainty ellipsoid surrounding the asteroid's nominal position evolves into a very elongated tube (see Figure 3-10). In order to increase the computational efficiency only the VAs along this central axis, known as the Line of Variations (LOV), are integrated forward in time and are assumed to be representative of the off-axis parts of the uncertainty region. The first step in the risk analysis is to detect close approaches with Earth for each of the VAs that are numerically integrated. Linear techniques and Monte Carlo approaches are utilized to determine if an impact is possible for a particularly VA.

The number of VAs that collide with Earth is divided by the total number of VAs integrated forward to compute an impact probability for a particular year. The construct of a target plane is utilized to analyze the specifics of a close approach with the Earth. The target plane is defined as a plane that passes through the Earth's center and is oriented perpendicular to the NEO's velocity vector. The projection of this elongated tube onto the target plane will reduce the uncertainty region to a thin elliptical strip centered on the LOV and passing a particular distance from the Earth's center. If the distance is less than 1 Earth radius (including an allowance for atmospheric effects) the VA becomes a Virtual Impactor (VI) since it can strike the Earth. The sigma LOV depicted in Figure 3-10 measures how well the VI fits the observational data. It is equal to zero for the nominal orbit while ±3-sigma values comprise approximately 99% of the VAs and are less likely to collide with Earth. "Sigma Impact" is calculated from the relationship (Distance - R_{Earth})/width, where the width is a measurement of the intersection of the uncertainty region with the target plane. Sigma Impact is zero when the LOV intersects the Earth and increases as the central axis of the uncertainty region moves away from the Earth in the target or impact plane. When the probability of impact reaches a sufficiently high value the warning time is calculated based on the time of the impact minus the current time when the NEO was determined to be an impact hazard.

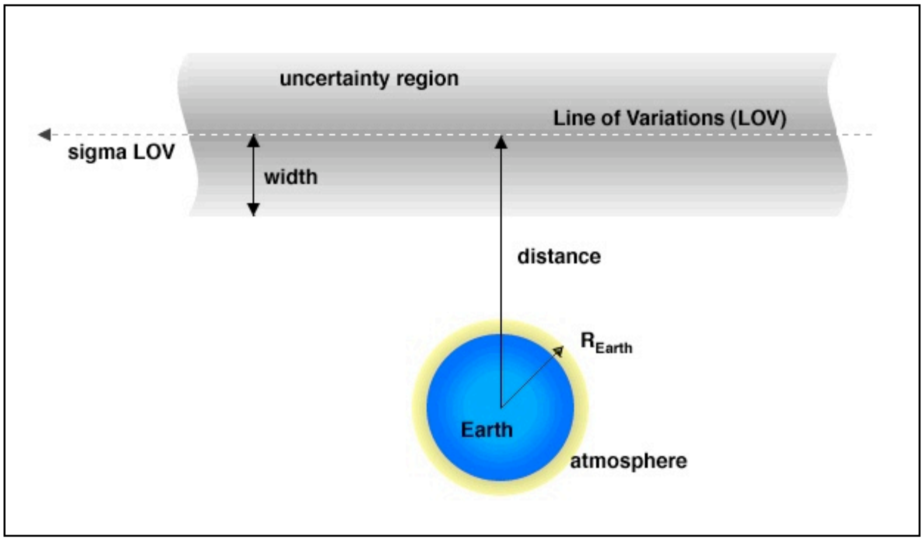


Figure 3-10: Illustration of parameters defined for NEO impact probability analysis (Courtesy NASA/JPL-Caltech)

It is important to note that when first detected with a sufficiently large number of observations to determine an orbit the collision probability with Earth of a NEO may be high. But this does not necessarily represent the real situation, and as further observations come in and the orbit is refined the collision probability has tended to greatly reduce in past situations. Since it is likely that initial dire predictions may well be reduced in time, great caution should be exercised in making predictions so as not to create undue public panic and potentially avoid having future announcements ignored (the "cry wolf" syndrome).

Relatively recently, NEO researchers have explored the complex orbital dynamics of NEO close encounters with Earth. Although an asteroid might miss the Earth on a close approach, the object may pass through one of several small regions in space (which could be as small as on the order of only 0.5 km) called resonance "keyholes" which causes the Earth's gravity to change its solar orbit period so that it is a multiple or sub-multiple of Earth's, and thus strike the Earth on one of perhaps many subsequent encounters. The size of these keyholes will only be a small fraction of the target plane error ellipse, and correspond to different resonances when the object returns to the same region in space where the first encounter occurred, causing a second encounter to take place. There can be several keyholes corresponding to different resonances which results in possible impacts on different dates in the future. In order to prevent an impact during a subsequent encounter the trajectory of the NEO must be modified only enough to miss the keyhole and thus avert a collision in the next resonance encounter (although it may not be a permanent solution since there could be many resonant encounters, though it certainly would gain years of additional time for defensive efforts).

Post Deflection/Disruption Effort Measurements

Various measurements will need to be repeated once the deflection or disruption mission has been completed to assess the effectiveness of the technique. It is going to be vital, particularly depending on the warning time permissible with a particular threat, that the instruments and resources are rapidly available to reassess the threat and recalculate the impact probability of the object (or potentially multiple objects if the original NEO becomes fragmented during the mission). The presence of local assets such as a measurement spacecraft orbiting or hovering near the NEO would permit accurate velocity change measurements. In addition, a radio transponder could be placed on the object. All of these techniques might be required to reassess the object orbit in a timely manner and recalculate its new orbit. Additionally, depending on the deflection/disruption method that was employed it might be highly desirable to send additional instruments to the NEO. This will be vital even if the object was successfully diverted to facilitate the refinement of engineering models and to characterize how successful the mitigation was, in order to be applied to the inevitable future NEO encounter.

Chapter 4:
PREVENTING OR MITIGATING AN IMPACT

The previous chapters defined, discussed, and refined the nature and scope of the impact problem and the vital capabilities needed to provide detection, tracking, and characterization of potentially hazardous objects (PHOs), which is a subset of NEOs and includes asteroids and comets whose orbit could bring them within 0.05 astronomical unit from the orbit of Earth

This chapter will build upon the prerequisites implied earlier and address various solutions for deflecting the orbit of the NEOs on a collision course so as to cause them to miss the Earth entirely. For, in contrast to the dinosaurs[1], we now have most of the technology that could, in many cases, be used to prevent an impact-caused catastrophe[2]. Given the detection of a NEO a number of years or decades before impact we should be able to modify a planetary scientific spacecraft in its design or development phase, or develop new dedicated space systems, either of which could be launched to rendezvous with or impact many NEOs in time to modify their orbit sufficiently to cause them to miss the Earth[3]. Nonetheless, given the immaturity of some of the technology and the uncertainties in mounting missions which have not yet been demonstrated, significant questions arise including: could the deflection attempt malfunction and move its impact point to perhaps create more damage than if the NEO were left alone? Could it fragment the NEO rather than deflect it and would that make several damaging impactors out of one? Could the hardware to attempt one or more deflection mitigation attempts be readied in time? Is a campaign of a number of attempts at deflection using different technologies preferable or necessary? Could the necessary budgetary, political, decision-making, and command and control mechanisms be mustered nationally or internationally to actually engage a NEO?

Recently, a comet rendezvous and intercept were successfully demonstrated. The collision imparted a velocity change of only 0.0001 m/sec to the comet, which, while being about two orders of magnitude smaller than probably necessary for deflection of a NEO, demonstrated that with proper scaling up the technology to mitigate many PHOs is either here, or is not unreasonable to assemble in a few years if we decided to do so. This chapter will address the means of mitigation in more detail.

1. Physics of Interaction

Potentially hazardous objects can be either asteroids or comets. While this chapter will address principally deflecting or fragmenting asteroids, the physics of deflecting or fragmenting comets is similar though the times, distances, and difficulty in predicting their trajectory far enough in advance to enable a practical mitigation mission are significantly greater.

Potentially hazardous asteroids (PHAs) orbit the Sun roughly in the same plane as the planets. Their orbits range from nearly circular to highly elliptical and their orbital velocities range upward to many tens of kilometers per second. There are fundamentally two options for mitigating NEOs: changing their orbit so as to cause them to miss the Earth, or fragmenting them so most of the damaging fragments miss the Earth or are small enough so as to do little damage. For objects for which there is sufficient warning time the former is far preferable since the fragmentation process may not be adequately predictable.

Changing the orbit of a NEO may be accomplished basically by two techniques. The first is a "fast" or kinetic change in which the interceptor collides with the NEO and the resulting momentum transfer changes the NEO's velocity; or explodes a warhead within it, or on or above its surface so that the impinging effects of the explosion cause the velocity change[4]. The second technique is a "slow" change in which the interceptor rendezvous with the NEO and applies force to it over a substantially long time, whose integrated effects cause the velocity change. Each of these options has its advantages and disadvantages, which will be discussed in the following sections. Both are capable of imparting the extremely large energy and/or momentum that is required to cause the desired orbit change to occur[5].

As discussed in the previous chapters no two NEO's are identical and will have different shapes, sizes, rotational or tumbling rates, and may consist of rocks, metals, ices, or some combination. The objects may be solid of various degrees of density, or may be a loosely aggregated pile of rocks. Thus the design of the preferred mitigation technique may well be very different depending on the characteristics of the specific NEO in order to accomplish the deflection and avoid fragmentation. This chapter will assume that the NEO to be mitigated has not only been detected and its orbit ascertained but that the object has also been adequately characterized in order to allow confident mounting of a mitigation mission.

The fundamentals of orbit mechanics dictate that the orbit of an object may be modified with the least expenditure of energy if its velocity along its orbital path is changed, as opposed to trying to change its velocity at an angle to its velocity vector. The detection systems discussed in the previous chapter indicate that many NEOs may be detected years or even decades ahead of predicted impact. If that much time is available, we can take advantage of the fact that a very small change in the NEO's orbital velocity will propagate with time to become a very large positional difference at the time it intersects the Earth's orbit. If applied later the velocity change imparted must be proportionally larger. Thus, whether the velocity change is applied in one short event or gently over months, and whether applied a long or shorter time before impact, the trajectory of a NEO can be modified so that it arrives sufficiently earlier or later to completely miss the Earth.

The velocity change that is required to accomplish this NEO miss is typically a very small fraction of its total velocity and typically in the order of centimeters per second; but the energies required are extremely large due to the enormous mass of even modestly-sized NEOs. While the deflection required to miss the Earth completely is at most one Earth's radius plus a few hundred kilometers to avoid an atmospheric shock, it is likely that substantially larger miss distances will be required in practice due to technical uncertainties and a desire for large margins to ensure a confident outcome.

The previous chapters also discussed an interesting but crucial aspect of celestial mechanics in which many NEOs could well be in orbits that may miss the Earth yet pass through one of a number of very small regions of space known as "keyholes" at specific but relatively near distances from the Earth, such that their orbit is altered just enough by the Earth's gravitational field that they enter a resonant orbit--one characterized by repeating encounters and thus potential collision threats to Earth. Hence, in this scenario, the Earth could be threatened by the same NEO periodically over many years or decades. For this special case, a NEO which is predicted to miss the Earth but pass through a keyhole for resonant return need be deflected only sufficiently that it misses the small keyhole so that, in many cases, it would not be a threat again. Since the dimensions of some keyholes are a small fraction of the size of the Earth the requirement to deflect it just enough to miss the keyhole involves changing its velocity by proportionally smaller amounts that those needed to prevent an impact were the NEO headed for a collision with Earth, and can involve velocity changes as small as micrometers per second. This is illustrated in the graph of Figure 4-1.

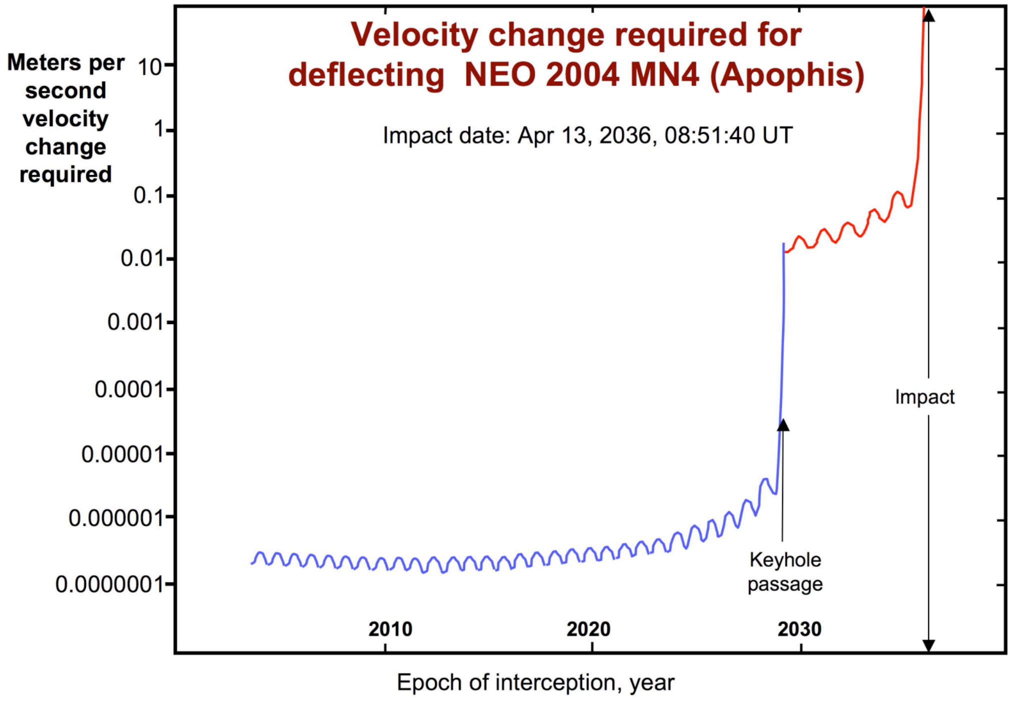


Figure 4-1: ΔV required as a function of time for Apophis (Credit: B612 foundation)

The accomplishing of the actual velocity change of the NEO is more complex than it would appear at first, particularly if the means is a kinetic impactor, because the composition, structure, and cohesive strength of asteroids varies considerably. It is quite possible that the force or energy applied to the NEO will fragment it as well as result in ejecta, particularly for NEOs which are characterized as loose rubble piles. If the energy of the impact is relatively low the diameter of the expanding fragmentation cloud could be of the same order of magnitude as the diameter of the Earth at the time of impact, and a single large impact would have been replaced by very many smaller impacts, possibly leading to a Hobson's choice. If it is assumed that some fragments would be relatively large their impact might cause worse damage on the Earth than one very large impact.

However Keith Holsapple[6] has shown that rather than the above, kinetic impacts at hypervelocity would likely create very large numbers of very small fragments possessing large transverse velocities. Accordingly the mass per unit area normal to the NEO's trajectory would be very much reduced at the time of Earth impact, and the consequences of multiple impacts, each being much less massive than the original body, could then be very much more benign locally as well as globally. For example, if most fragments are smaller than 50 meters they will burn up in the atmosphere and not reach the Earth's surface, with the net effect being a spectacular light show with little or no damage. Furthermore, even if a few remaining fragments of a 1 km diameter NEO have a diameter in the order of 100 meters, the global effects of their impact would certainly be less severe than the original impact of the whole body since their mass and energy are proportional to the cube of their diameter. Therefore, whether fragmentation is to be avoided at all costs or whether it can be used to advantage in the defense strategy is still very much an open issue. What is certain is that we must characterize the NEOs well so that we can optimize the mission and better predict the consequences of a mitigation attempt[7].

All intervention planning must take into account orbit prediction uncertainties, mitigation system delivery uncertainties, as well as additional adequate safety factors. In addition, since the lives of millions and vast property damage may be at stake no single mitigation system will have sufficient reliability given the state of the technology. Thus multiple missions in a coordinated and carefully planned campaign must be mounted to mitigate even a small NEO because the consequences of failure or even partial success will be horrendous and unconscionable.

2. Potential Mitigation Options

Recent investigations into NEO intervention by many researchers has resulted in the identification of a number of different feasible approaches. These can be divided roughly into a first class for which there is ample early warning of an impact and for which the objects' orbits have been well determined and their composition has been well characterized; and into a second class of objects that have been detected relatively much later before predicted impact or whose orbits and characteristics have not been well determined until much later. These two classes will be addressed separately. It should be noted at the outset, however, that given the state of the art or near term projected technologies a successful mitigation may be very much more difficult if a NEO is large enough, regardless of whether it is discovered with lots of warning time. Fortunately the number of NEOs decrease exponentially as their size increases and so does the probability of an impact threat materializing in any given time interval; the warning time also generally increases with their size because they are easier to detect when far away, and technology advancement should allow continued capability increase with time over the long term. Interestingly, mitigation missions could be designed so that the resultant orbits of the target NEOs would be convenient for mining or other uses after the threat is removed [8].

2.1. Long warning time is available

In this case the detection and characterization systems and process are assumed to be capable of providing many years to several decades of advance warning that a PHO is in a collision orbit and what its characteristics are, with reasonably high confidence. This certainly applies to asteroids and short period comets, whose orbits are essentially continuously observable with some ground based telescopes and partially so with ground based radar. It may eventually also apply to potentially hazardous long-period comets (PHCs) if dedicated high sensitivity space-based telescopes are developed and deployed, which initial studies have shown to be feasible and relatively low cost[9],[10]. However, even if such sensors were available the warning time would probably be limited to several years rather than decades, particularly for new apparition comets, because the outgassing of comets as they approach past the orbit of Jupiter result in orbit perturbations which cause significant uncertainties in orbit prediction. Nevertheless, most mitigation techniques that will work for asteroids will also, in general, work for comets. This includes techniques for intercepting the NEOs in their keyhole passage, should there be one, which, except for the requirements placed on the tracking and orbit determination aspects, should be as easy for comets as for asteroids. This technique will be discussed in more detail later. Unfortunately, relatively little work has been done in the detection of long-period comets when very far away, even though more is known about their composition from the space probes launched to date than about asteroids. As a result of the above considerations, except for the specifics of the launch systems, delivery spacecraft, and the composition of the NEOs the mitigation concepts that follow apply in general to deflection of both asteroids and comets unless specifically addressed. Therefore all NEO threats will be treated as though they were asteroids in the following sections.

2.1.1. Kinetic Impact

Kinetic impact is a practical and relatively simple technique of NEO orbit modification, and the technologies are the same as those that have already been demonstrated in planetary and cometary probes. The principle is the transfer of momentum to a NEO by simply ramming a spacecraft into it at high relative velocity. Ideally the impact should occur in the track of the NEO along its velocity vector in order to accomplish the greatest possible momentum transfer with the smallest possible impact mass, in the direction most desirable. While the impact would be as effective in a direction opposite to its velocity as along it, the launch energy to reach it at a given impact velocity is lower for the former as most NEOs revolve around the Sun in the same direction as does the Earth. The impact would transfer momentum to the NEO and cause a velocity change which, propagated in time, would cause the NEO to arrive later or sooner at the point of crossing the Earth's orbit. If the pre-impact NEO trajectory was predicted to pass through the center of the Earth then a positional change of more than the radius of the Earth plus a factor for orbital uncertainly and a safety margin would be enough to cause a complete miss.

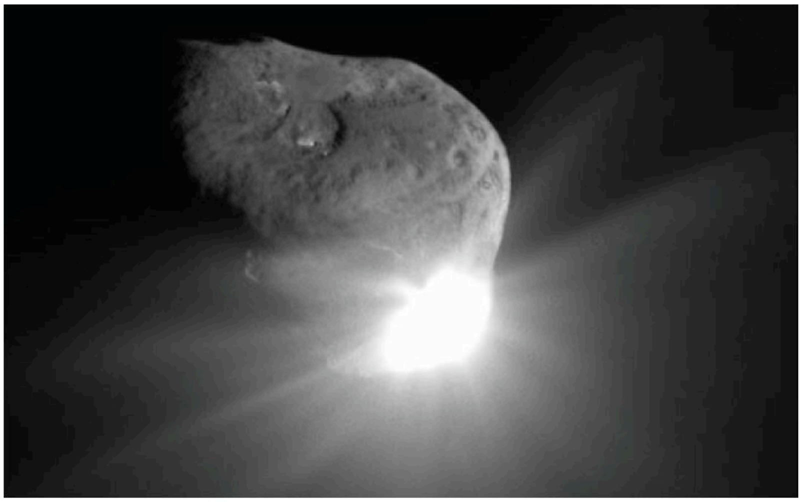


Figure 4-2: Deep impact spacecraft kinetic collision on comet Tempel-1 (Credit: NASA)

The risk of undertaking such a mission is low because a kinetic deflection technique has already been demonstrated in space. NASA's Deep Impact mission successfully demonstrated the technologies for an intercept of the Tempel 1 comet, impacting at about 10 km/sec with a kinetic energy release equivalent to about 19 gigajoules, and an image of the impact is shown in Figure 4-2. Since the comet's perihelion and aphelion lie between the orbits of Mars and Jupiter, this demonstration may have actually been more difficult than would be a typical NEO intercept. While the calculated positional change of the comet due to non-elastic momentum transfer was only about ten kilometers in three years, the actual velocity change attained may prove to eventually be somewhat higher due to significant thermal ablation that resulted from the heat of impact. In addition there is great uncertainty in the effect of impact fragments which are sure to be ejected as a result of a high velocity collision. Calculations indicate that these fragments could significantly multiply the momentum transfer delivered by a given mass above the results predicted from a simple inelastic impact by very large factors, depending on the composition of the NEO. This indicates that the composition of the NEO should be known so that the effects of a kinetic impact can be reliably calculated. In addition the previously discussed issue of whether the body of the NEO or PHO will fragment or be deflected whole remains open since a loosely aggregated body such as a "rubble pile" will respond differently than a monolithic one.

The mission is relatively simple and not unlike planetary and cometary probes that have been launched by a number of agencies in the past, requiring only a launch vehicle with sufficient energy to place the interceptor in a collision trajectory with the NEO and a stage that can perform trajectory corrections along the way. While conceptually daunting the requisite accuracy of the guidance accuracy capability has been amply demonstrated in the planetary probes, as well as in a number of anti-satellite and anti-ballistic missile interception tests carried out to date by several entities. Thus it is reasonable to say that the technology to perform kinetic impact mitigation exists today, even if dedicated systems to perform such missions do not. In an emergency it is also reasonable to expect that if a scientific planetary probe were essentially ready at the time of need it could probably be modified to perform a kinetic impact mission on a NEO instead.

A special case of kinetic "interception in a keyhole" exists which requires far less energy than interception far from Earth because the keyholes are by definition fairly close to Earth. One such concept was described by Ivan Bekey[11] in which a dead GEO satellite is used as the interception mass for the NEO Apophis, placed into the keyhole (which is near the altitude of the Earth's geostationary orbit) at the time the NEO is predicted to arrive there, and just lets the NEO run into it. The kinetic deflection or fragmentation would ensure that no large piece would survive for potential impacts in other resonant returns, and the interception mass does not have to be launched to GEO as the dead satellite is already there and "free".

The bottom line is that the kinetic impact concept is a viable mitigation approach that requires only current technologies, and has been demonstrated amply in a number of space intercepts as well as at least one comet intercept and impact, even though further work is required to characterize the NEO threats for confident design of a kinetic deflection mission. In fact, it is one of only a handful of concepts that could be initiated relatively quickly with reasonable expectation of success.

A major variant of the kinetic impact concept uses nuclear explosions to effect the deflection rather than the mass of the space vehicle, but is delivered by very much the same launch vehicle and spacecraft as the non-nuclear kinetic impactor. Nuclear concepts clearly have their advantages and disadvantages, and will be discussed in Section 2.2: Little warning time is available.

2.1.2. Tug Boat

A generically different concept is to impart a "slow push" to the NEO, slowly and gently enough to avoid severe stresses but for a long enough time to cause the desired velocity change, rather than imparting a sudden shock to it which could result in ejecta with uncertain effects and possibly causing it to completely fragment. The Tug Boat approach[12] envisions rendezvous and docking with the NEO with a propulsion-equipped spacecraft, attaching to its surface, and pushing it gently along its velocity vector. Implied in this concept are the requirements that sufficient warning time must exist for the longer and more energetic rendezvous trajectories required to make such long term operations possible; and that a hard dock sufficiently stable to transfer forces from the tug to the NEO be achieved. Furthermore, the propulsion system must operate for months to years with high reliability, and if electric, at megawatt power levels[13]. This concept is illustrated in figure 4-3.

Figure 4-3: Tug Boat docked to a NEO

Launch vehicle energy and time of flight requirements for the tug boat mission are substantially greater than for a simple impact trajectory as in order to rendezvous it must match its orbital velocity to that of the NEO, and subsequently perform proximity and docking operations to land on the NEO and fasten itself to it. Non-zero tumbling and spin rates are typical for NEOs[14], and the Tug would have to match these rates in order to achieve a hard dock with the NEO. These rates also would require either thrust vector control or a time-controlled thrusting after dock so that thrust is only applied essentially along the desired inertial thrust vector coinciding with the NEO velocity vector.

The difficulty of attaching the Tug Boat to the NEO must not be minimized because of the great uncertainties of surface shape, structure, and composition that could be present. Attaching explosively driven pitons into the NEO and then securing the Tug Boat with tethers would seem a reasonable option, but it has never been done and needs demonstration for confidence. In addition it is crucially different and more difficult to dock and fasten the spacecraft if the NEO composition is looser or more porous than for a monolithic rock or mineral NEO, and even more so for a loosely aggregated rubble pile. Missions to perform the crucial step of attaching to a NEO could be manned or unmanned. Although manned missions are much more complex, expensive, and logistically intensive in order to maintain life support, implying even greater demands on systems, being able to react to the actual NEO composition and characteristics at the time of attaching together with the ability to improvise at the target may justify this investment. On the minus side, however, in addition to their complexity and cost, manned missions also impose shortened dwell times at the NEO, and may thus require an increase of the thrust level to create the desired velocity change. That would negate the utility of a manned tug boat.

2.1.3. Mother ship with tug boat

This option is similar to the preceding Tug Boat concept except that it overcomes some of its problems by virtue of using a separate, dedicated, robotic propulsion system which would detach from a mother ship and dock with the NEO. This would permit the mother ship to remain relatively near the NEO or orbit around it, and thus to independently measure the actual velocity change that is imparted to the NEO as it occurs, thus allowing a real-time control of the propulsive action which is not possible with the simpler Tug Boat. Not only could the actual velocity being imparted be accurately controlled but if the tug boat failed to function as expected that fact would be detected in real time, as opposed to only after perhaps months of observation from the Earth. This would allow time to perform adjustments or equipment exchanges by the mother ship; the tug boat could be re-docked; or at the worst case a new mission launched.

In fact the ability to observe the action of a velocity-imparting space system with a separate near-by spacecraft in near real time is central to being able to accurately control the effect and the success of essentially all known mitigation concepts. Such a capability, which is planned to be demonstrated by the dual spacecraft Don Quixote mission being defined by ESA, will be crucial to virtually all the “slow push” concepts discussed.

While the dual spacecraft tug boat technique has the above discussed advantages it shares a serious negative aspect in common with all “slow push” concepts, which will be discussed in detail under the Gravitational Tractor in the next section.

2.1.4. Gravitational Tractor

An important variant of the Tug Boat allows avoidance of docking with the NEO and simply hovers the spacecraft near it by constant thrusting to maintain an essentially constant altitude above it. The NEO’s gravity attracts the spacecraft but the spacecraft simultaneously attracts the NEO with the same force, resulting in a force being applied to the NEO without contact with its surface. This force will effect a velocity change in the NEO identical to that were it to be docked to its surface. This is an elegant “Slow Pull” technique that allows imparting of a velocity change to the NEO regardless of its composition, rotation, tumble, of surface geometry, and is known as the “gravitational tractor”[15]. The hover point can be chosen so that it lies along the NEO’s in-track velocity vector for maximum effect, and its altitude above the NEO modulated or chosen so as to minimize the force variation as the NEO rotates. This concept is illustrated in Figure 4-4.

In addition to the above major advantages of this gravitational tractor are avoidance of docking and surface attach operations, and that it would in all probability avoid disruption of the NEO and potential fragmentation for all but the most loosely-bound rubble piles. However a negative factor associated with the gravity tractor is that, in contrast with the Tug Boat, the force transferred to the NEO is determined only by the mass of the spacecraft whereas the force imparted by a Tug Boat, with or without a mother ship, is determined by the thrust of the propulsion system which can be made much greater than the force caused by gravity alone due to a similarly-sized spacecraft. Therefore it would seem that the velocity imparted by a Tug Boat per unit time might be greater. This is misleading, however, because for a given specific impulse of both propulsion systems and for the same mass of the spacecraft, the total impulse imparted to the NEO, and therefore its velocity change, is the same for both techniques.


Figure 4-4: Gravity Tractor (Credit: Ed Lu, B612 foundation)

The gravity tractor shares a feature common to all “slow push” and “slow pull” approaches. Since its action is inherently slow and long, the instantaneous impact point of the NEO is slowly moved on the surface of the Earth until it eventually misses the Earth and its atmosphere entirely. The positive aspect of this, as mentioned before, is that the progress in velocity modification can be continually measured by co-orbiting instruments or from a transponder attached to the docked or hovering spacecraft so that the termination of thrust can be precisely controlled. The greatest negative aspect is that if there is an unrecoverable failure of the propulsive spacecraft before its job is done the impact point will not have been moved far enough to cause the NEO to miss the Earth entirely, and could well then lie anywhere on the locus of possible impact points. It could then lie on a major city for example, whereas it might have been on a desert initially. In other words the actual NEO impact point will have been changed from the initial one, and its location would have been determined by an unpredictable equipment failure.

While such a failure could result in less severe impact consequences than the originally forecast impact it could also result in more severe consequences if, for example, the nation attempting the deflection accidentally causes the destruction of a major population center in another nation or the creation of a tsunami with much wider destruction. The political consequences could be horrific, even to the possible extreme of being labeled a deliberate act of war. Even if not carried so far, the initial impact point is “an act of God” for which no one is responsible. However the accidentally created new impact point is an “act of man” and, and lacking internationally recognized “Good Samaritan” laws there could be no end of lawsuits and strife from the loss of life and property from such an outcome.

It is true that the exact impact point resulting from a kinetically caused deflection attempt that did not turn out as expected and did not miss the Earth might have similar consequences as that from a failed “slow pull or slow push” technique, however kinetic impact missions would not require the reliable operation of complex spacecraft and propulsion systems for additional months or longer during which failures could occur. Thus, for this as well as other reasons, the choice of fast vs. slow mitigation techniques is complex and must be carefully considered.

2.1.5. Laser Ablation

Another option for applying a slow push to a NEO is to use a sufficiently intense laser projection system to illuminate it, causing surface ablation and plasma ejection, whose reaction forces would result in a velocity change. Deploying the system on the moon, in low Earth orbit, GEO, or the Earth-Sun libration points are basing options. Since all these are remote from the location of the NEO, and for physically realizable optical projector mirrors, the energy density arriving there will necessarily be low and so what surface ablation occurs will cause very little heating at depth and hence could totally avoid fragmentation even of rubble pile NEOs. In fact there is some experimental evidence that this approach might serve to actually coax some such NEOs into a more structurally cohesive body[16].

A solar-pumped chemical or free electron laser could be used in this application, both powered by sunlight. Such lasers have been studied extensively for space-based missile defense but not developed or tested, and thus their technological maturity is still very low. However if sufficiently matured they could irradiate the NEO for months or years, as their energy source is unlimited and free, and some studies indicate that their attainable beam energy levels could be high enough to effect adequately large NEO deflections. Since these systems will be large and heavy the biggest obstacle to laser deflection systems, in addition to technological immaturity and system cost, is the cost involved in launching and deploying them, though if NASA develops the ARES family of launch vehicles they should be adequate to deliver such a laser system to a satisfactory space based location.

A much smaller space based laser could be delivered to the rough vicinity of the NEO by a conventional launch vehicle and spacecraft, and could impart a greater force on the NEO than the gravity tractor, yet enjoy the same advantages of not being affected by its surface shape or composition. It would also allow much greater standoff distances, and thus eliminate the challenges of hovering near a rotating and irregular NEO, but would entail a much greater technological challenge in the laser and optical beam generator. It would also likely be considerably heavier for the same effect due to the inefficiencies of at least current high power lasers.

A slow ablation variant similar to the laser ablation concept involves sending an accelerated beam of particles to the target, preferably neutral ones to avoid interaction with charged space plasmas. There are differences in using particle beams as opposed to laser beams in the degree of reaction caused by their incidence on the NEO. Their implementation and deployment would entail similar time and expense to that of lasers, and their technology is even more immature.

2.1.6. Solar Photon Pressure

Another "slow push" approach is to use the solar photon pressure to effect a velocity change in the NEO[17]. While there are several ways to do this, one technique would be to paint them with a highly absorptive coating to enhance the effect of the incident photon pressure. Since the photon pressure from the Sun is very small the resulting increased force on even a large NEO would be measured at most in a few Newtons, and thus an extremely long time would be required to effect a sufficient velocity change. In addition, since virtually all NEO rotate or tumble, the Yarkowsky effect results in the effective thrust probably being in a non-optimal direction due to thermal delay between absorption and reradiation of photons, and thus the effect of the thrust would be even smaller. The painting of the entire surface of even a small NEO has not even been seriously addressed. Attaching a steerable solar sail to the NEO would enhance the photon pressure, but the construction, deployment, and complexities in orienting the very large sail required would make the device complex and expensive, particularly on NEOs which are likely spinning and/or tumbling. Though the principle is understood the magnitude of the effective thrust is tiny and a very long time would be needed for sufficient deflection. Furthermore the uncertainties of prediction of the net thrust vector given tumbling bodies precludes this effect from being included in the higher confidence techniques.

One approach that offers more promise is to reflect sunlight onto the NEO with a large inflatable reflector in space, which is illustrated in Figure 4-5. In 10-20 years technology already demonstrated today might be scaled up to allow the deployment of 1 km reflectors in space, whose integrated effects on a NEO could be very large, and independent of the Yarkovsky effect. Thus the solar photo pressure approaches, though feasible in principle, are unlikely to be the most attractive in the near future though they certainly could be competitive with other slow push techniques in the long term future.

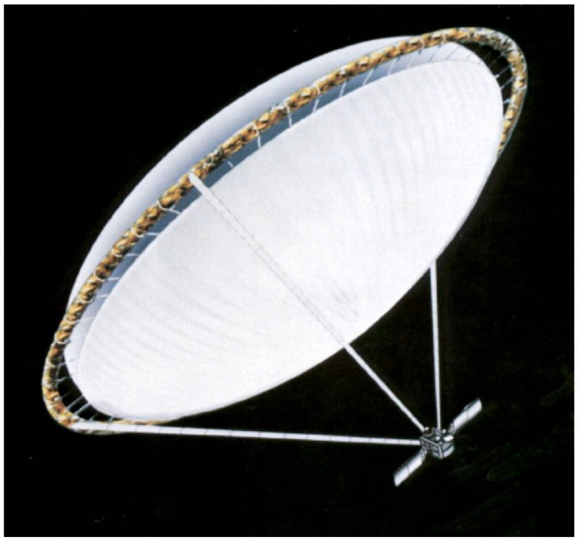


Figure 4-5: Inflatable large solar reflector (Marzwell, JPL)

2.1.7. Mass driver

This is another “Slow Push” concept which envisions imparting the requisite velocity change to a NEO by using one or more spacecraft docked to it, each of which ejects chunks of the NEO’s own mass to cause reaction forces, rather than propellants brought from Earth. The spacecraft would use either solar or nuclear reactor energy, and since supply of the reaction mass is essentially limitless the velocity change imparted is dependent principally on the operating time.

While visions of 1970s era kilometer-long mass driver concepts come to mind more recent concepts involve emplacing independent modestly sized vehicles on the NEO surface, anchoring them, drilling for the reaction mass, and ejecting tennis-ball sized chunks normal to the surface at velocities of a few hundred meters per second using small nuclear reactors as energy sources[18]. Such a concept is illustrated in Figure 4-6. The multiplicity of such mass drivers would allow them to “fire” on a rotating NEO only when pointed in the preferred direction, and would provide some redundancy for availability. Operating times of months to a year would be possible, and a large velocity change could be imparted to a NEO without the mass penalties of having to bring the reaction mass form Earth.

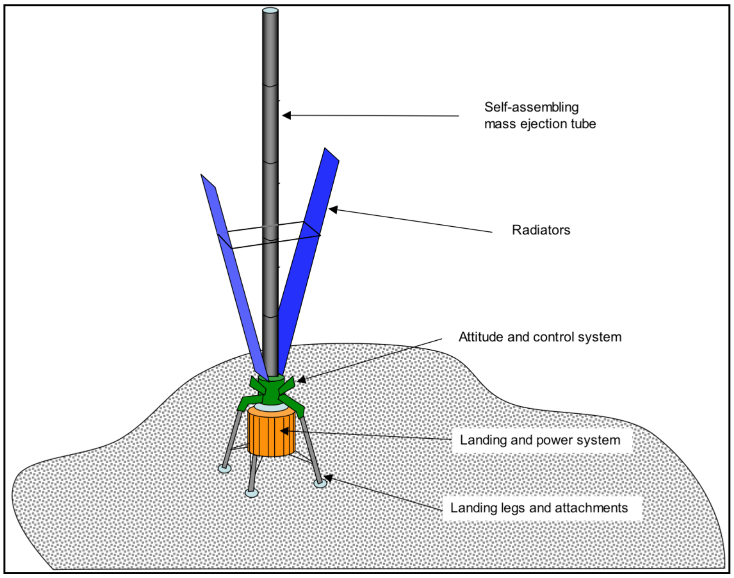


Figure 4-6: One of several mass drivers docked with the NEO (Courtesy John Olds)

These attractive features of such mass drivers are offset somewhat by the multiple challenges required, which are similar to Tug Boat concepts: docking and anchoring to the NEO being foremost. In addition the difficulties and unknowns of extensive drilling operations in an extraterrestrial almost zero gravity environment, development of safe and reliable nuclear reactor power sources, and development of a reliable mass ejector that must operate over extended times and be capable of self-cleaning and repair represents a long term challenge.

The advantages may well overcome many of the disadvantages, but the cost will certainly be much greater than, say, a simple kinetic impactor. Nonetheless the potential for generating a large total momentum change would make this concept a candidate for deflecting very large NEOs; and the use of a slow push technique which is unlikely to fragment it makes it a compelling candidate if lots of time is available for a deflection.

2.2. Little warning time is available

Suppose a dangerously large NEO is detected late by the surveillance system, or has been know to exist before but the contacts are insufficient to generate a confident orbit, and we now find ourselves with a high probability of collision in only a few months or at most a year or so. Can anything be done to mitigate an impact?

The answer is maybe or a qualified yes, depending on a number of crucial factors which include the availability and state of readiness of an appropriate launch vehicle, interception spacecraft, and deflection means including appropriate software; the existence of a protocol for national or international action including a command and control means; the size or mass of the NEO and its position in its orbit relative to the projected intersection of Earth’s orbit; the degree of characterization of the NEO's composition and internal as well as surface structure; and last but not least the estimate of resulting damage to life and property were the deflection attempt not to be undertaken (see ref. 4). The only confident statement that can be made in that situation is that "slow push or pull" techniques would not be able to move the impact point significantly in the remaining time, thus narrowing practical options to those that impart velocity change in very short time intervals. These are divided into those using non-nuclear and nuclear means.

2.2.1. Non-nuclear deflection techniques

A number of sufficiently massive kinetic interceptors launched sequentially from the Earth or possibly based in Earth orbit, on the moon or in the Lagrangian points, targeted to impact sequentially would be able to impart sufficient velocity change to a modest size NEO, even 6-12 months before impact, to cause the impact point to miss the Earth. For larger NEOs or substantially reduced time available the Earth impact point might not be able to be moved beyond the Earth but may be able to be moved to an area whose impact could perhaps be less destructive. The problem is that, in addition to the expense of developing, deploying, and maintaining such interceptors at the ready perhaps for many decades before use, a command and control system including control center that would have to emplaced, fully checked out, and constantly manned at the ready in order to make the response time short enough for the deflection attempts to have any chance of success. This undertaking alone would require many years and large budgets, and would most probably only be undertaken after international protocols and commitments covering funding, manning, and rules of engagement were in place. That process alone could easily require a decade or more. In addition these systems will be far more expensive to deploy and use than similar but smaller Earth-based kinetic systems that could take advantage of longer warning times were they available, but that is academic if such warning times do not materialize.

While this concept of multiple sequential kinetic intercepts has a finite probability of deflecting a small to modest sized NEO sufficiently even with only 6-12 months' warning, it loses effectiveness with the inverse cube as the size of the NEO increases, and will probably prove essentially ineffective for moderate-to-large NEOs. The stationing of multiple high energy lasers on extraterrestrial outposts is also possible and might offer similar deflection potential, but would suffer from similar expenses and difficulties as the multiple impactor concepts, in addition to being extremely expensive and even more sensitive to reductions in the available time. Perhaps as important is that due to the technology of launch vehicles at least 6 months, and more probably a year or more, will be required for an interceptor to travel from the Earth to the NEO in time to act, even assuming that zero time is required for decisions and launch readiness. For all the above reasons non-nuclear kinetic impact techniques, though theoretically capable of deflecting small NEOs with a warning time of a year or even less, are unlikely to become a realistic and practical solution to the problem of dealing with modest-to-large sized NEOs when less than about a decade warning time is available. This leaves only the nuclear option for mitigating such threats.

2.2.2. Nuclear Deflection techniques

This section will address the controversial subject of using the detonation of nuclear devices at or near a NEO to effect its deflection. The placement or detonation of nuclear devices in space is currently forbidden by signed international treaties and agreements. Nonetheless it must be recognized that nuclear devices represent a technologically mature means of deflecting NEOs that are either too large, or for which there is insufficient warning time, to practically and effectively employ any non-nuclear technique. This is because nuclear devices possess at least a million times the available energy density than can be delivered by any non-nuclear approach.

The international treaties regarding nuclear devices in space were formulated during the cold war and were intended to minimize the chance that they would be used by some nations against others--they were clearly not formulated with an extraterrestrial threat in mind. Thus it is not unreasonable to address the amendment of these treaties to allow the employment of nuclear devices to mitigate extraterrestrial threats, even though such considerations would require extensive political and policy deliberations by the world's major powers in order to assure verifiable international safeguards and use agreements. It is also a fact that enshrined in the 1969 Vienna Convention on the Law of Treaties is a fundamental rule that states that "..if the literal interpretation of a treaty obligation would lead to a result which is manifestly absurd or unreasonable, such interpretation should not be upheld". Clearly use of nuclear devices is less desirable than if non-nuclear means are known which could be as effective for similar investment, and therefore nuclear devices for mitigating NEO threats may be considered as a means of last resort, much as they are generally considered for use against targets on the Earth.

It is recognized that there are many for whom the use of nuclear devices for any purpose is abhorrent in principle. Nonetheless given the choice of having some or all of humanity's civilization destroyed by a NEO impact versus overcoming an aversion in principle to using nuclear devices and averting the cataclysm, the former becomes the clearly preferred alternative. Thus, while use of nuclear devices is not advocated by this report, their use for NEO mitigation is not ruled out either, and this section considers their use only in this context.

Engagement of a NEO using a nuclear device is very similar to that of a non-nuclear kinetic impact deflection technique, with the device being detonated just before or at impact. Similarly the trajectory is one of simple collision at high velocity, and neither rendezvous nor docking are required. Detonation of a thermonuclear device in space near a NEO produces a tremendous radiative flux. While the total energy from the particle flux may be relatively small, the hard x-ray, infrared, neutron, and gamma ray flux is extremely large. This radiation onslaught results in extremely rapid surface heating of the NEO that cannot be conducted away rapidly enough through the material. Hence, a layer of the surface ablates into a hot expanding plasma which disperses at extreme velocities, and its reaction forces on the surface accelerate the NEO and change its velocity. With sufficient stand-off distance, the area over which the energy is deposited may be relatively large and hence the "push" gentle enough to avoid fragmentation in some NEOs; however there would still be significant fragmentation risk to susceptible NEOs. In addition the detonation at a standoff distance from the NEO reduces the coupled energy by about one order of magnitude compared to that transferred to the body were the device detonated at the surface, and by about two orders of magnitude were it buried a few tens of meters below its surface and then detonated.

Notwithstanding the above, the energy and momentum transfer imparted by a nuclear device is so large that even very large NEOs discovered late may be deflected sufficiently. While the delivery and detonation of a nuclear device above or at the NEO surface can be accomplished in a straightforward impact trajectory, the most effective use with the device deeply buried would require a rendezvous trajectory, with subsequent docking and drilling operations to emplace the device using either automated/robotic means or manned systems. The deep explosion would result in superheated ablated interior material being ejected from the NEO in a jet-like fashion which, while extremely effective in transferring momentum to the NEO, would result in such extreme interior shock pressure that the danger of partially or totally fragmenting the body is a very serious possibility. The predictability of the effects of an explosion inside the NEO is even lower than that for external ablation or even kinetic impact, and requires a much better understanding of the composition and structure of the body in order to predict the outcome with any reasonable probability.

There is a persistent notion in lay circles that the way to deal with a dangerous NEO is to simply hit it with an ICBM and vaporize it in space. Unfortunately, reality is far removed from this illusion. While it is likely that we may be able to rapidly reconfigure an ICBM computer guidance system to intercept a point or object in near-Earth space, ICBM propulsion system performance is insufficient to enable intercept beyond a few hundred kilometers above the Earth's surface. Stages must be added to an ICBM to enable it to achieve the necessary escape velocity and to place the weapon on an intercept trajectory with a NEO. While these upper stage technologies are space qualified, such a system would have too low a reliability for the NEO intercept mission given the potentially horrendous consequences of an Earth impact, and might thus require many sequential launches of several such vehicles to have any reasonable chance of successfully deflecting a NEO. Such attempts would be part of a dedicated "campaign" utilizing several different launch vehicle types, designed with different upper stages, using different end game techniques, and different nuclear warhead types, in order to obtain a high probability of success. Furthermore at least one failed launch attempt is likely if many are required, and with a nuclear payload this could result in serious environmental effects in and of itself. Thus, it is clear that for the nuclear concept several dedicated designs of a inherently highly reliable launch vehicles and multi-stage interceptors would be extremely desirable to loft the nuclear warheads, and thus the use of existing ICBMs, even if outfitted with current technology upper stages, is highly undesirable if not essentially ruled out.

Nevertheless, if there were no other option due to insufficient warning time we might want to do all we can with the tools at hand rather than sit passively like the dinosaurs, and attempt intercepts with current space launchers and current upper stages if no dedicated vehicles exist or could be developed in the time available. It would be perfectly rational to divert any and all launchers and spacecraft being designed for planetary exploration to becoming NEO interceptors, whatever their state of development. Finally it must be made clear that many nuclear warheads intended for ICBMs exist that could be used with few, if any, modifications as payloads for the purpose of deflection of NEOs, whatever launch vehicle and upper stage is used to get them to the NEO (see ref. 4).

Many analyses have been carried out to compare the various techniques discussed briefly above. While much detail exists the fundamentals of orbit dynamics are simple: The longer the action time of a force applied to a NEO the lower is the energy required to move its impact point off the Earth and the larger is the NEO than can be so moved. Conversely the greater the energy available the shorter the action time can be and the larger is the NEO that can be moved. One comparison is shown in Figure 4-7, which clearly shows that if the NEOs are large and if little time is available then there is no choice but the use of nuclear devices to prevent impact. It also shows that in general there will be a significant advantage to a kinetic "fast push" approach over any "slow push" technique for the same available action time, at least for the parameters considered in this comparison.

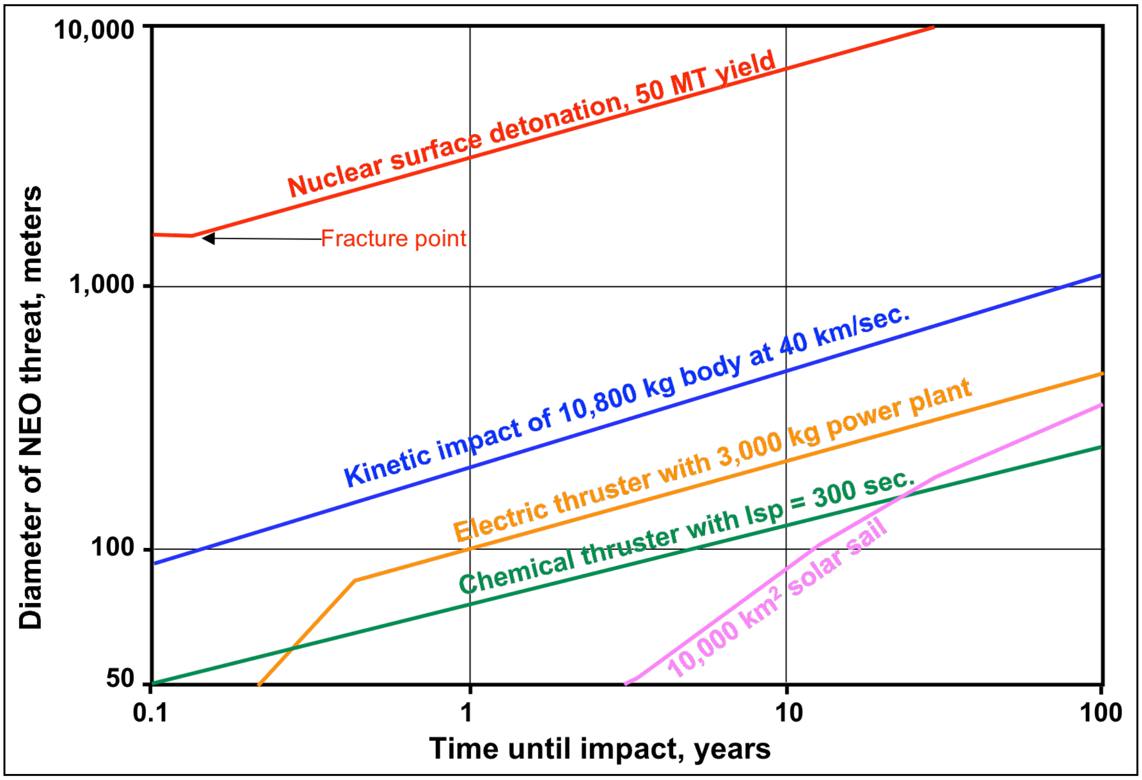


Figure 4-7. Comparison of nuclear and non-nuclear deflection techniques (Rogers, Izenberg, JHU)

In summary, although there are well founded aversions to use of nuclear devices, their use against NEOs in space is probably one of the best and most desirable applications of these devices; and is the only technique that might be able to prevent a horrendous regional or global catastrophe when we are faced with a large NEO, or one with little warning time, or both. And the occurrence of such a situation is not a question of IF, but rather a question of WHEN.

3. Infrastructure and system deployment

The detection and cataloguing of 90% of asteroids of 1 km size or larger is essentially completed by now through the Spaceguard Survey, and NASA has been instructed to extend the survey to asteroids as small as 140 m within the next decade. However, even if those goals are met most of these asteroids are not and will not be characterized in that time frame. Given the wide diversity in characteristics of these objects and the continuing dynamics in the NEO population the certainty of a successful deflection, even if all systems of the mitigator work as designed, is not great. Furthermore neither today's technologies nor those likely to be available in the next decade or two lead to systems with extremely high reliability.

Thus the probability of a successful deflection of a NEO with single mission using any known concept is far lower than desired, given the likely horrendous consequences of a failure. It is therefore clear that the development and deployment of a robust, multiple option, redundant, coordinated system of multiple and diverse systems is needed; and that the deflection of a NEO cannot be a mission but must rather be a campaign of multiple orchestrated missions[19]. Furthermore, these missions will probably have to be deployed sequentially in increasingly capable stages, with means in place to rapidly assess the status and effects of the missions as they unfold. All this requires not only the hardware and software to physically mount the campaign against a NEO but an extensive, expensive, and well coordinated command and control infrastructure which has been internationally designed, vetted, manned, and accepted. This task is technically not very different from structures emplaced by the adversaries during the cold war, or from current means in place by the space-faring nations for command and control of their space activities. However the political and policy obstacles to be overcome are much greater, even if the payoff will also be greater. These issues are discussed in depth in the Policy chapter.

The implementation of a planetary defense system will likely occur in stages of increasing capability. A likely first step will be to rely on modifying and reprogramming one of a number of lunar and planetary/cometary exploration probes, that are continually being developed by several nations and consortia for scientific purposes, to impact on a NEO. This first step, though modest, could have a small but non-zero chance of successfully deflecting a NEO threat if at least a decade of warning time were available, and if the NEO size was small-to-modest. It would share command and control facilities with those that address scientific space probes.

A second step could be the development of a dedicated command and control system but continue to rely on modifying non-dedicated launch and mission spacecraft on an as-available basis. The alternative of designing and developing a dedicated launch and intercept system kept continuously at the ready would probably be considerably more expensive, and so could comprise a third step. A likely fourth step in this hypothetical sequence would broaden the diversity of systems arrayed to deflect NEOs, involving several different kinds of systems launched on different launch vehicle types and commanded by redundant means, in order to increase the chances of successful deflection. A fifth step could expand the arrayed system to emplace the capability to deflect considerably larger NEOs, or those for which the warning time was short enough as to render the above fourth generation systems ineffective. This last step might or might not be the first one to employ nuclear devices. (Dr. Anatoly Zaitsev, Director of the Planetary Defense Center in Russia has described in the literature one vision for such a dedicated layered planetary defense concept he calls Citadel, which is briefly described in the Appendix).

While the above scenario is hypothetical it is much more realistic than to attempt to deploy a dedicated, fully capable system in one step. Such an attempt would likely be horrendously expensive, extremely difficult to make operational with the required reliability, politically unacceptable to most nations and consortia, and thus unlikely to be agreed upon in the first place. Nonetheless, planning to attain such an eventual capability though by a number of measured steps over a longer period of time needs to begin immediately if we are to obtain even a rudimentary capability in the near future.

Of course, there is always the chance that a NEO on a verified high probability impact trajectory will be discovered in the near future, whose impact was predicted to cause great destruction and loss of life, and we will not be in a position to do much about it even though we possess the technologies for preventing it. We would be in a situation not much better than were the dinosaurs 60 million year ago--but they had an excuse that we do not have.

Unfortunately, too often it seems to take a catastrophe to spur actions that could have been prevented had they been implemented before the event.

Chapter 5:
ORGANIZING FOR THE TASK

1. Characteristics of the Impact Threat Emergency

International character of NEO threat and alerts

The threat posed by a pending asteroid impact is inherently international in scope. While the physical extent of an impact could range from local to regional to global, the entire world would be engaged in the unfolding drama from the announcement of a potential collision through either the successful mitigation or the disastrous consequences of impact. Fortunately, the resources of the global community would also be available to respond to the challenge. Effectively harnessing and applying these resources, however, will require unprecedented cooperation and organization. Without adequate planning and preparation before an event is underway, the challenge may overwhelm even the most enthusiastic international proponents of a coordinated response.

There is an international community of astronomers participating in surveys of the asteroid population. But beyond that, technologies to prepare, respond, and recover from asteroid impacts can also be drawn from throughout the world. Budget resources and talent are limited within individual nations, even in countries making significant contributions today, such as the United States. Pooling and leveraging funds and talent through wider cooperation in commonly agreed upon priority areas and more effective use of resources can substantially improve the posture of future responses. Many nations approach technological solutions differently and offer specialized areas of competence that, when shared widely, can illuminate issues and help other nations develop effective responses.

Considering and accounting for cultural differences and sensitivities in dealing with mass evacuations, establishment of relocation centers, and eventual remediation add perspective that, when applied early in the planning cycle, can save time, money, and more importantly, lives, if a call for action is necessary.

Differences Between Impact Threat and Other Natural Disasters

The world does not lack for examples of natural disasters with global extent or local horrific impact. Earthquakes, floods, mudslides, and storms annually take hundreds of thousands of lives and impose significant economic and social costs[1]. In 2005 157 million people—seven million more than in 2004—required immediate assistance, were evacuated, injured or lost their livelihoods. Frequently, significant fractions of the deaths or other consequences of natural disasters are attributable to single events. The Indian Ocean tsunami accounted for 92 per cent of the deaths in 2004, and a South Asian earthquake accounted for 81 per cent of the deaths in 2005. Disasters in 2005 cost a total of $159 billion in damage, but of this, 78 percent were for losses caused by Hurricane Katrina in the United States.

Consequences of an asteroid impact share many characteristics of natural disasters the world has experienced, but there are significant differences also:

- Few natural disasters have the potential for near instantaneous global devastation.
- The time, the effect, and to some degree the location of an asteroid impact can be forecast weeks to years in advance
- The impact can be completely prevented

These differences shape the international response to the unique characteristics of an asteroid impact.

The Need for International Participation

No place on Earth is safe from an asteroid impact. The most probable impact, roughly every one hundred years, would be limited to local effects, such as the Tunguska impact in 1908. However, to first approximation such an impact is equally likely at any location on Earth. Larger but rarer impacts with regional effects, roughly every few thousand years, would cross political boundaries with impunity. In this category are ocean impacts which have the potential to produce tsunamis that would affect thousands to tens of thousands of miles of coastline. Far less probable, but still possible every few hundred thousand years, are impacts with global consequences. Since *a priori* the risk for each category is distributed throughout the world, there is a need to engage the resources of the global community to prepare for the eventuality of an impact.

Given today's allocation and availability of deep space survey resources, it is likely that projections of the location of impact, and even high confidence projections of the probability of impact will carry substantial uncertainties even close to the time of projected impact. This significantly complicates international planning for mitigation and recovery, potentially forcing such plans to exist in "contingency mode" until very near the time of expected impact. Understanding the societal and political implications of this degree of uncertainty is critical to developing a comprehensive strategy for responding to the threat of asteroid impacts.

1. With adequate resources applied to the problem (but deferring for now the cost to develop and apply these resources, to include high power radar, high resolution optical instruments, and perhaps even the deployment of a beacon on a threat object) the trajectory of a threat object can be precisely projected, providing high confidence estimates of impact time and location perhaps weeks to months in advance. This will allow for orderly and measured responses, such as evacuations of direct threat regions, hardening of surrounding regions, and prepositioning of recovery assets. However, this will require international cooperation on a scale that could dwarf the outpouring of humanitarian support that is typically observed after major natural disasters. What national economies can absorb the establishment of refugee camps with populations in the millions? Can evacuees be absorbed by dispersing them to neighboring countries? Why should country "A" pay to restore the infrastructure of country "B?" What are the implications of knowing in advance that an entire country is about to cease to exist? Even the case of a forecast of a local event (most probable scenario) would have significant economic consequences months before impact, as residents and local businesses scramble to relocate, leaving behind an economic ghost town of staggering proportions.

Fortunately, the long lead time that may be available prior to projected impact also makes it possible in principle to prevent the impact entirely by diverting the asteroid from its natural course. Deflection techniques and the technical challenges associated with them were treated more fully in chapter 4. There are many political issues that stress the need to engage the international community. A mitigation attempt may fail to engage, may fail to fully deflect, or may fracture the asteroid into multiple fragments. This in turn could move the impact point to another region or spread the impact to cover a larger area. In the event of a sufficiently large impact, there may be no survivors to second-guess the planning and execution. But in the more probable case of a local or regional threat, a failed attempt carries political and legal consequences. This risk of failure and subsequent censure may impede plans to proceed with a deflection attempt, particularly if the country or countries that have the capability to respond are not directly in danger.

False Alarms

False alarms, often referred to within the NEO community as "one day wonders," are another unique characteristic of NEO impact threats, and deserve special attention. In the early phases of discovery and orbit refinement the impact time and location will be very imprecise. False alarms, even and perhaps especially from authoritative sources who may in fact believe in their projections, excite the media and engage the public. The periodic outbreak of attention from a false alarm may seem to be beneficial at first glance, as it serves to raise public awareness of the threat. However, any awareness enhancing features are outweighed by detrimental consequences including inducing panic and unnecessary anxiety; desensitizing the public or trivializing the threat; and diverting the attention and damaging the credible of the NEO community.

For example, in May 2006, a report appeared on a thoroughly unscientific website that fragments of a comet (73P/Schwassmann-Wachmann 3) would strike the Earth and create destructive tsunamis. Despite the fact that this report was quickly and completely discredited, the Moroccan public reacted with alarm. As reported in the Morocco Times[2]:

> It didn't prevent many Moroccans from panicking. Some are already packed to go to the mountains; others have decided to travel to another country. Even those who believe it is only a rumor are anxiously waiting for May 25.

Significant media-generated excitement was propagated in December 2004 in response to legitimate initial concern over estimates that the asteroid "Apophis" could strike the Earth in 2029. The impact estimates from December 20 to December 27 climbed steadily upward to 2.7 percent chance before archive searches of pre-discovery observations of Apophis taken in March 2004 effectively ruled out a 2029 collision[3]. Some residual concerns remain that Apophis's near-encounter with Earth in 2029 may put the asteroid into a close-encounter with Earth in 2036.

2. A Framework for Response

Existing Frameworks

Recognition of the threat and the need for more coordinated response has been affirmed by multiple significant scientific and professional organizations through the formation of NEO-focused subgroups, including

- The United Nations Committee on Peaceful Uses of Outer Space (COPUOS)
- International Council for Science, Committee on Space Research (COSPAR)
- The Planetary Society
- The International Astronomical Union
- The World Federation of Scientists
- The B612 Foundation
- Association of Space Explorers
- National Space Society [United States]
- American Institute of Aeronautics and Astronautics

Asteroid Survey

The most important contribution of the NEO scientific community in recent years has been the implementation of a process to verify and validate the threat of asteroid impact. The establishment of an international clearing house of information, including the International Astronomical Union's Minor Planet Center, the NASA Near Earth Object Program, the Near Earth Object Dynamic Site in Italy and several international components of the Spaceguard Foundation has significantly improved the scientific credibility of the NEO community. It has also generated a core within which additional international cooperative activities could be proposed and evaluated.

The international organization that coordinates the discovery and naming of astronomical bodies within the solar system in general, and NEOs in particular, is the Minor Planet Center[4].

The Minor Planet Center (MPC) operates at the Smithsonian Astrophysical Observatory, under the auspices of Division III of the International Astronomical Union (IAU), with significant funding coming from subscriptions to the various services offered by the Center.

The MPC is responsible for the designation of minor bodies in the solar system: minor planets; comets (in conjunction with CBAT [Central Bureau for Astronomical Telegrams]); and natural satellites (also in conjunction with CBAT). The MPC is also responsible for the efficient collection, (computation,) checking and dissemination of astrometric observations and orbits for minor planets and comets, via the Minor Planet Circulars (issued generally on a monthly basis), the Minor Planet Circulars Orbit Supplement (MPO) (issued three or four times per year), the Minor Planet Circulars Supplement (MPS) (issued three or four times a month) and the Minor Planet Electronic Circulars (issued as necessary, generally at least once per day).

In 1998 the United States Congress established within NASA the NEO Program[5].

> "The purpose of the Near-Earth Object Program is to coordinate NASA-sponsored efforts to detect, track and characterize potentially hazardous asteroids and comets that could approach the Earth. The NEO Program will focus on the goal of locating at least 90 percent of the estimated 1,000 asteroids and comets that approach the Earth and are larger than 1 kilometer (about 2/3-mile) in diameter, by the end of the next decade [by 2010]. In addition to managing the detection and cataloging of Near-Earth objects, the NEO Program office will be responsible for facilitating communications between the astronomical community and the public should any potentially hazardous objects be discovered".

NEO Dynamic Site (NEODyS) is a service offered by the University of Pisa (Italy). It provides catalogues, computes orbits, and projects the behavior of NEOs in the future, in order to identify possible impacts in advance[6].

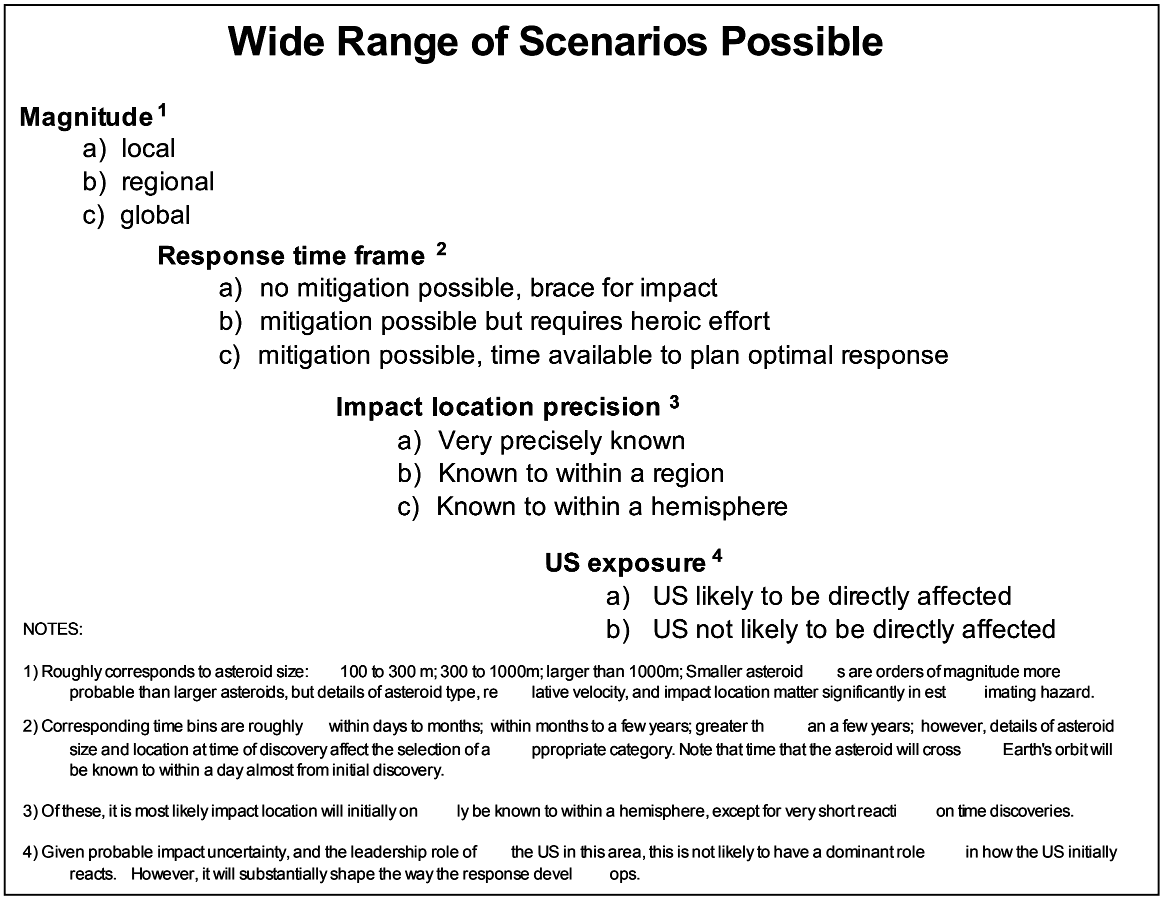
The NEO Survey process is shown in Figure 5-1. An international collection of observatories daily forward roughly six to twelve observations of candidate "potentially hazardous objects" to the IAU Minor Planet Center. These candidates are posted on the IAU NEO Confirmation Page[7]. Observatories throughout the world then target these candidates to verify the location of the object, generally within 24 hours of the initial posting. Validated objects are then forwarded to the NASA NEO Program and to NEODyS, where their orbits are projected one hundred years or more into the future using detailed propagation models. Confirmed candidates are cataloged[8]. Both the NEO Program and NEODyS provide independent information and services for all cataloged NEOs[9].

Observations	Confirmations	Projections	Catalogues
World-Wide Independent Surveys and Observatories	**International Astronomical Union, Minor Planet Center, Harvard University**	**NASA Near Earth Object Program, JPL (USA)** **Near Earth Objects Dynamic Site (NEODyS) University of Pisa (Italy)**	
Major Surveys: **LINEAR** **NEAT** **LONEOS** **Spacewatch** **Catalina Sky Survey** **JSGA** **ADAS** **Hundreds of additional int'l observatories** **Nominally 6 – 12 candidate NEOs are submitted to IAU per day**	**Candidates posted daily on NEO Confirmation Page [1]** **Observatories throughout the world target candidates to verify orbit, generally within 24 hours of initial posting**	**Orbits are projected 100 or more years into the future using detailed propagation models** **Confirmed candidates are cataloged [2]**	**JPL and NEODyS provide independent information and services for all Near Earth Asteroids** **Search and sort capabilities put the information in easy reach [3]**

Figure 5-1: The NEO Survey Process (Credit: JPL)

Emergency Response Plans

In the event that a candidate asteroid was found to pose a credible threat of impact, i.e. sufficient observations to make it more than just a "one day wonder," several steps would be taken. The first "official" notification would be from the NASA NEO Program, likely with participation of the Minor Planet Center, to the NASA NEO Program Scientist in NASA Headquarters, Washington DC. The central element of this call would be to relay the nature of the threat (timing, location, projected extent of damage, magnitude of uncertainties). The Program Scientist would then report to the NASA Administrator. Beyond this, the formal process becomes less clear and undoubtedly will depend on the nature of the threat (see Figure 5-2). In the most stressing situations, the NASA Administrator would contact the President of the United States with a request to declare the pending impact an "incident of national significance." In less stressing circumstances, the request may trigger a less aggressive response, leading, for example, to a heighten level of monitoring.



Wide Range of Scenarios Possible

Magnitude[1]

- a) local
- b) regional
- c) global

Response time frame[2]

- a) no mitigation possible, brace for impact
- b) mitigation possible but requires heroic effort
- c) mitigation possible, time available to plan optimal response

Impact location precision[3]

- a) Very precisely known
- b) Known to within a region
- c) Known to within a hemisphere

US exposure[4]

- a) US likely to be directly affected
- b) US not likely to be directly affected

NOTES:

1) Roughly corresponds to asteroid size: 100 to 300 m; 300 to 1000m; larger than 1000m; Smaller asteroids are orders of magnitude more probable than larger asteroids, but details of asteroid type, relative velocity, and impact location matter significantly in estimating hazard.

2) Corresponding time bins are roughly within days to months; within months to a few years; greater than a few years; however, details of asteroid size and location at time of discovery affect the selection of appropriate category. Note that time that the asteroid will cross Earth's orbit will be known to within a day almost from initial discovery.

3) Of these, it is most likely impact location will initially only be known to within a hemisphere, except for very short reaction time discoveries.

4) Given probable impact uncertainty, and the leadership role of the US in this area, this is not likely to have a dominant role in how the US initially reacts. However, it will substantially shape the way the response develops.

Figure 5-2. The nature of the threat will have a significant impact on the steps taken

Within the United States there are formal plans and procedures for dealing with natural disasters at a federal level: the National Response Plan, the National Incident Management System, and the Catastrophic Incident Annex to the National Response Plan[10]. These plans can be set in motion by the Presidential declaration of "an incident of national significance."

The *National Response Plan* defines a *catastrophic incident* as[11]:

> Any natural or man-made incident, including terrorism, that results in extraordinary levels of mass casualties, damage, or disruption severely affecting the population, infrastructure, environment, economy, national morale, and/or government functions. A catastrophic event could result in sustained national impacts over a prolonged period of time; almost immediately exceeds resources normally available to State, local, tribal, and private sector authorities in the impacted area; and significantly interrupts governmental operations and emergency services to such an extent that national security could be threatened.

Unfortunately there is no clear path from the discovery of a probable threat asteroid to the implementation of the United State's NRP, and further, there is no identified process at all for expanding the implementation of the NRP to include international participation.

Asteroid Deflection

In addition to the science-based problem of asteroid surveys, the NEO community has devoted substantial resources to developing concepts that may be employed to deflect threat asteroids. Among the technical issues that have been raised are what techniques are appropriate for various asteroid sizes, compositions, and lead times; what is an appropriate threshold for action; what cost-effective measures can be held in operational readiness; and what can be done to shorten the deployment time of "off-the-shelf" responses.

The technical issues are only part of the mitigation challenge; coordinating an internationally sanctioned response may be equally challenging, particularly if the work begins only after discovery and during a period of highly uncertain impact projections. In principle there are many organizational models that could be used. Samples include, but may not be limited to:

- A globally coordinated and funded effort managed and/or mandated through an international body, such as the UN
- A global consortium of countries established via multilateral negotiations, with technical leads accepted voluntarily as appropriate to aggregates of tasks (tracking, characterization, transportation, engagement, etc)
- Minimally coordinated independent attempts, each managed entirely within the resources of a single country or team of countries
- Agreement to hand the entire mission development, management, and execution by a single country.

While multiple models are possible, there has been no international agreement on any particular approach, nor has there been serious discussion in multilateral forums beyond the NEO community on a process to even identify effective schemes for international cooperation.

Expanded NEO Framework

To date the NEO community has focused almost exclusively on technical issues of asteroid characterization, survey, and mitigation. Proper disaster response planning is about far more than the asteroid and its impact. There is a need to engage the broader international community in the larger framework of plans for preparation, response, and recovery. One measure of the scope of full-spectrum disaster planning is illustrated by the list of fifteen emergency support functions and responsible organizations included in the United States National Response Plan:

Emergency Support Function (ESF)		Responsible Agency
ESF #1	Transportation	DOT
ESF #2	Communications	DHS (IAIP/NCS)
ESF #3	Public Works and Engineering	DOD (USACE) and DHS (FEMA)
ESF #4	Firefighting	USDA (Forest Service)
ESF #5	Emergency Management	DHS (FEMA)
ESF #6	Mass Care, Housing, and Human Services	DHS (FEMA) and American Red Cross
ESF #7	Resource Support	GSA
ESF #8	Public Health and Medical Services	HHS
ESF #9	Urban Search and Rescue	DHS (FEMA)
ESF #10	Oil and Hazardous Materials Response	EPA and DHS (U.S. Coast Guard)
ESF #11	Energy	DOE
ESF #13	Public Safety and Security	DHS and DOJ
ESF #14	Long-Term Community Recovery and Mitigation	USDA, DOC, DHS (FEMA), HUD, Treasury and SBA
ESF #15	External Affairs	DHS (FEMA)

Another way to illustrate the scope of full-spectrum disaster planning is to organize the stages of activities appropriate before, during, and after an incident.

- Pre-Event (prior to identification of specific threat)
    - Prepare
        - Increase scientific understanding of threat objects
        - Improve modeling of impacts
        - Improve analysis of consequences
        - Develop mitigation options
        - Educate the public
    - Plan

    - Develop scenarios
      - False alarm management
      - Local event
      - Regional event
      - Global event
    - Prepare response options
    - Conduct exercises
  - Survey
- Peri-Event (after validation of threat object, prior to impact)
  - Response planning
  - Response implementation
- Post-Event (After successful mitigation or post-impact)
  - Recovery
  - Maintenance (return to vigilance mode)

There are significant roles for the global community (including contributions from governments, the United Nations, non-governmental organizations such as the International Red Cross, global corporations, academic institutions, and professional organizations and societies) in each stage of response. This framework helps to optimize the contributions of those communities that are already concerned about the NEO threat, but more importantly, it helps to identify and engage communities that are not, but should be, involved in preparing for a coordinated global response to an asteroid threat.

Pre-Event (prior to identification of specific threat)

Fortunately the modern world's experience with impacting cosmic objects is generally limited to upper atmospheric air bursts and the occasional low impact meteorite. The single dramatic exception was the 1908 Tunguska event (which by some estimates had the energy of an event that should be expected only every thousand years). Hence it is reasonable that most of the activity of the NEO community has been appropriately focused on "Pre-Event" activities. Preparing, planning, and actively surveying the asteroid population.

"Preparing" entails those activities that increase understanding of the threat, including the physical properties of NEOs, the impact consequences, mitigation options, and educating the public to the nature of the threat. To a significant degree, this is where most of the international scientific and technical community is engaged.

An understanding of the nature of asteroids has dual benefit: in addition to knowing more about NEO characteristics to enable effective countermeasures, NEOs are remnants of the early solar system and have tremendous inherent space science value. Indeed, the most costly and sophisticated efforts underway are concentrated in space missions to the neighborhood of asteroids. Many of these missions are international in scope, and include Missions[12]: Near-Earth Asteroid Rendezvous (NEAR), Deep Impact, Deep Space 1 (DS1), STARDUST, Hayabusa (MUSES-C), Dawn, and Rosetta .

Typically studies of impact consequences focus on the physical parameters of the NEO collision with the Earth's atmosphere and surface. There are tools on the internet that enable the user to dial in asteroid characteristics and get estimates of energy release, crater size, and other blast effects[13]. Very detailed simulations of impacts using parallel processing supercomputers have been run [14]. Estimates of the human, physical, and economic consequences have typically been abstract. In May 2006, NASA released a "Call for Papers" that listed many of the outstanding technical issues that need to be addressed[15]. The questions posed are shown in Table 5-1.

Detecting, Tracking, and Cataloging NEOs

1. What are current US & international capabilities to discover and track NEOs? What size objects can be seen at what distances from the Earth? How much of the sky is covered?
2. How does warning time vary with object size for an object on a likely collision course?
3. What currently limits the ability to discover and track objects at 140 m? What technologies are currently in use?
4. What improved capabilities, expected to become generally available within the next 10 years, could enhance discovery and tracking?
5. What is the best possible ground-based system for discovering and tracking NEOs? How much coverage is possible using ground-based systems?
6. Is there a need for space-based systems? Do space-based systems provide advantages over ground-based systems? If so, what is the optimal mix of ground and space-based systems?
7. Can amateur or other astronomers assist with discovery and tracking? How can they be encouraged to do so (e.g., cash awards for new objects)?

Characterization of NEOs

1. What is currently known about the physical characteristics of comets?
2. What is currently known about the physical characteristics of asteroids?
3. How much do comets and asteroids vary in characteristics?
4. How common are smaller bodies orbiting asteroids? What sizes of primary and secondary bodies is expected?
5. How can physical characteristics of NEOs be resolved in more detail? Will the ability to characterize near-Earth objects be improved by ground or space-based capabilities expected to become available in the next 10 years?
6. If a threatening object were detected, what assumptions should be made about its composition and structure to assure the highest likelihood of success of a deflection mission (assuming there is no opportunity for a reconnaissance and characterization mission)?

Deflection and Threat Mitigation of NEOs

1. Which deflection options are best suited to which object size, types, and warning times?
2. Estimate the state of readiness of each option.

Evaluation of Concepts

The authors of those white papers deemed most appropriate will be invited to present their white paper during the workshop. Submitted white papers will be evaluated according to the following criteria subsequent to the workshop as part of the NASA study. Authors are requested to present detailed analysis that supports their concept's satisfaction of these criteria:

- Ability of proposed concept to detect and track Near Earth Objects down to at least 140 meters in size passing within 50 million kilometers of Earth's orbit; **and**
- Ability of proposed concept to detect within 15 years at least 90% of the total projected population of Near Earth Objects equal or greater than 140 meters in size; **or**
- Ability of proposed concept to characterize, either remotely or in situ, a NEO for factors related to mitigation, including the size, composition and structure; **or**
- Ability of proposed concept to mitigate the impact effects of a Near-Earth Object determined to be on a likely collision course with Earth during a determined time period in the future; **and**
- Credibility of presented schedule and cost information.

Table 5-1. NASA Call For Papers, May 2006

The NASA request was the result of a directive from the US Congress, and unfortunately it had a mixed message with regard to international participation:

> Workshop attendance is limited to U.S. persons only, as defined in 22 CFR § 120.15. Persons representing foreign entities or interests may not attend.

The NASA Call for Papers starkly illustrates the NEO community focus on NEO physical characteristics and engineering details, and an unfortunate US-centric view and exclusion of the international community. There is a need, especially from the international community, to provide more detailed studies of the economic, social, and political consequences of an impact (See Chapter 6, Behavior Factors and Chapter 7, Policy Implications). In particular, there is a need to identify specific options for international cooperation and to better understand the consequences of knowing in advance that an impact is imminent.

Much has been written about options for asteroid mitigation. As of May 2008, on the popular web search "Google" there were 78,600 hits on the phrase "asteroid mitigation." Many of these were technical description of proposed concepts. However, there is no approach for mitigation currently available for implementation should an impact be forecast. There are many reasons for this, as it is a challenging problem technically and organizationally. The optimum solution depends heavily on the precise nature of the threat and the time to respond. However, the fact that it is a challenging problem is reason enough to engage the international community in a dialogue to explore technical options and to identify a process for selecting the appropriate political response under a variety of scenarios[16].

An additional important element of planning for the possibility of a NEO impact is educating the public. An informed public is less likely to panic from false alarms and is more likely to react positively to mitigation efforts should an impact appear probable. An informed public is also more likely to engage fruitfully in an intelligent debate of what measures are appropriate in the absence of a clear and present danger. The NASA NEO Program in the United States is specifically "responsible for facilitating communications between the astronomical community and the public should any potentially hazardous objects be discovered". Each professional society that has taken on the issue of the NEO risk is obligated to conduct outreach to the public[17]. But there is also a need to identify at the international level a single credible clearinghouse of information analogous to the NASA NEO Program.

Conducting studies and analyses and exploring options are important background tasks necessary to *prepare* for a potential impact. The next level up in intensity, requiring more substantial international coordination and commitment are activities associated with *planning* specific response options to various scenarios. Progress among the NEO community has been made to some degree in the case of infrequent false alarm management. As surveys become more and more sensitive, the rate of false alarms will naturally increase, and an international standard for responding to false alarms will become more important.

Beyond false alarms, there is a need to consider concrete options for dealing with potential asteroid impacts. This would no longer be the purview of professional societies acting on their own. The breadth of scenarios suggests it would be unreasonable to create and file away contingency plans for every conceivable alternative NEO impact. This is not unique to NEO disasters, but is also true for other natural disasters. Nevertheless, governments and non-governmental organizations do work together to prepare for other natural disasters. Prudent preliminary steps toward planning for a potential impact could involve enlisting appropriate professional organizations to create credible and detailed scenarios of local and regional NEO impacts. These scenarios, once validated by recognized experts in an international commission, could be shared with disaster relief organizations familiar with detailed implementation of natural disaster response. Thus could begin a dialogue that would lead to the creation of response templates. These templates would be a first attempt to produce an international version of a comprehensive response plan, incorporating realistic recognition of the complexity of mass evacuations and recovery and remediation on vast scales.

Upon attaining a mature level of planning, the NEO community, working with other relief organizations and international government representatives could lead virtual exercises to test the efficacy of the plans.

Just as other natural disasters have active components dedicated to monitoring the environment to predict the potential onset of a pending event, the NEO threat community has the ongoing, operational task of monitoring the skies for evidence of an imminent impact. Unlike other natural disasters, a NEO impact in principle could be detected weeks to years in advance. With adequate lead time, there are more mitigation options and more opportunities for planning.

While the US has a leading role in NEO surveys, there are many international partners in the effort. However, there is also significant opportunity to substantially increase the international community involvement. The majority of new asteroids are detected by just a few dedicated centers, as discussed in Chapter 3. Modest funding could bring on line many additional dedicated observatories. This would not only contribute to the US (NASA) goal of identifying ninety percent of all asteroids one kilometer in diameter or larger by 2010, but would also help with plans to push the threshold of routine surveillance down to the order of 100 to 200 meter diameter NEOs.

In addition to locating NEOs, there is a critical need to bring on line a capability to more precisely locate high threat objects. A significant contribution to the inability to implement response plans in an early and measured fashion is the inherent uncertainty in object location and propagation. The ability to precisely forecast the path of a NEO threat would remove ambiguity in whether the object is or is not going to impact Earth, a critical piece of information if a deflection scheme is to be employed, knowing that any deflection scheme could fail or only partially deflect the object. In addition, if an impact is inevitable, knowing the precise impact point and the nature of the asteroid would enable focused response and recovery planning.

Peri-Event (after validation of threat object, prior to impact)

It is clear from the media and the public's response to false alarms and to news releases following major NEO workshops that, if a pending impact is forecast with reasonable and credible probability, there would be an immense and near-instantaneous global reaction. This is not necessarily a good thing. Without an adequate foundation prepared ahead of time, there is significant risk of "too many cooks spoiling the soup." The "Peri-Event" period, after validation of a specific threat object and prior to impact or confirmation of successful deflection, will require intense international coordination and cooperation. Delays in reaching consensus on the approach to mitigate damage will reduce the options and increase the technical risk.

The first step in this stage will be to communicate to the public the exact nature of the threat, from a credible and trustworthy source. Options and a process to decide upon effective courses of action also must be competently and authoritatively communicated to the public to minimize panic. Assuming this has been established ahead of time (prior to an identified threat), such actions could be enacted within days of the impact discovery. If a process or procedure has not been fully vetted prior to discovery, it could easily be weeks before international concurrence is obtained.

Deflection attempts will not be easy. It will be desirable to engage the NEO as far from Earth and as soon as possible (conflicting requirements that call for an optimization). Even relatively simple space science missions cost hundreds of millions of US dollars and typically take two or more years from concept to execution, using proven hardware and software. Deep space missions requiring high initial velocity, significant launch mass, and potentially complex engagement schemes with untested components will easily cost a few billion US dollars and from concept to execution using nominal aerospace design practices would require five to ten years. Clearly an engagement attempt will call for a novel management and development scheme, the creation and execution of which would benefit from the intellectual capital of all the space-faring nations of the world. Without preparation however, planning by committee requiring consensus agreement is a recipe for mission failure.

It is not cost effective to maintain a "launch ready" one-size-stops-all asteroid-deflecting stand-by capability. However, it may be cost effective to maintain a quick-response capability to defend against NEOs under 100 meters in diameter requiring less than one centimeter per second change in velocity, while maintaining a blueprint and critical components to scale up the response. Even while technically feasible, there must also be international financial support and agreement to the terms and conditions that would initiate implementation.

After engagement, there must be a means to confirm the effect on the NEO, to determine if it was successful or if it failed to adequately deflect the object. If an attempt fails, detailed calculations of new estimates of impact point will be needed and additional attempts perhaps already poised to act, may be called upon. Whatever the result, it needs to be quickly and effectively communicated to the public.

Since the deflection attempts may fail, backup measures must be implemented from the outset. It is probable that this will mean massive evacuation of the projected impact zone. But evacuation is more complex than the difficult logistics of moving perhaps tens of millions of people out of immediate harm's way. The relocated individuals will require food, water, shelter, and health care at a minimum. Relocation centers must provide for the daily well-being of the inhabitants, maintain order, and provide public utilities (power, communications, wastewater treatment, etc). Evacuees will need assurances that there is a process to eventually restore their livelihood. The evacuated areas must be monitored to prevent looting and to respond to fires and other emergencies that will happen routinely prior to impact. Areas surrounding the immediate impact zones must be hardened to minimize post-impact collateral damage from spreading fire, smoke and other debris, floods and contaminated water sources, failed power grids, and loss of agricultural areas. Equipment needed to respond to the impact must be propositioned and maintained. All of this must be accomplished under conditions of uncertainty in NEO impact and most likely across national boundaries.

Post Event (after successful mitigation or post-impact)

If the encounter does not result in impact, either because the asteroid naturally missed the Earth or because it was successfully deflected, there will still be a substantial recovery effort. Evacuees will be able to return home, but it must be done in an orderly fashion. A lesson from the United States' experience with Katrina is that not everyone will be anxious to go home. Restoring the economic viability of the evacuation zone may be a non-trivial task, if many of the inhabitants and much of the industry relocated. The entire infrastructure created in response to the crisis will need to be decommissioned or converted to other uses. All of these factors can have international dimensions if the evacuees relocated to other countries.

If the encounter does result in an impact, the international community must be ready to respond quickly and effectively to a level of destruction that could easily eclipse anything seen in the global experience with natural disasters. While loss of life may be minimized by effective evacuation, the loss of infrastructure alone could measure upward of hundreds of billions of dollars. Undoubtedly however, evacuation will not be total and hardening of surrounding areas will be incomplete. Immediate casualties will stress even a prepared response. Disease, both to humans and to agriculture, will be rampant. The environmental impact will be tremendous, both in the immediate zone of impact and perhaps globally. Wide area biological restoration, a concept that has only recently achieved significant attention and is being applied to the area surrounding New Orleans post-Katrina, will be required on a dramatically new scale.

With the "Sword of Damocles" no longer hanging over humanity's head, the various nations must return to dealing with the issues of economic, social, and political costs accrued over the course of responding to the crisis. Where there are no homes or businesses to return to, a permanent solution must be found for the evacuees. If the processes employed "Peri-Event" are essentially those that have been established in less urgent times (Pre-Event), then this phase could be significantly less painful than if the steps taken are less than optimal actions forced upon the global community in the heat of the moment.

Finally, the NEO community must return to a state of vigilance, ready again to monitor the heavens for the next threat object.

3. Summary

The threat posed by a pending asteroid impact is inherently global in scope. Recognition of the threat and the need for more coordinated response has been affirmed by multiple significant scientific and professional organizations through the formation of NEO-focused subgroups.

The most important contribution of the NEO scientific community in recent years has been the implementation of a process to verify and validate the threat of asteroid impact. To date the NEO community has focused almost exclusively on technical issues of asteroid characterization, survey, and mitigation. The technical issues are only part of the mitigation challenge; coordinating an internationally sanctioned response may be equally challenging, particularly if the work were to begin only after discovery and during a period of highly uncertain impact projections. In particular, there is a need to identify specific options for international cooperation and to better understand the consequences of knowing in advance that an impact is imminent.

Proper disaster response planning is about far more than the asteroid and its impact. The broader international community must be engaged in the larger framework of plans for preparation, response, and recovery. The "global community" with a role in preparing for and mitigating the consequences of NEO impact includes governments, the United Nations, non-governmental organizations such as the International Red Cross, global corporations, academic institutions, and professional organizations and societies. Unfortunately there is no clear path from the discovery of a probable threat asteroid to the implementation of a coordinated response that includes effective global participation.

Some specific steps that could be initiated include:

- Increase international involvement in NEO surveys, enabling detection sensitivity down to 100 meter diameter and more precise location of specific "high-risk" objects
- Establish an authoritative, credible, international clearinghouse of NEO threat object information and NEO mitigation options
- Conduct more detailed studies of the economic, social, and political consequences of an impact.
- Organizations dedicated to the NEO threat should engage international disaster relief organizations to develop full-spectrum response templates for a range of impact scenarios

.

Chapter 6: BEHAVIORAL FACTORS AND PLANETARY DEFENSE

Very few people claim an intuitive understanding of astrophysics, but since everyone has to get along with one another, many people fancy themselves as experts in the behavioral sciences. Matters approached intuitively by most people are approached more scientifically by behavioral scientists. They assess hypotheses in light of the available evidence, discover how people typically act in given situations, and seek combinations of conditions that are likely to yield healthy, effective behavior. A thorough understanding of behavioral factors will aid with planning, preparing the public, withstanding the event itself, and rescue and recovery work. The purpose of the present chapter is to begin outlining some of the behavioral issues whose resolution will increase our ability to withstand a NEO threat or impact.

At the outset we acknowledge that many people are resourceful, hardy, and resilient. Contrary to popular belief, as Helsloot and Ruitenberg point out, citizens do not panic in disaster situations. [1] Rather, they act rationally, and more lives are saved by average citizens than by disaster relief workers. Auf der Heide presents strong evidence against widespread expectations of panic, lawlessness, and helplessness.[2] Many of us are aware that during the World Trade Center disaster in September 2001, people within the disaster area selflessly helped one another, sometimes at risk to themselves, for example by taking time to carry a person in a wheelchair down many flights of stairs.[3] This type of pro-social behavior has been typical in disasters throughout the world. Other examples include the German response to the dreadful air raids over Hamburg and the Japanese response following the explosion of the atomic bomb in Hiroshima.[4] We see many pictures of these devastated cities, but few descriptions of how effectively and quickly local relief teams were able to get help for survivors and restore essential services. In Hiroshima, some electrical and rail service was restored within a day. One of the unfortunate consequences of exaggerated fear of panic is that authorities may withhold information that they think will lead to chaos when in fact it would promote sensible, self-protective acts.[5]

Disasters are common. John A. Cross catalogued 38 major disasters that occurred between 1990 and 2001. Eleven of these involved over 5,000 deaths, and the most severe claimed 135,000 lives.[6] Of course, this does not count many highly localized disasters or those in rural regions that claim few lives. Each year approximately two million households are affected by disaster. Since we have had had much experience with hurricanes, earthquakes, tidal waves and other “everyday” disasters we look to these as prototypes for understanding NEO threats. There is a long history of using analogues to understand cosmic matters. Drawing on historical analogues to forecast human reaction to the discovery of extraterrestrial life and or conducting research in Antarctica to better understand human adaptation to space are two examples. Yet analogues are imperfect as there are some substantial differences between hurricanes, or tornadoes, and NEO impacts.

First, although it is possible that there will be little or no warning time, under most scenarios we will know well in advance when (and to a lesser extent where) the strike will occur. There are enormous implications for planning if the strike hits a major metropolitan area, which is likely to suffer the most casualties and economic losses, as opposed to a smaller city or rural area where immediate losses are lighter but there is less capacity to rebound. Second, while a NEO strike could be of any magnitude, there is potential for a global disaster, conceivably an extinction level event. Finally, because of potential after effects such as the equivalent of a nuclear winter, we cannot expect the post-disaster environment to return rapidly to its previously normal state.

Usually even the largest catastrophe is limited in the sense that there is a convenient adjacent "safe zone" which provides a staging ground for rescue efforts as well as a safe haven for escapees. Yet, in a major NEO impact, supposed "safe zones" are problematic. Predicting likely reactions to nuclear devastation, Allen noted that "unscathed" areas are likely to be flooded by refugees, suffer from disrupted communication and transportation systems, and, after an initial period of altruism and sharing, become hotbeds for black markets and hoarding.[7] In the case of a global disaster – one that affects everyone but not necessarily to the same extent – no country will be in a position to provide much relief to other countries.

As we apply the tools of behavioral science to plan for disasters that could beset any part of the globe – or many parts, simultaneously – we must remember that not everyone accepts scientific interpretations of disasters nor welcomes scientific remedies. It will not be possible to warn and assist people from different cultures without understanding their interpretations of the situation, their felt needs, and the services that they believe will help. For example, the kinds of psychological healing techniques that work well in prosperous and scientifically literate countries (counseling, structured debriefings, support groups) may not be effective among Pacific Islanders where dancing, prayer, and commemoration may have greater benefits. The programs that we expect to work well in some societies may do poorly in communities that resort to supernatural interpretations, especially if on theological or other grounds they feel helpless and resigned to their fate, or feel guilty for having in some way brought on the catastrophe and consider themselves obligated to expiate their perceived sins to avoid a recurrence. For example, Christian clergy on Cook's Islands interpreted a recent typhoon as the wrath of God brought on by unspecified transgressions, an interpretation that interfered with the healing process.[8] Such interpretations are not limited to pre-industrial societies that lack scientific explanations but occur also in modern, technologically advanced societies. "In many disaster prone regions" writes David K. Chester, "religion is an essential element of culture and must be carefully considered in the planning process, and not simply dismissed as a symptom of ignorance, superstition, and backwardness" (p. 319).[9]

So far, relatively little has been written about psychological and social factors in managing and surviving NEO impacts. A notable exception is a 2000 paper by Garshnek, Morrison, and Burke.[10] These authors note it makes little sense to prepare detailed plans for relatively small impacts that do little damage and can be managed by normal rescue and relief agencies, nor does it make sense to plan recovery from extinctors that leave Earth as an ash-covered cinder. Rather, we should prepare organizationally and psychologically for a broad intermediate range of disasters, where foresight, preparation, and training can make a difference. Following their lead, this paper is organized along pre-impact, impact, and post-impact issues.

1. Pre-Disaster Phase

We know of past NEO impacts and expect others in the future. So far, these predictions gain scant attention because they are very low probability and are unlikely to be confirmed. The pre-disaster phase will become meaningful when the probability mounts and the date and then location are confirmed. As the implications of being in a true pre-disaster stage sink in – as the problem becomes acute - we can expect planning to begin in earnest. In the absence of an educational and political program that encourages beginning right now, planning may be too little and too late. But for several reasons it will be difficult to interest political bodies, non-governmental organizations, the military, science organizations and other potentially helpful partners to begin at once, partly because people see the threat as in the distant future. People in the United States, for example, are notorious for their inability to adopt a broad time perspective.

Serious planning will be resisted by critics who ignore or deride low probability high-impact events. Practical people, those who lack foresight and are absorbed by the immediate here and now are not likely to be particularly interested in a problem that is unlikely to materialize within their lifetimes. Sensationalized and rapidly abandoned dire predictions coming from unskilled professionals or based on sloppy analysis do little to ease the situation.

The very idea of an asteroid or comet impact has a certain "science fiction" ring to it, and will be associated in some people's minds with millennial cults and end of the world prophecies. The *giggle factor* refers to the raised eyebrows, stony silence, ridicule and laughter that are attached to ideas and projects that fall outside of the range of mainstream science. This factor reflects a mix of pre-existing beliefs, data, ego-defensiveness and professional norms, and diligent efforts on the part of granting agency gatekeepers. One way to minimize the giggle factor is to highlight top scientists in the planning effort as this will encourage other scientists to come aboard.

Relatively low probability disasters come to the attention of policy makers and become part of the agenda as the result of *focusing events*.[11,12] These are infrequent, sudden and harmful events that become known to the public and to the government simultaneously. As attention-grabbers they initiate a major push on the part of the public and the elite to "do something" about redressing the situation and preventing its reoccurrence. A hurricane, earthquake, major oil spill or technological catastrophe generates a "spike" in interest that peaks in a few weeks in the media and in a few months in governmental deliberations. Typically it opens a two year window of opportunity for preparing for similar disasters, a window that closes slowly in the absence of another focusing event.

Progress during this window of opportunity depends on the interest, organization, and activity level of scientists and "policy entrepreneurs" that have the organization and expertise to press the issue. Until recently there was little organized expert interest in hurricanes. For this reasons, discussions following a hurricane typically focus on relief efforts. Many skilled scientists and policy entrepreneurs are interested in earthquakes. Following this kind of focusing event, discussions turn to prevention and mitigation, not just relief. For instance, earthquake-resistant buildings have become a part of the public agenda while hurricane-resistant buildings have not. Because of the high level of interest of geologists, engineers, and safety experts, the United States had a National Earthquake Hazard Reduction Program while until recently there was no coherent overall program to deal with hurricanes. Thus, a (hopefully minor) focusing event coupled with an organized and scientifically-oriented advocacy group that can analyze the disaster and offer convincing recommendations could go a long way towards promoting sustained and effective planning for a NEO threat.

The media will have many and profound effects on both planning and disaster relief. The media could prove useful for educating and informing the public. Accurate reporting would help people make realistic assessments of the developing situation and find ways to take self-protective action. On the other hand, sensationalized or inaccurate reporting, foolish editorializing and other unprofessional practices can cause harm. The media has a field day with people who cry wolf, first by exaggerating and publicizing their claims and then by leading the attacks on the fallen prophet. A reporter's failure to distinguish between real and self-styled experts; a tendency to focus on interviewees who are overly fearful or defensive; the difficulties inherent in presenting complex, multidimensional stories, in a cogent and understandable manner; a thin and eroding line between fact and fiction; and the temptation to offer "instant closure" are among the forces that work against the effective distribution of reliable and useful information.

1.1 Emotion and Reason

Inevitably people will experience fear and anxiety in the pre-impact period as the authorities and communities prepare for the predictable arrival of the NEO. *Fear* is attached to the anticipation of the actual event and its consequences: injury or loss of life, loss of dwelling and possessions, disruption of social relationships, and loss of means of livelihood. *Anxiety* is vague and non-specific and has its roots in personal inadequacies and insecurities and anticipated adverse reactions from others. Fear is the more helpful response, while anxiety causes a frantic search for non-existent magic remedies. Fear can be countered or channeled along positive lines to some extent by the early promulgation of factual information by authoritative agencies such as those that responded after the 9/11 terrorist attacks on the World Trade Center in New York and the Pentagon. Unless it reaches overwhelming proportions, fear can be helpful by motivating people to learn the actions that they can take to avoid or minimize the harm. Concrete, specific, compelling instructions coming from credible authorities will help with this.

In contrast the reduction of anxiety requires more of a personal and sustained effort. In the meantime those at risk will be prone to the entreaties of charismatic leaders of fringe cults who dictate policies with religious fervor that promise survival in this world or the next. Some might be persuaded to hunker down with strategic reserves behind fortifications to isolate themselves and keep others at bay, or dutifully to follow instructions to commit mass suicide – as happened most notoriously in November 1978 at the Peoples Temple in Jonestown, Guiana – or even to allow themselves to become victims of systemic murder as came to attention recently in Buhunga, Uganda and a few other countries. In a bizarre but nevertheless tragic occurrence in March 1997 in San Diego California, 39 members of the Heaven's Gate cult were led to believe that the approaching comet Hale-Bopp shielded a vehicle that would transport them spiritually to join a spacecraft of aliens. They were convinced that they represented the next stage of human evolution that required them to be on standby to be called to outer space for reincarnation, and that the crucial summons would come with the destruction of the Earth at the turn of the 21st century. To prepare for such eternal life 18 of the men were castrated, and both sexes were dressed in identical unisex clothing, with their travel bags packed, before they committed suicide.

We must avoid the temptation of thinking of wise, dispassionate scientists and policy makers generating flawless rational decisions to benefit the masses. Certainly intelligence and training help, but even the best of us rarely achieve perfect rationality. Rather, we are hampered by limitations in our knowledge of the situation, and in our information processing power. Like everyone else scientists, policy makers and leaders can be swayed by emotions and succumb to social pressures.

The seminal work of decision-making under stress by Janis and Mann illustrates how emotional factors can reduce the quality of the decision-making process.[13] A high quality decision requires developing a full range of options and remaining open to new information right up until that time that a decision must be finalized. There are many ways that this strategy is defeated. Sometimes lazily we stick with the status quo, failing to probe for weaknesses in the favored plan or to seek alternatives. For example, on the basis of skimpy information, the US Weather Bureau badly assessed both the direction and strength of a hurricane that ravages Galveston just over a century ago.[14] Contradictory information that would have shown that the city was at risk was either ignored or twisted in such a way as to fit initial predictions. The situation was exacerbated by the fact that the Bureau refused data from Cuba that would have established the strength and the path of the storm; the Cubans, some of whom were excellent meteorologists by the standards of the day, were seen as “too emotional” and too prone to exaggerate risk to take seriously.

A second danger is that after overcoming inertia, we may latch on to the first viable alternative without properly probing its weaknesses, or evaluating what will be lost by abandoning the initial strategy. This pitfall is exemplified Hitler’s snap decision to abandon the eminently successful Blitzkrieg war of motion to stagnant trench warfare in siege of Stalingrad, a decision that rested upon a gross overestimation of the Luftwaffe’s ability to supply the isolated Sixth Army.[15]

A further problem arises when there is little hope that the problem can be solved. In this case we fail to address the issue, at least in meaningful and potentially fruitful ways. This is typified by denial, rationalization, buck-passing, and preoccupation with other matters. In an organizational setting, the problem may be “kicked into administrative orbit.” Procrastination, dithering, joking around and other wasteful activities take the place of effective planning.

The fourth danger is panicky, ineffective decision-making prompted by extreme time pressures. This was exemplified by U.S. President Ford's 1976 decision to inoculate the US citizenry against the swine flu. This snap decision was based on an overestimation of the flu's lethality (initially it was reminiscent of the deadly Spanish flu of 1918), a failure to recognize that pharmaceutical companies could not manufacture enough high quality vaccine within a very limited time, and a failure to foresee that the effort would trigger innumerable lawsuits.[16]

1.2 Organizational Considerations

Organizational structure, culture and process also affect planning efforts. Organizations vary, for example, in terms of their conformity pressures, openness to new ideas, internal politics, external affairs (relationships with the government, the public, and other organizations) and the ability to complete necessary work in a timely manner. Of interest here are *High Reliability Organizations* or "HROs" as described by Mason.[17] In these performance and success driven organizations, safety, respect, honesty, and fairness are integral. They are "mindful" in the sense of continuously looking for the unexpected and taking it into account. Contrary or annoying news is embraced rather than ignored. Knowledge and expertise are valued highly and encouraged to flow to wherever need be. As much as possible, operations are "out in the open." Truth is more important than reputation, and there is limited use of secrecy, confidentiality, and cover-up. There is a refreshing lack of the kind of excessive self-admiration and exaggerated pride that turn self-confidence into arrogance and encourage people to think of themselves as somehow above the rules.

Dynes argues that the story of Noah's Ark has for centuries influenced views of disaster and disaster management and even today encourages the development of powerful, centralized forces to keep rioters and looters in check.[18] Whereas we may be drawn to establishing new, highly centralized, powerful agencies we should not overlook the advantages of localized planning and relief agencies. Remember that it is those people who are already within a particular area that will be the first to provide other people with help - it was other passengers, not emergency service workers, who provided first aid after the London Underground bombings of 2005. "Locals" understand the geographic region and are usually good at accessing the resources that are available to them. Locals can operate within the prevailing culture, and have immediate, first hand knowledge of the unfolding of events. Encouraging people to help fellow community members demonstrates confidence in peoples' abilities to help themselves, reduces logistics costs, eliminates the need for translators, and avoids overburdening an area with superfluous aid. However, this should not be construed as discouraging coordinated action. There are advantages to finding or developing organizations that help coordinate many different agencies and serve in a facilitative role. "Low-key" overall coordination was very effective during recovery from 9/11, minimizing conflicts of interest, reducing redundancy, and bringing many different sub-communities into the healing process.

Another issue is the relationships among different organizations. Whereas it might seem that they are united in pursuit of a common goal, apparent collaboration may obscure hidden agendas, rivalries, and the interest in garnering resources. Additionally, different organizations may favor different technologies that do not mesh synergistically. This could occur, for example, if two sets of rescue workers were unable to communicate with one another because their respective radios did not operate on the same frequency. Similarly, differences in procedures each organization takes for granted can imperil communication or lead to delayed or flawed decisions. An example here would be when one field representative has to consult with a superior, while another is encouraged to make on-the-spot decisions. There are many other potential problems associated with a lack of coordination, such as food and medicine rotting at an assembly point because the drivers are not available to deliver them.

We suggest that five core values serve the interests of disaster planning and management. The first is *empathy*, or the ability to relate to people within the disaster area. Empathy discourages the mindless application of rules, for example, refusing to issue rescue equipment on the grounds that it might be damaged, keeping workers and supplies from entering areas that are occupied but "too dangerous," and prohibiting the only physician who is present from administering artificial resuscitation because he is not government certified. The second critical value, *trust* is a sense of confidence in partner organizations and in residents of the disaster area. People can and do misbehave, but the "starting position" should be that people are rational, civil, and efficacious, rather than irrational, criminal, and helpless. The third critical value, *sensitivity to differences*, is recognition that disaster management requires working with many different political and ethnic groups. We have to understand how a NEO threat seems not just to ourselves and the scientifically literate public, but also to children, oldsters, and people who are often overlooked because they are marginalized or physically isolated. The fourth critical value, *openness*, is expressed in the recognition that pre-set plans may fail when they are put into action; that facilities or rescue personnel may not quite be up to the job, and that seemingly innocuous problems may cascade out of control. The final critical value, *flexibility*, is reflected in the capacity to respond creatively and quickly to changing conditions. Flexible organizations are not hopelessly burdened with rules and procedures, bureaucrats with meaningless assignments, and blocked information channels.

1.3 Warnings

There is a reliable body of evidence regarding warnings and their effectiveness; here we draw extensively from a paper by Miletti and Peek.[19] First, the warning must reach potentially affected parties. The warning has to gain attention against the many competing demands and general noise level of daily life. (For example, a siren is unlikely to be heard if winds are already very high). It is important to communicate both the nature of the risk, and the consequences for the individual. As much as possible warnings should provide accurate descriptions of magnitude, location, and timelines, goals that may be difficult for us to achieve.

The risk must be made understandable to everyone who faces it. Terms must be clear and as much as possible unambiguous: although we may have to deal with probabilities we need to be aware that the same probability that one person takes as "minimal" another person considers all but certain. Repetition helps, but there is no need to follow the lead of commercial advertisers who assume an attention span of 30 seconds. People are interested in events that can affect them adversely and tend to seek additional news.

The message should be presented by credible sources. Since different people assign different degrees of credibility to different sources – for example, scientists, governmental leaders, religious leaders, and political action groups – it will be best if many sources converge to get the same message across. Consistency is important (both within a message and across different messages), but we should not be surprised if some media sources undermine this by publicizing self-proclaimed experts who stoutly maintain idiosyncratic points of view. Furthermore, the warning should be delivered in such a way that the speakers give the sense that they believe in what they are saying. Credibility, certainty and consistency are important if we want people to take self-protective steps.

If residents of the disaster area or refugees are empowered to make decisions and informed about the conditions that confront them, they will feel better protected than if they feel helpless or ignorant. Personal choice and commitment enhance responsibility and strengthen intentions to take protective action against impending disasters.[20] Educational efforts will have to inform people from very different demographic and cultural backgrounds. [21] Furthermore, as DeMan and Simpson-Hously point out, people "select, organize and interpret information about the hazard, and, rather than relying on objective information provided by environmental agencies, they draw conclusions which are meaningful to them but not necessarily congruent with the true nature of the hazard (p. 280)."[22]

2. Impact

Almost all of the many ways that people are injured and killed during natural disasters could apply in the case of a NEO impact. These include pulverization, incineration, and entrapment including live burial, asphyxiation, drowning, and electrocution. The term "casualty" is preferred to the term "victim" because the latter implies defeat and resignation and diverts attention from what residents of the disaster area can do to better their own lot. The most obvious casualties are those that experience the direct physical trauma and these appear in two waves: first, the injured that are nearby the rescue site and second, victims that arrive from the hinterlands. But there are also casualties from the destruction of the infrastructure including pipelines, power grids, food distribution systems, water lines, schools, and so forth. Even after basic services are restored people may have lost their means of livelihood so secondary casualties may emerge long after the event.

2.1 Psychological Casualties

Anxiety and fear, a sense of being "scattered" or unable to focus, memory problems and "difficulties with decisions" are likely to be pronounced during the disasters themselves. Under acute stress, behavior becomes energetic which is very useful if the person knows what to do (i.e., a well-trained soldier springing into action). However, if there is no clear goal the person may become disorganized and ineffective.[23] Increasing anxiety, a loss of resourcefulness and the perseverance of ineffective behaviors intensify a state of "mental crisis" which is self-sustaining and self-amplifying. The inability to allocate attention to peripheral but potentially important aspects of the situation increases the stress, which further restricts focus and encourages repetitious ineffective behavior. Thus, in emergency situations that demand resourcefulness and creativity people may find it difficult to scan alternatives, find new goals, and initiate or implement a new plan of action. Certainly many other disaster sequelae work against good decision-making processes. These include physical pain, hunger and thirst, almost certainly physical and mental exhaustion, and psychological trauma.

We may expect many forms of psychological trauma in the days leading up to and following impact.[24, 25] Some of these are considered serious and incapacitating. In the *acute stress reaction*, which typically lasts a few weeks, people feel overwhelmed or unable to cope. This may be accompanied by other stress-related physical systems such as insomnia, headache, abdominal pain, chest pain and palpitations; acute anxiety or depression, sadness, worry, increased use of alcohol or other substances. In the widely known *post traumatic stress disorder*, casualties continue to live in the emotional environment of the traumatic event, with enduring vigilance for and sensitivity to the threat. Principal features include persistence of startle response and irritability, proclivity to explosive outbursts of aggression, fixation on the trauma, constriction of the general level of personality functioning, and atypical dream life. In addition, hyper-alertness, hyper-reactivity and traumatic re-experiencing have been documented in a vast literature. Finally, there is severe depression - a sense of helplessness and hopelessness and inner-directed aggression, adversely affects thinking processes, makes life not seem worthwhile. All of this will be complicated by the bereavement process for those survivors who themselves lost family and friends.

Reviewing the work of Robert J. Lifton and others, Hodgkinson and Stuart summarize common indicators of disaster-related psychological trauma.[26] Many survivors are imprinted with indelible imagery of their encounter with death. Intrusive scenes of death and destruction intrude when the survivor is awake, as well as during dreams. There may also be a "psychic numbing." In a sense, the person's emotional life is shut down to stop the psychological pain. In these cases, the person may appear "calm and collected" but this only because they are not processing the disaster at an emotional level. Feelings of guilt are common, these stem in part from ruminating over existential questions (Why did God choose me to survive?) as well as from a sense that they did not do all that they could to help other people. Guilt can be particularly severe for survivors who are also bereaved. It can be exacerbated by shame, a sense that because of their failure to "do enough" they are held in low regard by other people. On a more positive note, after overcoming the immediate effects psychological casualties may re-visit great existential questions. Why did God let this happen? Why was I allowed to survive? What does this say about religion and morality? Activities that were formerly enjoyed – work, hobbies – may be redefined as meaningless. This quest for meaning places the experience into a larger philosophical and religions framework and may cause a shift to a new worldview.

Reactions to trauma vary over the life cycle and special attention must be given to the trauma of children. Children are likely to be more vulnerable to certain types of physical trauma due to their small size and limited strength. For example, because they are short they are more susceptible to aerosols that concentrate close to the ground, and because they have relatively large surface area relative to body mass they are highly susceptible to cold. Common psychological symptoms among children include regression to earlier modes of behavior such as thumb-sucking and bed-wetting, clinging to parents and other behaviors suggestive of a fear of separation, concern that the event will happen again, social withdrawal, crying and screaming, and sleep disturbances including insomnia and nightmares.[27] One study of preschoolers 14 months after a hurricane showed that in comparison to children who had not been exposed the victims showed higher anxiety, greater withdrawal, and more behavioral problems, although the behavioral problems decreased steadily over the first six months after the earthquake.[28] At least one study found that children are less distressed than their parents. A study of survivors of an earthquake in Turkey found that worry, depression, psychosomatic complaints, and perceived lack of control were higher among parents than among children. [29] Many of the recommendations for minimizing psychological casualties among children revolve around providing a good model, offering honest and understandable interpretations, spending extra time with one's family, maintaining a balance between flexibility and discipline, and praising positive behaviors.

2.2 Disaster Workers and Their Families

Disaster workers and their families are exposed to multiple stressors.[30] Oftentimes, disaster workers are called up on short notice. They usually live under primitive conditions without good communication with home. The disaster environment itself is strange and foreboding and may be quite dangerous. Disaster workers deal with corpses, and screaming mangled victims. They must work also with psychologically traumatized and bereaved people who are disoriented, uncooperative, and perhaps angry. The workload is heavy and may include intense time pressures, perhaps brought about by the need to extract survivors from buildings before they asphyxiate and transport people who are hovering on the brink between life and death to emergency medical facilities. Although disaster workers may be unwilling to take breaks and thus push themselves to the point of exhaustion they nonetheless feel guilty about not having done enough to alleviate other people's suffering. They may become quite resentful of spectators, journalists, and other "time-wasters."

It is important to identify the dead in order to resolve uncertainty and then facilitate bereavement on the part of the survivors. Health professionals have begun to unlock the taboos on disaster victim identification, with Keller and Bobo studying the aftermath of the terrorist attacks on the Pentagon, and Stehr and Simpson doing the same for on the World Trade Center.[31, 32] The Pentagon study was based on the descriptive reports of uniformed health care workers with an almost universal lack of experience in handling human remains. They were said to have displayed remarkable variability in emotional reactions and coping strategies before, during, and after exposure to the remains. These mechanisms included emotional detachment and the use of "black humor." The World Trade Center review focused on the organizational aspects of dealing with mass casualties and victim identification. It concluded that emergency planners must now be prepared to plan for events that include thousands of casualties and fatalities to initiate planning and emergency drills, paying attention to information management and communication, and to responder education and training, and to give consideration to a number of research matters.

Families of disaster workers recognize many of the pressures on rescue workers and worry about their welfare. These worries are likely to be enhanced by intermittent nature of the communication, reflecting poor lines of communication and a felt sense on the part of the disaster workers that they should "keep going" and not take time out to reassure their families. Sleep deprivation takes a terrible toll on performance. Disaster workers are likely to return home exhausted and with many conflicting feelings: happiness at having contributed to the rescue efforts, sadness over the death and destruction, and guilt and anger at not having been able to do more. The returned disaster worker may be somewhat introspective and uncommunicative and experience difficulties in the course of becoming re-integrated into the family. A thorough debriefing, the opportunity to work through strong emotions and social support are among the tools that can ease tensions and facilitate reintegration.[33][34]

2.3 The Public

Widespread death and destruction challenge everyone's assumptions about a just and fair world as well as serve as potent reminders that nobody is invulnerable. These effects may be stronger closer to the disaster's epicenter than further away, for example, people in North America may be more disturbed by a disaster that occurs in New York or London than by one that occurs in India or Rwanda. Yet, within North America were there any geographical limits on people who were at least briefly traumatized by the events of 9/11? As a major event that challenges everyone's sense of security we can expect psychological distress among the public, including people who have no direct ties with residents of the disaster area.

In his review of studies of vicarious grief, Chochinov points out that public grieving is related to global visibility and media coverage.[35] People who identify with the victims are more affected than those who see the victims as dissimilar to themselves. The setting makes a different, for example, more people can relate to being in an office tower or on a beach than in a submarine or spacecraft. Sudden, dramatic events, such as the crash of a jumbo jet, are more upsetting than chronic events such as a string of automobile accidents that leads to a far greater loss of life. He writes:

"In total, about 6 million people die of AIDS, tuberculosis, and malaria each year - over 16,000 preventable deaths a day. Yet, ubiquitous chronic tragedies do not seem to move people the same way as those that are sudden or dramatic. Besides the acute and intense media attention that the latter receive, there is the issue of imagination. Whilst most westerners can readily evoke images of sudden disasters, the prospect of dying from a chronic illness in the sub-Sahara lies beyond imagination" (p. 697).

In North America and much of Europe people enjoy a strong economy and a high level of security. Disasters and other unhappy events tend to be highly scrutinized, and often sensationalized, by the media. Generally, people in such economies are prepared to spend massive amounts of money to reduce casualties. We find national grieving for local catastrophes such as the massacre at Columbine High School in the US. We cannot expect people from such a society to adapt easily to the loss of hundreds of thousands or even millions of their fellow citizens. On the other hand, we have to make sure that our efforts to provide grief counseling and other services for the general public do not inadvertently cause minimally affected people to redefine themselves as victims.

Media's efforts to make the event "indelible" can make matters worse.[36] In brief, after a disaster people turn from entertainment to serious news discussions. Repeated broadcasts of "signature" or focusing events (an airplane hitting a building, a tidal wave smashing ashore) create stress and symptoms of neuropsychiatric dysfunction in viewers. There is a self-selection problem (people who are already experiencing mental health difficulties may be particularly likely to develop new symptoms) but for adults and children, more TV coverage means more people afflicted with more and stronger symptoms of psychological distress.

3. Post-Impact

Recovery begins with the first adaptive reactions to the disaster and continues through restoring the infrastructure. Typically, recovery involves four phases. In the initial or *heroic* phase, community members help one another long before outside assistance arrives. During the *honeymoon* phase there is high optimism based on promises of lavish outside support. And, indeed, such support sometimes materializes although there may be problems due to spoilage or difficulties getting the supplies into the hands of the needy. The third phase is *disillusionment*, resulting from a combination of internal dissension, a sense that the outside world has not done enough, or the putative benefactors exact too high a price for the aid. Finally, the, *Restabilization* phase is entered when the catastrophe is surmounted and becomes part of the communal culture.[37]

3.1 Triage

By definition, disasters exceed our capacities to respond. We have to leave many people unassisted so that rescue efforts can proceed in the most useful directions. A position statement issued by the American College of Surgeons points out that in such situations surgeons have to shift from the application of unlimited resources for the greatest good of each individual patient to the allocation of limited resources for the greatest good of the greatest number of patients.[38]Authorities and rescue workers will have to make difficult choices, withstanding media assaults and bitter reactions on the part of individuals and the public as a whole. And, in a large-scale disaster, we may be forced to rethink our propensities to assign blame and entertain litigation. One of the unfortunate consequences of the swine flu inoculation program was a long parade of lawsuits, dissuading manufacturers from further participation in emergency widespread inoculation programs.

In medicine, triage is the accepted procedure when health services are overburdened with the sick and the injured and medical personnel are required to make life-death decisions in order to allocate medical resources wisely. In order of declining priority the triage categories identified by the World Health Organization are: (1) *Immediate* - the victim requires immediate attention to live; (2) *Delayed* - the victim can wait for treatment without unduly compromising a successful recovery; (3) *Minimal* - the victim can do without aid or can be redirected to another station or care facility, and (4) *Expectant* – even with good treatment the victim is so unlikely to survive that medical resources are better used elsewhere.[39]

Life-death decisions have been made on the basis of moral values or a sense of what's "right." for example, women and children first. There are also practical considerations giving the nod to powerful and influential people, presumably because they are seen as more useful than other candidates. Thus, in the event of an impending nuclear attack, the US government had plans to whisk top leadership to a secret shelter hidden below a world-famous Virginia resort. There, they could button up and survive the nuclear winter. Few people would be shocked or surprised when government leaders and their families are delivered to safety at the outbreak of a war, but they may not look at the situation with the same level of equanimity if a neighbor is saved because of her medical skills while they themselves are expected to sit out the Tsunami on the roof of their house.

Need is an important factor related to receiving help in a disaster.[40] Severely stressed people do, on the whole, receive greater aid. In keeping with principles of evolutionary psychology, people are more likely to provide aid for next of kin and members of their own communities. On the whole, though, females, younger victims, married persons and more educated people receive more help than are males, older people, and single people. In some societies whites receive more help than do blacks. There is, in effect, a “pattern of neglect” that disadvantages minorities, the uneducated, and people who are not financially well off.

3.2 Psychological Support and Therapy

Although it may take more than a "few days in the country" to eliminate the last vestiges of psychological trauma, to some extent immediate pressures can be reduced by transport to (or restoration of) a safe secure environment, and by rest. (Few people recognize the devastating psychological and performance effects of cumulative sleep deprivation.) Pharmaceuticals that counter fatigue, calm emotions and increase focus may be of use but these are by no means a panacea. Oftentimes their success depends on very careful diagnosis, and on titration to insure proper dosage. Psychotherapy can reduce fear, grief and other emotions so that the casualty can be restored to some semblance of his or her normal life. Goals included abreaction (expressing emotion), education to help people understand that their reactions are natural, and cognitive restructuring, which essentially involves redefining the event within a framework that reduces fear and guilt. In a disaster situation forget about the psychoanalyst's couch: there will be no time for expensive, time-consuming forms of psychotherapy. Rather, rescue workers will have to rely on relatively simple and cheap approaches that can be applied quickly to large numbers of people. Psychological services should be proximate (readily available) and fast. Many techniques are available, but few of these have been validated in disaster situations that might approximate a NEO impact. As Raphael and Wooding point out, "although the advances of medicine have done much to develop effective and life-saving emergency interventions and more rapid healing processes, the search for emergency mental health measures has been more problematic."[41] Clearly, here is an opportunity for more research.

3.3 Survival Communities

In the event of a severe worldwide catastrophe the foremost life-death issue is whether or not enough people can be protected to assure continuation of Homo sapiens. This might be possible through establishing a series of well-provisioned community shelters that people would enter prior to the impact and exit much later, perhaps as much as two years later if the impact led to a nuclear winter. Accomplishing this would require wrestling with four enormous issues: authority, criteria, implementation, and acceptance.

The first issue in developing a survival community is the issue of authority. Who speaks for humankind? Who decides who lives and dies and shapes post-impact society? Should government-sponsored survival communities be under the control of international, national, regional, or local authorities? Could such communities be established in an open and above-board matter? What is their relationship to unofficial survival communities perhaps set up as a commercial venture or volunteer efforts? Should commercial communities and communes be regulated?

The second issue is selection criteria. That is, what are the criteria for choosing who lives and who dies? These criteria will reflect the number of people who can be offered maximum protection and the mix required to ‘restart” society. The size of these communities may be limited by our estimates of the number of people that Earth can support following re-emergence. These criteria must reflect the needs of post-impact society, not society as we think of it today. For example, the most useful prospects might be couples that are willing to have large numbers of children, or who are into hunting and gathering or simple forms of farming, skills that are not in high demand in much of the modern world.

Implementation requires finding appropriate secure locations, constructing and stocking shelters, ensuring that the people who are entitled to be at the shelter are present and accounted for, ejecting stowaways, and maintaining law, order and morale during the period of confinement. There is an extensive literature on life in isolation and confinement, and the study of life in polar outposts, submarines, underwater research vessels and space stations can inform our preparations for life during the button-up phase.[42, 43, 44]

Finally, there are issues of public acceptance and buy-in. Not everyone will believe that the authorities are making rational and fair decisions. Authorities may be convinced that they are making choices on the basis of people's skills, but if that leads to over-representation of people from North America and Europe, people from elsewhere may believe that the choices rested on religious or economic criteria. We can expect many spirited discussions flowing from diverse conceptions of equity and contrasting interpretations of intent.

As we contemplate survival communities we can find guidance from anthropologists, economists, sociologists and others that have explored ways to establish sustainable human settlements in space.[45] In some respects, post-impact Earth may resemble an off-world destination: a dangerous place bombarded with harmful forms of radiation, toxic atmosphere, and little or no useful vegetation. To some extent there are analogies between post-impact citizens coping with a nuclear winter and the first Martians coping with a dust storm, and both groups will be concerned with increasing the habitability of their respective planets. But in two respects the post-impact humanity will have the advantage. First, they are likely to exist in far larger numbers than early generations of Martians, and second they are likely to have access to more raw materials, such as materials that survived the disaster, and downed power lines.

From the space settlement literature we can make educated guesses about population increases and rate of recovery of the economy. J. B. Birdsell has described how small founding populations, on the order of ten people, have been able to survive for multiple generations.[46] A man, a woman and a child were the first arrivals on the main island in Tristan da Cunha, a 2.5 square mile lava bed. This was not an entirely closed community, but the population doubled over forty years, rising from three in 1817 to 95 in 1857. Six men and eight women settled Pitcairn Island, another tiny island but one with decent vegetation: this entirely closed society more than doubled over each of three generations. Again, on the Bass Strait Islands, a founding population of eight males and thirteen women doubled over the years eventually attaining a population of 345 before there were additional immigrants. In another case a lone male living as fugitive with "one or two" women was able to increase his family by a factor of five over two generations. Kenneth Wachter adds that it is not uncommon for Hutterite women to bear ten children during their reproductive years.[47] The actual growth rate following emergence will depend not only on lust and fecundity, but also on mortality rate, resource constraints, and the level of demand for luxury.

Hodges questions the viability of small communities, particularly if the goal is to rapidly move beyond a subsistence-level society.[48] Larger populations have the advantages of increased specialization of labor, and economies of scale. In smaller populations, people are forced to be generalists. Because they must know many different jobs they cannot know any of them in any detail. For example, the electronics technician, who is responsible for a broad range of devices, will only be able to replace modules, not undertake genuine repairs. The dentist, who is also the physician, environmental toxicologist and social worker, will find her dental practice limited to yanking teeth. Small communities cannot support specialists such as people who design computer chips or perform competent root canals.

Similarly, many of the luxuries that we take for granted are available to us at an acceptable price only because there is widespread demand. Hot tubs would grace fewer backyards if they were not mass-produced. Books that are profitable when published in English and accessible to hundreds of millions if not billions of English readers around the world would be entirely unprofitable if translated and printed in Danish and released to a market of perhaps 20 million people. Hodge's point is that as communities grow and gain strength, increased specialization of labor and improved economies of scale will make it possible to gradually regain the quality of life that so many of us take for granted.

Hodges offers the following overview of isolated communities. During the "button up" stage the isolated community's population remains relatively stable. It lives off stored up equipment and supplies. Stored supplies are likely to be used up sometime after emergence but before the survivors can re-establish basic industry. There are likely to be lean years following emergence from the shelter, and an increased sense of deprivation may accompany population growth. But then as farming is restored and basic industries are established, survivors will be less and less reliant on stores. At first, output will be low, which means that products will be scarce and expensive. Emphasis should be placed on building new means of production rather than to producing consumables. As basic industry such as agriculture and housing continue to grow, more complex industries begin producing such items as electric motors and power tools. As the population continues to grow it becomes possible to support "high tech" industries. Slowly, advanced technology and luxury items re-appear, but at a much higher price than during the pre-impact days. This is accompanied by greater specialization. It is no longer necessary for the dentist to work as a physician and social worker as well. Finally, with continued growth, the technological sophistication and quality of life catches up with and eventually surpasses that of pre-impact society.

Psychological problems and social conflicts may be kept under control during the impact stage but then "break loose" during the re-emergence stage. Hopes generated by looking forward to emerging from shelter will be overpowered by the realities of living on a dying planet. Problems will include the loss of family and friends, loss of employment, and loss of capital, wealth, savings, retirement and personal property.

Since they will function in isolation from one another during the worst of the nuclear winter, there may be some tendency for different communities to be separatist when they emerge from their shelters. They may have to interact with other groups of survivors who were not accorded government support. To reduce the risk of hostility, aggression, and destructive competition, we suggest imbuing a strong overall culture and make sure that these different communities remained in constant communication throughout the "button up" period.

Chapter 7:
POLICY IMPLICATIONS

1. Introduction

As the body of scientific evidence grows that past encounters with NEOs have had a major influence on the evolution of life on our planet, governments are obliged to examine the potential threat that future possible impacts can pose to our society. There is a need to assess our vulnerability to such events and to determine whether there are prudent and judicious actions that we should consider in order to minimize or mitigate their potential effects. Further, there is a need to establish a suitable policy framework to enable such actions to be undertaken when they are required.

Over recent years, we have learned a great deal about the asteroids and comets that strike the Earth. Every day, thousands of small (centimeter-size) objects burn up harmlessly as meteors in the atmosphere. Impacts of very large (multi-kilometer) NEOs have in the past been catastrophic but are, fortunately, extremely rare. Objects of intermediate size can cause significant damage when they hit the Earth at random intervals of hundreds or thousands of years. It is this relative infrequency, spanning many generations, which makes it difficult for governments to consider the NEO risk in a comparable manner to the more frequent natural hazards that we are familiar with, and which are therefore of a more immediate concern to the public. The consequences of NEO impacts however can be much more severe than those resulting from earthquakes or extreme weather events, although a great deal can be done to prevent some of the impacts (which can be predicted many years ahead), and to reduce the damage of others significantly, provided timely actions are undertaken. It is this combination of the potentially catastrophic scale, the predictability of the events, and the ability to intervene which obligates governments to set in place a framework to address the NEO threat which complements the existing response to meteorological and geological hazards.

The mitigation of large-object impacts must begin with detection. To prevent impact, larger asteroids have to be identified many years before the collision, allowing sufficient time for technology development and a possibly lengthy period of gradual deflection. Smaller asteroids are more difficult to detect, because they are very faint at large distances from Earth. Thus, a small object might be detectable heading towards Earth with relatively little warning. Even with little or no advance detection, some mitigation of the effects of impacts of small and medium -sized objects is still possible via existing emergency response mechanisms such as tsunami warning systems and evacuation procedures. Should any impactor be detected only months ahead of impact, deflection might still be possible via a direct high-energy intercept although the technology would need to be developed and ready to use.

Given the global nature of the NEO hazard and the scale of any effective response, it is unlikely that one country will decide independently to take action when an impact threat is identified. There must be international involvement in decision making and whatever actions are to be taken, as the consequences of action or inaction are unlikely to be constrained within a single territory. Thus any ultimate policy framework will need to be of an inter-governmental nature, requiring regional and international communication and cooperation between states. The governments of a small number of countries already have national policies which support programs to evaluate the risk from NEOs, and to detect one category of potential colliders: the large asteroids that, if they struck the Earth, could produce a global-scale catastrophe with billions of casualties. Many other governments have not undertaken any official actions related to the NEO threat, although, in some of these latter countries, scientists do participate in scientific NEO studies and observations. There are only a few administrators or offices whose responsibilities include dealing with NEO issues as they relate to public safety. This limited consideration of NEOs as a public safety issue is a source of consternation amongst many observers as they advocate that the response to the NEO issue should be consistent with the approach adopted for more familiar natural and man-made hazards that nations may encounter. They argue that the threat to life and property from NEOs, when averaged over long time periods, can be considered to be comparable to that from geological and meteorological hazards, and accordingly a commensurate level of response to NEOs should be established by governments.

While the probability of a NEO impact is effectively the same for all points on the Earth's surface, the magnitude of the risk is not the same for all countries. It depends, amongst other factors, on the country's size, population distribution, topography, economic infrastructure, proximity to the ocean, and vulnerability to other natural hazards (e.g., earthquakes). The evaluation of the NEO risk requires data and expertise from many scientific fields and other domains relevant to risk analysis. It is worth emphasizing however that NEOs do not recognize national boundaries and that the consequences of future impacts are unlikely to be isolated to any individual country or region. For this reason amongst others it is important that the policy framework which is established should encourage nations to work together to share data, expertise and resources to assess and mitigate the risk of a future impact, wherever it may occur on the Earth.

In looking for a formal response from government in relation to the NEO hazard, we also need to be realistic and pragmatic. The current surveys have demonstrated that a global-scale asteroid impact is not imminent, and so there are few immediate actions which need to be taken, the most urgent perhaps being the need to reduce the size threshold of detection of the survey programs to include objects which still pose a very significant threat to society should they impact the Earth. Instead we need to exploit existing policy platforms and infrastructures where appropriate, and bridge the gaps in capability (whether it be process or infrastructure) with specific actions related to NEOs. There is however a compelling argument for embarking on the establishment of a policy framework to address NEOs now. We need to use this finite window of opportunity, before a specific impact threat has been identified, to develop our policies in a balanced and objective manner. Experience has shown us that decisions made “in the heat of the moment” can be flawed, ill-judged, and compromised by subjective influences such as exposure to an impact threat (or lack of it). Mitigating the impact of a NEO will represent one of the greatest challenges ever posed to society, and the resulting technical solutions will be intrinsically coupled with wide ranging policy implications. We are obliged to ensure that a policy framework is set in place which will support these efforts rather than undermine them.

2. National Policy Background

United States of America

The activities within the USA have been extensively treated in previous chapters and thus will only be briefly summarized here.

- Two broad workshops on the NEO threat carried out in 1990-1993
- Formation of a NEO program office at NASA/JPL
- Initiation of the Spaceguard survey in 1998 to find NEOs 1 km and larger

- Report of the Science Definition Team in 2003, recommending extending the surveys to significantly smaller NEOs
- Congressional direction in 2005 on alternatives to detect NEOs larger than 140 m.
- NASA response in 2007 on survey alternatives, most of which would cost about $ 1 B

United Kingdom

In 2000, the UK Minister for Science invited a "Task Force on Potentially Hazardous NEOs" to make proposals to the Government on how the UK could best contribute to international effort on NEOs. The Task Force recommended that the Government explore, with like-minded countries, the case for mounting a number of coordinated space rendezvous missions based on relatively inexpensive microsatellites. It also recommended that together with other governments, the UK seek ways of putting the governance and funding of the Minor Planet Center on a robust international footing, including the Center's links to executive agencies if a potential threat were found.

The Task Force also recommended that the UK Government, with other governments, set in hand studies to look into the practical possibilities of mitigating the results of impact and deflecting incoming objects. In addition, the Task Force recommended that the Government urgently seek with other governments and international bodies to establish a forum for open discussion of the scientific aspects of Near Earth Objects, and a forum for international action, preferably covering science, impacts, and mitigation.

Finally the Task Force recommended that the Government appoint a single department to take the lead for coordination and conduct of policy on Near Earth Objects, supported by the necessary inter-departmental machinery. Finally it recommended that a British Centre for Near Earth Objects be set up whose mission would be to promote and coordinate work on the subject in Britain; to provide an advisory service to the Government, other relevant authorities, the public and the media, and to facilitate British involvement in international activities.

As a result, the British National Space Centre (BNSC) took on the role of promoting and coordinating NEO issues within UK Government. At a national level, BNSC set up links with the Cabinet Office Civil Contingencies Secretariat with the aim of establish response measures for NEOs, similar to those developed for the re-entry of man-made space objects. A number of studies were also initiated within academia, ranging from the development of quantitative tools to assess the impact risk to persons and property, through to techniques for the interception of hazardous NEOs. As the UK representative within ESA, BNSC promoted debate on NEOs within the Agency's International Relations Committee and supported a number of NEO mission studies within the Agency and the subsequent NEOMAP (Near-Earth Object Mission Advisory Panel) initiative. Within the developing space surveillance activities of the Agency, BNSC ensured that consideration of NEOs was included in the terms of reference for a possible operational surveillance system. Finally, BNSC set up a national NEO Information Centre to communicate NEO issues to the public and press, and to advise and inform Government. At an international level, the UK promoted discussion on NEOs within a wide range of fora, resulting in UK Chairmanship of the NEO activities within both the Global Science Forum (GSF) of the Organisation for Economic Cooperation and Development (OECD), and the Action Team and Working Group on Near Earth Objects within the Scientific and Technical Subcommittee of the United Nations Committee for the Peaceful Uses of Outer Space (UNCOPUOS).

Russian Federation

In February 2007, the Working Group on Asteroid-Comet Hazard was established within the Russian Federation. Governmental, research and educational structures related to NEOs within Russia are involved in this Group's activities. The group has been tasked with developing a *National Program for Asteroid-Comet Hazard Problem*, to include detection and remote characterization, orbit determination and cataloguing, consequence determination and mitigation of NEOs.

Japan

The Japan Space Forum (JSF) was established to coordinate an alliance of industry, government, and academia for the development of Japan's aerospace industry. JSF operates under policies established by the Japanese government and the Japan Aerospace Exploration Agency (JAXA) while providing support for research proposals and implementing programs designed to educate the public on aerospace issues such as NEOs. JSF was the recipient of grants from the Japanese Ministry of Education, Culture, Sports, Science and Technology, which were used from 1998 to 2004 for the establishment of the Bisei and Kamisaibara Spaceguard Centers in Okayama Prefecture, where scientists track asteroids and space debris with optical telescopes.

Germany

Scientists at the DLR Institute of Planetary Research in Berlin-Adlershof have been engaged in international NEO research for many years. Their work includes observation campaigns for physical characterization of NEOs using major ground-based and space-borne astronomical telescopes, maintaining a data base for physical properties of NEAs, risk assessment and impact mitigation, development of impact simulation tools and contributions to space missions to NEOs. DLR is in close contact with the German Federal Foreign Office to support activities of the Action Team and Working Group on Near Earth Objects within the Scientific and Technical Subcommittee of the United Nations Committee for the Peaceful Uses of Outer Space (UNCOPUOS).

Currently a major area of activity for Germany is observational work in the thermal-infrared spectral region with telescopes such as the Keck and the NASA Infrared Telescope Facility, both on Mauna Kea in Hawaii, and the NASA Spitzer Space Telescope. In addition to these research activities, an on-line data-base of physical properties of all known NEOs is maintained by DLR. Within Germany, various potential techniques for diverting asteroids and comets from a collision course with the Earth have been investigated and modeled. In the course of this work a software package to simulate a possible impact scenario and to determine an optimal deflection strategy has been developed. The formation of craters and associated effects of asteroid/comet impacts on the Earth, both on continents and on oceans, are currently being analyzed in a theoretical study involving advanced computer modeling and simulations. A major future participation for Germany in the planning of the Don Quixote mission is anticipated. DLR is also involved in other space missions to investigate minor bodies, such as Rosetta and Dawn.

The DLR Institute of Planetary Research has proposed the establishment of a German Spaceguard Center, which, like its existing counterparts in the US (JPL NEO Office) and the UK (NEO Information Center), should act as a link between research activities and the general public, convey scientific information in easily understandable terms to the public and government departments, and be prepared to support policy makers in administering German participation in international activities relating to the impact hazard and NEO mitigation plans. This proposal has been considered by the DLR authorities; a decision on establishing the Center was pending as of the end of 2007.

3. International Policy Background

The existing international policy is limited to a number of instruments calling upon states to consider adopting a range of voluntary measures related to the NEO issue.

Council of Europe

In 1996, the Parliamentary Assembly of the Council of Europe based in Strasbourg passed a "Resolution *on the detection of asteroids and comets potentially dangerous to mankind*": This Resolution:

"*..invited governments of member states and the European Space Agency (ESA) to give the necessary support to an international programme which would:*

- *establish an inventory of NEOs as complete as possible with an emphasis on objects larger than 0.5 km in size;*
- *further our understanding of the physical nature of NEOs, as well as the assessment of the phenomena associated with a possible impact, at various levels of impactor kinetic energy and composition;*
- *regularly monitor detected objects over a period of time long enough to enable a sufficiently-accurate computation of their orbits, so that any collision could be predicted well in advance;*
- *assure the coordination of national initiatives, data collection and dissemination, and the equitable distribution of observatories between northern and southern hemispheres;*
- *participate in designing small, low-cost satellites for observing NEOs which cannot be detected from the ground, and for investigations which can most effectively be conducted from space;*
- *contribute to a long-term global strategy for remedies against possible impacts. "*

The Resolution, aimed primarily at its members states (currently 47 European states with the USA, Canada and Japan as observers) was focussed on discovery, follow-up and characterisation but makes reference to consideration of a "*..strategy for remedies against possible impacts..*", a reference to the need to consider mitigation of the NEO hazard, whether it be deflection of the threatening NEO or evacuation of the area where it will impact.

UNISPACE III

The first wholly international instrument which made specific reference to NEOs was produced in 1999. During the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III) held in Vienna, participating states, through the so-called *Vienna Declaration*, stated that action should be taken:

"*To improve the international coordination of activities related to near-Earth objects, harmonizing the worldwide efforts directed at identification, follow-up observation and orbit prediction, while at the same time giving consideration to developing a common strategy that would include future activities related to near-Earth objects".*

A dedicated Workshop on NEOs held as part of the proceedings of UNISPACE III elaborated this action through the following recommendations:

(a) That the United Nations promotes education and information on near-Earth objects, especially in developing countries.

(b) That the United Nations take the initiative of inviting all Member States to support near-Earth object research in their own countries, through the establishment of national or regional "Spaceguard" centres to be coordinated by the international Spaceguard Foundation;

(c) That every effort be made to provide financial support for near-Earth object research, both theoretical and observational (from ground and space), and especially for the encouragement of exchanges and training of young astronomers in developing countries;

(d) The United Nations support and promote greater involvement of scientists and observatories from nations in the southern hemisphere as an opportunity for cultural and scientific development.

Again, the emphasis was on observation (discovery and follow-up) and international cooperation with no explicit reference to mitigation. This did however lead to the establishment of Action Team 14 on Near Earth Objects and subsequently the Working Group on Near Earth Objects within the Scientific and Technical Subcommittee of the United Nations Committee for the Peaceful Uses of Outer Space (UNCOPUOS).

OECD GSF

In an attempt to generate more policy-orientated outputs than these previous science-focused recommendations, in January 2003 the Global Science Forum (GSF) of the Organisation for Economic Cooperation and Development (OECD) convened a Workshop at the headquarters of the European Space Research Institute (ESRIN) in Frascati, Italy. The Workshop organisers deliberately sought to engage those responsible for natural hazard and public safety issues within respective nations in addition to the normal academic experts. The Workshop was attended by government-appointed delegates from fifteen Global Science Forum Member countries and Observers[1], representatives of three inter-governmental organizations[2], and representatives of four non-governmental organizations.

The resulting recommendations focused on policies related to NEOs, and actions that governments, inter-governmental organizations, and scientific organizations can undertake, separately and jointly, at national and international levels. The specific elements can be summarized as:

".. to assess the NEO hazard as it relates to public safety, determine the commensurate level of response, and undertake appropriate actions at national and international levels."

".. each government that has not already done so consider designating a responsible official (office, administration, etc.) within the government, tasked with following the ever-growing body of knowledge about NEO impacts, and, where appropriate, advising the government regarding the implications for public safety of the NEO risk."

"Interested countries that designate officials/offices that are responsible for NEO issues could profitably consider working jointly to quantify and assess national exposure to the NEO hazard/risk. A co-operative international effort would allow the sharing of relevant resources (e.g., expertise, data, methodologies). The results of these analyses should indicate the extent of the national threat relative

to more familiar natural and man-made hazards, and should accurately reflect the sources and magnitudes of the associated uncertainties. Such an assessment exercise should be compatible with methods and procedures that national and international bodies already use when evaluating risks to lives and property."

"The scientific community could provide the information and advice that government officials require to carry out the national risk assessments. This scientific work should extend beyond the traditional NEO community (principally astronomers) to include experts in areas related to the consequences of NEO impacts on the Earth, on society, and on the biosphere in general. Consultation among experts could also focus on optimizing internationally-agreed principles and procedures for communicating information about predicted potential impacts and near-misses."

".. explore strategies for mitigating the impact of a range of characteristic NEOs, identifying the scientific, technical, legal and policy implications of mounting a NEO negation mission against a range of potential impactors and timescales. Countries at particular risk of certain impacts (e.g., coastal regions susceptible to ocean impact induced tsunamis) should consider enhancement and co-ordination of regional monitoring and response activities, and should consider assessing the adequacy of their emergency response procedures for dealing with hypothetical NEO-related scenarios."

The recommendations for the first time explicitly called for governments to explore strategies for mitigating the impact of a NEO, resulting in January 2004 with ESA, on behalf of its member states[3] establishing an international panel, called NEOMAP. Near-Earth Object Mission Advisory Panel (NEOMAP) consisted of six European scientists active in studies of Near-Earth asteroids, were given the task of advising ESA on cost-effective options for participation in a space mission to contribute to our understanding of the terrestrial impact hazard and the physical nature of asteroids. This subsequently led to the selection by ESA of Don Quixote, an asteroid deflection precursor mission, to proceed to industrial competition within the ESA process. The Don Quixote mission is designed to assess and validate the technology that could be used to deflect an asteroid threatening the Earth.

United Nations Committee for the Peaceful Uses of Outer Space (UNCOPUOS)

The United Nations Action Team 14 on NEOs was established in response to a recommendation from UNISPACE III with the following terms of reference:

(a) Review the content, structure and organization of ongoing efforts in the field of near-Earth objects (NEOs);

(b) Identify any gaps in the ongoing work where additional coordination is required and/or where other countries or organizations could make contributions;

(c) Propose steps for the improvement of international coordination in collaboration with specialized bodies.

In its report to COPUOS in 2007, the Action Team recognized that significant efforts were being addressed internationally to detection and, to a lesser degree, follow-up observations of potentially hazardous NEOs larger than 1 kilometer in size but noted that objects in the 100m to 1km size range, for which the current surveys are not optimized, still pose a significant impact threat.

The Action Team recognized that the role of the MPC is critical to the dissemination and coordination of observations noting that the system is already working at capacity and it is clear that the current system can not cope with the significant increase in tasking associated with the anticipated goal of reducing the systematic detection threshold for NASA telescopes from 1km to 140m.

The Action Team also recognized that in considering a science-based policy to address the risk posed by NEOs, it is important for governments to evaluate the societal risk posed by such impactors and compare this with the thresholds established to deal with other natural hazards so that a commensurate and consistent response can be developed. Accordingly it was felt that more work was needed in this area, especially for sub-km impactors.

The Action Team further recognized that the impact threat posed by NEOs is real, although it is a low probability event, but potentially catastrophic when it occurs. However it knew of no countries with national NEO strategies and as such the United Nations has an important role to play in informing the process of policy development that is needed.

The Action Team also noted that a further challenge for the United Nations was that it will likely be confronted within 15 years with making critical decisions about whether and what action should be taken to protect life on Earth from a potential NEO impact. Since the entire planet is subject to NEO impact and since the process of deflection intrinsically results in a temporary increase of risk to populations not otherwise at risk in the process of eliminating the risk to all, the United Nations will inevitably be called on to make decisions and evaluate trade-offs. During the 43rd meeting of the UN COPUOS STSC, the Association of Space Explorers (ASE) made an intervention stating its intention to facilitate this process by convening a series of workshops, calling on experts from around the world with relevant experience, to address this challenge in detail and to prepare, for submission to COPUOS, a draft NEO deflection protocol for its consideration.

A multi-year Work Plan for the period 2008-2010 was agreed at the 44th session of the Scientific and Technical Subcommittee of UNCOPUOS. The Action Team anticipated that by 2010, it was expecting to be drafting (or agreeing on) international procedures for threat handling.

Association of Space Explorers

The Association of Space Explorers (ASE) is an international non-profit professional and educational organization of over 300 individuals from 32 nations who have flown in space. Founded in 1985, ASE's mission is to provide a forum for professional dialogue among individuals who have flown in space, support space science and exploration for the benefit of all, promote education in science and engineering, foster greater environmental awareness, and encourage international cooperation in the human exploration of space. The ASE Committee on Near Earth Objects was formed to oversee the delivery of the ASE initiative related to NEOs, seeking opportunities to support both national and international efforts to address the challenges implicit in protecting the Earth from near-Earth object impacts, including organizing meetings and workshops dealing with NEO issues as well as providing expert testimony for such meetings.

In the February, 2006 meeting of the UN COPUOS Scientific and Technical Sub-Committee, the ASE made an intervention in the NEO agenda item stating, in its penultimate paragraph,

> ".. To facilitate this process [the UN dealing with NEO deflection] the ASE, through its Committee on NEOs, proposes to convene a series of workshops, calling on experts from

> around the world with relevant experience, to address this challenge in detail and to prepare, for submission to COPUOS, a draft NEO deflection protocol for its consideration."

The ASE had recognized that the UN was in a position, due to the accelerating discovery of the population of NEOs and the evolution of human capability to intervene in an anticipated impact by proactively deflecting the NEO, where it would likely be confronted in the next 15 years with making critical decisions about whether and what action should be taken to protect life on Earth from a potential NEO impact. Given early warning that an impact is expected, and knowing that a deflection capability exists to prevent this impact from occurring, ASE noted that humankind cannot avoid responsibility for the outcome of either action or inaction. Further, the ASE recognized that since the entire planet is subject to NEO impact and the process of deflection intrinsically results in a temporary increase of risk to populations not otherwise at risk in the process of eliminating the risk to all, the United Nations would inevitably be called on to make decisions and evaluate trade-offs.

In order to provide the UN with a specific proposal on which to begin its deliberation ASE-NEO chose to bring together a small international group of pre-eminent and experienced experts, in a workshop setting, to produce a draft United Nations Protocol on NEO Deflection. These workshops (nominally four) would be conducted over a period of two years to develop and draft this proposed document which will be introduced via Action Team 14 , to the Scientific and technical Subcommittee of UN COPUOS during its 2009 session as part of an agreed agenda item. The Workshop participants include former UN diplomats, ambassadors, international law experts, national space program leaders, risk management specialists and re-insurance executives, among others.

4. The Required International Policy Framework

Approach

With the United Nations Committee for the Peaceful Uses of Outer Space (UNCOPUOS) in mind as the ultimate focus for the development of policy relating to NEO mitigation, we can now consider the required international policy framework. The intention here is not to prescribe the resources needed for implementation of the policy, nor to attempt to influence national funding priorities, as these will vary from country to country. Instead the aim is to identify those elements which require consideration by, or on behalf of, governments with the expectation that when international consensus is reached on these issues, the necessary prioritisation and availability of resource at a national or regional level will follow accordingly. We can break the activities down into a number of distinct phases:

Detection

The United States of America leads the worldwide effort on NEO detection through the existing Spaceguard Survey programme, with additional support from international observatories. This programme is currently on track to locate its target population of NEOs greater than 1 km in size by 2008. The participants of the OECD Workshop held in January 2003 raised the question of whether the sub-km population should be the subject of a dedicated survey programme. The SDT Study report published by NASA later that year concluded that the impact risk of objects in the 140m-1km range posed a very significant and more imminent threat than the 1km+ population, resulting in US Congress in 2005 directing NASA to review what was needed to lower the minimum size threshold for detection to 140m. In its response in 2007, NASA reported that it was confident that it could deliver the required survey performance with significant new investment in dedicated resources, but that it currently had insufficient funding to embark on this new phase of the detection programme. Although it is not a scientific imperative to reduce this threshold for detection to sub-km impactors, there is scientific consensus that it is critical from a public safety perspective if we are to minimise the risk posed by NEOs.

POLICY REQUIREMENT #1: Establish the threshold of detection for international surveys to NEOs which are greater than 140 m in size

The next aspect of detection which requires policy consideration is the management of the observational data generated by the surveys. At the current time, the Minor Planet Center (MPC) is fundamental to this process and is operated by the Smithsonian Astrophysical Observatory in coordination with the International Astronomical Union (IAU) through a Memorandum of Agreement (MOA), giving the center an international charter. Pursuant to the MOA, since 1978 the MPC has served as the international clearing house for all asteroid, comet, and satellite astrometric (i.e., positional) measurements obtained worldwide. The MPC processes and organizes data, identifies objects, computes orbits, assigns tentative names and disseminates information on a daily basis. For objects of special interest, the center solicits follow-up observations and requests archival data searches. At the current time the MPC is singly responsible for the coordination and archiving of NEO observations, and the identification of targets for follow-up observations. This role of computing orbits, checking observations, cataloguing and disseminating observational information is critical. There is already concern about dependence upon the MPC alone to perform this role. UN Action Team 14, in its 2006 report to COPUOS, noted that ".. the MPC is already working at capacity and it is clear that the current system can not cope with the significant increase in tasking associated with the anticipated goal of reducing the systematic detection threshold for NASA telescopes from 1km to 140m". The UK Task Force also recognized the importance of ".. putting the governance and funding of the Minor Planet Center on a robust international footing". A possible way forward would be to establish a "mirror" capability to the MPC, possibly hosted in Europe or Asia. The two nodes could share analysis protocols, processes, and could have a common data management/access policy but would perform a complementary operational role, perhaps performing the same operations on a different subset of the observation data, but independently maintaining a complete database. The two sites could also then act to validate/verify their more critical respective outputs.

POLICY REQUIREMENT #2: Establish a facility with complementary capabilities to the Minor Planets Center (MPC)

POLICY REQUIREMENT #3: Establish common data management policy/protocols for the MPC "nodes".

These should include/address: processes & calculations, data designations, data duration, data dissemination, data verification & validation, and data access/security

Notification

On a daily basis, NEO astrometric data are made available by the MPC to the SENTRY facility hosted by NASA JPL and to a parallel, but independent, orbit computation center in Pisa, Italy called the Near Earth Object Dynamics Site (NEODyS). Within the JPL SENTRY system risk analyses are automatically run on those objects which have a potential for Earth impact – usually when the object has been recently discovered and lacks the lengthy data interval that would make its orbit secure. These objects are prioritized for the SENTRY system according to their potential for close approaches to the Earth's orbit and by the existing quality of their orbits. The JPL system automatically updates the orbits of ~40 NEOs per day and close approach tables are generated and posted to the web. Approximately 5 risk analysis cases are run each day with each run providing 10,000 multiple solutions run out to 2105. This process is run in parallel with NEODyS and significantly non-zero Earth impact cases are manually checked between JPL and Pisa before the impact risk analysis results are posted on their respective web sites.

The SENTRY and NEODyS systems are completely independent systems which employ different theoretical approaches to provide impact risk assessments. Hence if the long term orbit propagations from each converge to a single solution, we can have some confidence in the predicted outcome. Whereas the SENTRY system is funded as part of the NASA NEO Program Office and thus its operational future can be considered relatively secure, the long term funding for NEODyS is not so clear. As with the operation of the MPC, it is clear that an independent but complementary capability to SENTRY is desirable for the purposes of independent verification and validation of predicted close approaches, but also to address possible concerns about free access to data, especially regarding cases where a high level of risk is determined.

POLICY REQUIREMENT #4: Secure long term operational status of "NEODyS" capability

Since its inception in 2002, ~400 objects have appeared on the SENTRY risk page. For recently discovered objects of unusual interest, the MPC, JPL, and Pisa will often alert observers that additional future or precovery observation data are needed. This brings us to the question of what information is pertinent to the evaluation of the magnitude of threat and how, and in what form this is communicated, and to whom. There are two scales currently in use which seek to compare the relative impact risks posed to the Earth by respective NEOs. The Palermo Scale was developed to enable specialists to categorize and prioritize potential impact risks spanning a wide range of impact dates, energies and probabilities. The Palermo Scale compares the likelihood of the detected potential impact with the average risk posed by objects of the same size or larger over the years until the date of the potential impact. This average risk from random impacts is known as the *background risk*. For convenience the scale is logarithmic, so, for example, a Palermo Scale value of -2 indicates that the detected potential impact event is only 1% as likely as a random background event occurring in the intervening years, a value of zero indicates that the single event is just as threatening as the background hazard, and a value of +2 indicates an event that is 100 times more likely than a background impact by an object at least as large before the date of the potential impact in question. In contrast, the Torino Scale is designed to communicate to the public the risk associated with a future Earth approach by an asteroid or comet. This scale, which has integer values from 0 to 10, takes into consideration the predicted impact energy of the event as well as its likelihood of actually happening. Currently the SENTRY risk page presents values for both scales for an individual object. Clearly there is a threshold of risk above which the originators of the risk data should actively communicate the threat to those officials responsible for public safety rather than passively post this to a web page.

POLICY REQUIREMENT #5: Identify the criteria and thresholds associated with a potential impact event requiring active communication through official channels

POLICY REQUIREMENT #6: Identify the communication channels, both at national and international levels, for communication of the NEO risk

POLICY REQUIREMENT #7: Identify the officials in government who are responsible for receipt of notification of a significant impact threat and taking appropriate action at national and/or regional level

In looking to governments to take action in response to a potential NEO threat, we need to understand how they might interpret the threat. Whereas an individual may simply consider risk to life posed by an impact, governments will see the broader spectrum of consequences such as financial cost of infrastructure damage and environmental impact along with the scale of casualties. Governments also tend to draw a distinction between the risk to an individual and the risk to groups of people. *Individual risk* is defined as the frequency at which an individual may be expected to sustain a given level of harm from the realization of specified hazards, whereas *societal risk* is the relationship between the frequency and the number of people suffering from a specified level of harm in a given population from the realization of specific hazards. There is a widely held view that while the individual may primarily be concerned about risk to self (i.e. individual risk) the 'state' should be concerned with societal risk. The UK Health and Safety Executive's interpretation of societal risk, "the risk of widespread or large scale detriment from the realization of a defined hazard, the implication being that the consequence would be on such a scale as to provoke a socio-political response, and/or that the risk provokes public discussion and is effectively regulated by society as a whole through political processes and regulatory mechanisms", is well suited to dealing with the infrequent but potentially catastrophic events characteristic of asteroid or cometary impacts with the Earth. Thus a set of criteria should be established which require action to be taken to assess the consequences of a specific impact threat, and then consider the range of options for managing the risk.

POLICY REQUIREMENT #8: Establish risk threshold for conducting detailed assessment of the consequences of an impact threat

POLICY REQUIREMENT #9: Establish a methodology, taking into account factors such as topography, population distribution and proximity to ocean, for assessing the consequences of a specific impact threat

POLICY REQUIREMENT #10: Develop a detailed protocol for the consideration of risk mitigation options and agree the criteria which will help to guide the choice and implementation of an appropriate response

Deflection/Evacuation

In addition to the probability of, and time to impact, the other parameters that will influence the response strategy will be the anticipated intersect locus on the surface of the Earth and the vulnerability of that area to the impact. Further the different options for deflection and the implications (technical readiness, political acceptability, cost of development and operation, translation of intersect locus) of a particular deflection strategy will also have to be weighed up against the alternatives. It is quite possible that countries without the capability to mount a deflection mission may be threatened by an impact, whereas those with the capability are not. Further it may be considered more attractive for one capable actor to take the lead in mounting a particular deflection mission rather than a grouping of agencies with different roles, due to the complexity of the mission, and the political expedient of protecting sensitive technical information. Hence one can envisage a matrix of options, with agreed responses to a range of impact scenarios, with identified players performing specific roles.

In considering this matrix of responses, we can identify a timeline from the initial detection of a potentially hazardous object through characterisation of the body and its potential effect should it impact, on to development of a solution tailored to that object and the development and production of the necessary infrastructure, followed ultimately by the deployment and operation of a deflection mission. It would seem prudent that prior to the emergence of a specific threat, that we should develop a number of solutions encompassing the range of impact scenarios that could be encountered, and to advance the solutions along the timeline to a level of maturation appropriate to the likelihood of implementation and cost-effectiveness of the associated activities. Hence for the full range of impact scenarios that we can envisage, we could evaluate deflection concepts employing all feasible technology solutions and consider the implications for their deployment. Hence we might anticipate taking all scenarios through initial requirements capture, establishing performance requirements and identifying possible mission concepts, along with outline cost and schedule estimates and determination of critical mission elements. This could be followed by initial feasibility studies to explore and evaluate possible system concepts, and refine costs, schedule and utilisation constraints, leading to a preliminary system concept selection. The next step would be to advance the chosen solutions through to preliminary definition phase resulting in a precise definition of performance requirements, a coherent definition of the system, identification of sourcing of components of system, and pre-development work on critical technologies where necessary. On completion of the preliminary definition phase, a particular solution would be adopted for each impact scenario and the associated critical technologies would be brought up to a minimum level of technical maturation. Cost and schedule estimates can then be developed with some confidence to feed into the overall decision timeline. It is important that this process is conducted in a coordinated manner to ensure that the full range of probable impactor scenarios and deflection options are considered and to avoid duplication of effort. Additionally, the baseline conditions for evaluation of the mitigation options and the metrics for comparing solutions would need to be agreed and applied consistently. Hence there is a need for a forum to be identified with the mandate to coordinate this activity and manage the process of establishing baseline mitigation options for the range (size, composition, orbit, epoch) of impactor scenarios.

POLICY REQUIREMENT #11: The identification of an international technical forum wherein a range of probable impactor scenarios can be determined and a corresponding matrix of mitigation options developed to a level of maturation to permit reliable mission timelines to be mapped onto a decision timeline for the envisaged Protocol.

It could be anticipated that different space agencies would be prepared to fund advancement to this preparatory stage without recourse to others, although the actual cost of mounting a deflection mission would be on a different scale. Each of the possible mitigation responses will also have a range of consequences from a technical, political and economic standpoint. Each of these consequences would need to be addressed before the solution could truly be considered a viable option. It would seem practicable for those promoting specific capability to champion a particular solution, working through the consequences, and working as advocate and agent for action within the appropriate forums, with informed and implicit support from the wider international community on whose behalf the action would be taken. This would require a degree of transparency, either within the technical forum, or subsequently when the political and economic consequences of a particular technology solution are considered. We can anticipate a number of issues that would result from developing this matrix of baseline responses to the impact threat. In all cases where the intersect locus on the Earth is modified through active intervention by an actor, it is important that this is conducted with the full understanding and support of the international community on whose behalf the action is being taken. Further where the nature of intervention requires nuclear technology, there are treaty issues which would need to be addressed. Again, it would seem prudent to scope these issues and advance the debate to a stage where necessary modifications to existing treaties could be identified and drafted. Whereas the technical solutions would be best developed amongst a group of capable space-faring nations, it would be appropriate for the policy aspects of the anticipated actions to be developed and debated by global community within an international policy forum. However it would be premature to embark on this debate before consensus had been reached within the technical forum and the outline solutions introduced into a corresponding international body for consideration and general endorsement.

However, there are a number of policy aspects of the NEO mitigation strategy, which are independent of the deflection solution, and which are pertinent to the international community. One issue is the consideration of whether to act or not, i.e. where it might be decided not to mount a deflection mission and instead to allow the NEO to strike the Earth, but to minimise the impact on the population and infrastructure through a combination of evacuation and protection. This would require consideration of the range of hazards presented by NEOs, namely impact debris, blast waves, heating, tsunami waves, material injection into the atmosphere and electromagnetic pulse for a specific location. The approach to this analysis and the results would need to be endorsed by the community as a whole.

A second aspect is <u>when</u> a decision should be made to launch a deflection mission, or otherwise. Although this is somewhat dependent upon the impactor scenario (i.e. the time we would have to make a decision and mount a deflection mission), experience tells us that it would be prudent to make this decision as soon as a credible threat has been identified. These criteria and thresholds would need to agreed in advance of implementation, and hence are an immediate, if not urgent, requirement.

Finally, it is clear that consideration should be given to the political implications of deflection, regardless of the technology used to effect this. Hence a review of existing treaties and legal instruments should be conducted to understand the implications of action, and to identify possible means of indemnification and/or cross-waiver of liability for agreed actions on behalf of the international community. The constraints on the parameters for this action would need to be agreed by all parties and addressed through some form of "contract" between the acting agency and the international community, though a literal contract with the international community is not possible.

POLICY REQUIREMENT #12: Consideration within an appropriate international forum of the criteria requiring action by the international community to mount a deflection mission (or otherwise), the criteria and thresholds requiring the community to make this decision.

POLICY REQUIREMENT #13: Consideration of those aspects of existing legislation which require modification to permit agencies to mount a deflection mission, without fear of liability for the consequences when acting within agreed constraints and drafting of a "contract" between the chosen actor and the international community.

Should an impactor strike the Earth as a result of lack of sufficient warning time to mount a deflection mission, the failure of a deflection mission to prevent an impact on the Earth, or a decision to "take the hit", it is critical that the NEO hazard is incorporated into the mandates of both national and international agencies responsible for dealing with natural and man-made catastrophes. The existing framework for disaster management would provide an effective response to a NEO impact but would require the education of officials to recognise the unique characteristics of the NEO hazard and modify their procedures to respond accordingly.

POLICY REQUIREMENT #14: Incorporate the NEO hazard into the mandates of both national and international agencies responsible for dealing with natural and man-made catastrophes.

Finally, there is a significant subset of the NEO population which merits special attention. Asteroid 99942 Apophis is representative of a class of objects which could have a close approach to the Earth a number of years prior to impact. There will be major uncertainty associated with the outcome of the intervening gravitational encounter and the resulting perturbed trajectory of the object, hence such NEOs cannot be addressed in the linear, sequential manner envisaged in the case of a direct impact with the Earth. A different strategy will be necessary, both in terms of the way that the risks are considered and the hazard is addressed. It will be important to monitor such objects to assess the likelihood of passage through a "keyhole" resulting in a resonant return to impact the Earth, and balance this against the criticality or otherwise of the spectrum of possible mitigation options. Governments are naturally uncomfortable when confronted with a range of options when they are not fully cognizant of the issues involved, which is why consideration should be given to invoking the "precautionary principle" in the case of this special class of NEOs. The purpose of the precautionary principle is to create an impetus for government(s) to take a decision notwithstanding scientific uncertainty about the nature and extent of a risk, i.e. to avoid 'paralysis by analysis' by removing excuses for inaction on the grounds of scientific uncertainty.

POLICY REQUIREMENT #15: For the case of "keyhole" objects, embed the philosophy of the precautionary principle in the development of the detailed protocol for the consideration of risk mitigation options, adopting qualitative criteria if necessary to help to guide the choice and implementation of an appropriate response where scientific evaluation of the consequences and likelihoods reveals such uncertainty that it is impossible to assess the risk with sufficient confidence to inform decision-making.

5. A Possible Way Forward

In considering how to address the policy requirements previously identified for NEOs, we can learn much from the approach adopted for analogous topics such as man-made debris. Within a relatively short time frame from identifying that man-made orbital debris posed a significant threat to future space operations, an international inter-agency forum[4] was established with different nations performing complementary roles, to review and seek scientific consensus on related aspects of debris measurement, modelling, risk evaluation and identification of measures for mitigation. The resulting outputs were then used to inform the debate on the subject within the Scientific and Technical Sub-Committee of UNCOPUOS which led to international agreement on a series of guiding principles to minimise the future proliferation of such debris. The resulting international policy subsequently became widely recognised and is in the process of being adopted in national regulatory activities with resources being made available accordingly. Such a model for policy development is appropriate for NEOs, not least because many of the assets and techniques, and the Executive Agencies involved, are the same.

An IADC analogue for NEOs involving space-faring nations would be able to deal with a number of the policy issues identified previously, such as establishing data management policies/protocols, developing a recognised risk assessment methodology, and performing a technical assessment of the mitigation options for a range of impactor scenarios. Such a body would not however be well placed to identify the criteria and thresholds for the communication of a specific impact threat, or identifying the channels for communication of this risk and those responsible for subsequent action. Further, the international community may be reluctant to trust the establishment of criteria and thresholds for actions such as when to act, how, and on what basis, to a body with limited international representation, especially when the outcomes of the (in)action would have direct consequences for those not involved in the governance of that body. Hence the role of UNCOPUOS is critical to ensuring any response is proportionate, consistent, targeted, transparent and accountable[5]. The anticipated input from the ASE-sponsored workshops involving principals with significant experience and broad-ranging responsibility and representation will be key to informing and advancing the decision making process. Whereas there was reluctance within the international community to debate the issue of space debris within the Legal Sub-Committee of UNCOPUOS until consensus was reached on the technical basis for discussion, there are clear activities relating to NEO policy which could be advanced within the Legal Sub-Committee in parallel with the technical discussion such as liability issues, and the need for modification or addition to the existing international treaties such as the Outer Space Treaty, the Liability Convention, the Partial Test Ban Treaty and the Anti-Ballistic Missile Treaty, should they be needed.

There is now an opportunity for one, or a number, of the established players within these forums, to show leadership and champion the development of appropriate policy frameworks to address the NEO hazard. There are clearly benefits for governments in taking such initiative, such as influencing the guiding principles for engagement on the issue, and building partnerships within the international community to share resources and responsibility to act. Further, given the scale of economic and human costs that we would inevitably incur as a result of an impact, governments are obliged to establish a credible, science-based approach to dealing with the NEO threat.

Chapter 8:
FINDINGS

This chapter presents detailed findings. They are summarized in the Executive Summary.

Chapter 2: The problem

1) NEOs may be asteroids or comets. Earth has been struck frequently, particularly in its early history. 99% of the impacts are believed to occur from asteroids, but the vast majority of the largest and deadliest bodies are long-period comets. The most recent large NEO was due to a 6 km NEO which impacted in Yucatan 65 million years ago, and caused the extinction of the dinosaurs and 60% of all species.

2) There are about 1100 asteroids greater than 1 km and an estimated 100,000 greater than 140 m diameter.

3) The damage and number of fatalities produced by a NEO impact rise rapidly as the diameter of the NEO increases, but the probability of such an impact decreases.

4) 45 m diameter NEOs will typically not reach the surface, but could kill thousands with blast and heat since they release an amount of energy equivalent to 1,000 Hiroshima-size weapons. They are believed to impact on the average every 100 years, so the probability of an impact this century is near 100%. The Tunguska NEO of 1902 was an example of this class, though the Meteor Crater in Arizona, USA is also one.

5) 300 m NEOs will cause great regional damage as they release 1,000 MT TNT equivalent of energy. They could result in millions of deaths. They impact on the average every 10,000 years, so the probability of an impact in this century is 1 %.

6) 1 km diameter NEOs are civilization killers, with billions of deaths expected from one impact. Their energy release is equivalent to 1,000,000 MT of TNT. They are believed to impact on the average every 1,000,000 years and the probability of one impacting in this century is 0.01 %.

7) 6 km diameter NEOs are so large they will cause mass extinctions as well as kill all human life. Their energy release is 100,000,000 MT TNT equivalent, and they are believed to impact on the average of every 100,000,000 years. The probability of an impact this century is 0.0001%. The impact that killed all the dinosaurs and 60% of all species of life 65 million years ago was a 6 km NEO.

8) The NEO impact hazard (in terms of average fatalities per year over the time scale of the occurrence) is greater than that due to shark attacks, botulism, or terrorism (to date), however is lower than that due to major wars, disease, famine, car accidents, or murder. Thus in the spectrum of hazards mitigating the impact of NEOs is very important in the context of all serious hazards of concern to humanity.

Chapter 3: Detection, orbit determination, and impact warning

1) Current surveys and systems

Several current NEO survey teams participate in the current Spaceguard survey, and are focused on finding near-Earth asteroids (NEAs). This is truly an international effort, with participation by Italy, the USA, Japan, Australia, ESA, and the Czech Republic. The principal telescope systems that conduct the Spaceguard survey include LINEAR, NEAT, Spacewatch, LONEOS, and Catalina Sky Survey.

The Spaceguard goal is to catalog 90% of NEAs larger than 1 km by 2008. The survey is almost complete now with over 4,000 NEAs already discovered, of which 1,100 are 1 km or larger, and 850 are potentially hazardous asteroids (PHAs). The current activity is aimed at asteroids only. There is no systematic program or goal to discover and catalog long-period comets on Earth-crossing trajectories.

2) Future surveys and systems

ESA's NEOMAP and the NASA SDT recommended searching for smaller NEAs. In 2007 NASA recommended a set of options to extend the Spaceguard survey to cataloguing 90% of PHAs larger than 140 m by 2020. Principal options include adding a dedicated LSST telescope to complement the shared PanSTARRS and LSST systems, adding a 0.5-1.0 m space telescope, or both. All options cost in the vicinity of $1B and as yet are unfunded.

3) Orbit determination and information management

The Horizons ephemeris computation facility located at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, USA and the Near Earth Object Dynamics Site (NEODys) at the University of Pisa in Italy provide independent orbit cataloging, confirm NEO close approach, and perform risk assessment. The large Goldstone and Arecibo radars are extraordinarily useful for orbit refinement and NEO characterization, but Arecibo is currently planned to be phased out for lack of funds.

The International Astronomical Union's Minor Planet Center, operating at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, USA, is the organization that collects, computes, checks, and disseminates astrometric observations and orbit information for asteroids and comets from hundreds of observatories worldwide. A space based telescope can have up to 18 times the observing time compared to a ground telescope due to lack of weather and nighttime. Canada and ESA plan to orbit small telescopes that could be used for the NEO discovery mission.

Discovery of 1 km diameter long-period comets and the provision of many years' warning time would require a large space based telescope. Studies indicate that a new technology adaptive membrane mirror space telescope with aperture of 25 meters, weighing under 1,000 kg, could be deployed in space within 15 years. It could detect a 1 km new apparition comet well beyond 10-15 AU and yield 5-6 years' warning time.

4) Characterization of NEOs

A number of space flight missions have already been undertaken by several nations/consortia that demonstrated the ability to fly by and/or rendezvous with some asteroids and comets, perform proximity operations there, and begin to characterizing the bodies. These are very sophisticated operations and most are successful, but the technology is not yet mature enough for humanity to depend on for its very survival.

5) Impact prediction and warning

The Palermo Scale was developed in order for the ability to uniformly assess potential impact risks spanning a wide range of impact dates, energies and probabilities. It is now in general use. Computing Earth impact probabilities for NEOs is a complex process and requires sophisticated mathematical techniques. Due to the usual paucity of early observations computed collision probabilities tend to be initially too high, but reduce as more observations are obtained.

The likely warning time available will be decades for known NEAs, years for newly discovered NEAs and short-period comets, and a few months to less than one year for Small Earth-Crossing Asteroids and Long-Period Comets (if no space-based telescopes exist). However, approximately 6 years of warning time of the potential impact of Long-Period Comets would be possible if a large space-based telescope is developed.

Chapter 4: Preventing or mitigating an impact

1) Physics of Interaction

The orbit of an object far from Earth may be modified with the least expenditure of energy if its velocity along its orbital path is changed. With warning times of many years or decades only centimeters/second change in the NEO's orbital velocity will ensure that it arrives sufficiently earlier or later to completely miss the Earth.

Some NEOs could well be in orbits that come near the Earth yet miss, passing through very small regions of space known as "keyholes", and enter a resonant orbit with repeating encounters and threats to Earth periodically over many years or decades NEO velocity changes of only millimeters per second may suffice to cause them to miss a keyhole, which would prevent an impact one conjunction later, but not necessarily all subsequent impacts.

2. Major Mitigation Options

Changing the velocity of a NEO may be accomplished "fast" or essentially instantaneously by forces from spacecraft impact or explosion, or "slowly" by applying small forces from propulsive spacecraft, energy impingement, or gravitational perturbations whose integrated effects over time cause the velocity change.

a. "Slow" deflection approaches

A number of slow approaches exist. Those that require contact and thus rendezvous and docking with a propulsion-equipped spacecraft on the NEO include a *Tug Boat* having chemical or electric propulsion, and a *Mass Driver* which ejects chunks of the NEO's own mass rather than propellants brought from Earth to cause reaction forces. The principal non-contact approaches include a *Gravitational Tractor* in which a spacecraft simply hovers near the NEO by constant thrusting and its gravity attracts the NEO, resulting in a force being applied without contact with its surface; *Laser Ablation* which uses a illuminates the NEO with an intense laser causing surface ablation and plasma ejection, whose reaction forces result in a velocity change; and *Photon Pressure* which uses sunlight to effect a slow push by attaching a large reflective solar sail to the NEO, illuminating it with a large solar reflector from a distance; or altering its albedo to take advantage of the Yarkovsky effect.

Contact approaches require secure attachment to the surface of the NEO as well as thrust vector and/or timing control to assure force generation mainly along the NEO velocity vector due to the spin/tumble of most NEOs. Non-contact approaches avoid these difficulties.

All "slow" approaches develop small forces, and thus have the advantage that NEO fragmentation may likely be avoided. However they all result in the instantaneous impact point of the NEO being slowly moved on the surface of the Earth until it eventually misses. If there is an unrecoverable failure of the propulsive or reaction force-inducing means before its job is done the impact point could lie anywhere on the locus of possible impact points, and the damage could well be greater than had the NEO been undeflected. The risk of such a failure is substantial since the technologies for slow deflection are not yet fully demonstrated and the operating times are long.

b. "Fast" deflection approaches

There are two principal options for fast deflection: non-nuclear and nuclear.

Non-nuclear fast deflection

Kinetic impact by simply ramming a spacecraft into a NEO at high relative velocity would provide an instantaneous velocity change of the NEO. The technologies and systems are the same as already demonstrated for planetary exploration. Whether the body of the NEO or PHO will fragment or be deflected whole depends on the composition of the NEO.

Contrary to popular belief K. Holzapple has shown that kinetic impacts at hypervelocity would not create a small number of large and thus dangerous fragments, but rather likely create very large numbers of very small fragments possessing large transverse velocities. Thus the mass per unit area normal to the NEO's trajectory would be very much reduced at the time of Earth impact. The consequences of a large number of impacts, each being much less massive than the original body, are therefore likely to be very much more benign locally as well as globally than if the NEO were not deflected at all.

Kinetic impactors are best suited for deflecting small NEOs and when there is lots of warning time. While theoretically capable of deflecting a NEO with a warning time of only a year or even less, there would not be time for observation of the actual velocity change imparted or for a second attempt were it needed, and so the probability of success would be low.

A unique case exists for kinetic interception within a "keyhole" because a very small change in velocity will cause the NEO to miss the Earth at least in the next encounter of the resonant orbit which results from the keyhole pass. In addition, since keyholes are by definition relatively near the Earth a low impulse interception stage will suffice, and could use dead satellites picked up in GEO as essentially "free" mass for the intercept.

Nuclear fast deflection

There is only one option for changing the velocity of a large NEO or one with little warning and that is to use nuclear devices because the energy requirements can be enormous, and the energy release of nuclear devices can be millions of times greater than that produced by kinetic impacts. Standoff nuclear explosion engagement of a NEO is very similar to that of a non-nuclear kinetic impact deflection technique, with the device being detonated just before or at impact. The tremendous radiative flux from a nuclear explosion ablates the surface of the NEO and results in a hot expanding plasma, whose reaction forces accelerate the NEO and change its velocity essentially instantaneously. With sufficient stand-off distance the area over which the energy is deposited could be large, and hence the forces low enough to possibly avoid fragmentation in some NEOs, but others could still fragment. A variant is to bury a nuclear device in the NEO which gains greatly in deflection force but requires rendezvous and surface operations; and would probably fragment most NEOs.

New design highly reliable launch vehicles and upper stages would be highly desirable for safety reasons, though current designs could be used in the interim, recognizing their limitations. The popular conception of using ICBMs with added existing upper stages would have very low probability of success and is thus is unwise for reliability reasons, though if there were no other means available at the time of need they could indeed be used. Existing nuclear devices could be used with few, if any, modifications regardless of the type of launch vehicles or upper stage designs.

Although some people object to the use of nuclear devices on principle, and indeed current international cold-war era treaties would require modification to permit their use, the use of nuclear devices against NEOs in space is probably their best and most desirable application; and the only known technique that might be able to prevent a horrendous regional or global catastrophe when we are faced with a large NEO, or with a smaller NEO but little warning time. And it is an established fact that the occurrence of such a situation is not a question of if, but rather a question of when.

3. Infrastructure and system deployment

   The probability of successfully deflecting a NEO with a single mission using any known concept and developed technologies is unacceptably low, given the likely scale of the consequences of a failure. It is therefore clear that the development and deployment of a robust multiple option, redundant, coordinated system of diverse systems is needed. The deflection of a NEO cannot be a mission but must rather be a campaign of multiple orchestrated missions deployed sequentially in increasingly capable stages, with means emplaced to rapidly assess the status and effects of the missions as they unfold.

   The initial mitigation system or systems could well use current systems in order, whether dual-use or dedicated, in order to have at least some capability available should it be needed. Implementation of a dedicated planetary defense system to undertake the required campaign must eventually be undertaken, and will likely occur in stages of increasing capability over a substantial period of time, both due to costs and technological/operational maturity.

Chapter 5: Organizing for the task

1. The threat is inherently international, and therefore so must be the organization and resources to address it.

2. The consequences of a NEO impact share many characteristics of natural disasters the world has experienced; however in contrast a NEO can create near-instantaneous devastation, the disaster date can be forecast years ahead, and most impacts could be prevented.

3. A wide range of damage scenarios is possible. The means and consequences of relocating or evacuating many millions of people are unknown. Where to? Who pays?

4. False alarms must be taken into account as they cannot altogether be avoided, they excite the media, engage the public, and can create great damage without any impact occurring

5. Current organizations for detecting a threat and notifying some authorities may be adequate for initial addressing of the threat if they would develop response plans and coordinate them internationally; but such plans currently do not exist

6. A spectrum of organizational models in current existence, such as the US National Disaster Plan, could be used to model a national NEO response mechanism.

7. Many national internal organizations and many nations/consortia need to participate in an international effort to develop a coordinated response plan and means. These could range from a UN managed effort through a non-UN international consortium to a national effort commissioned by either.

8. Planning for coping with disasters is well developed in some nations, but planning to avoid the disaster to begin with is generally not. While detection and establishment that a threat exists is underway, planning for intervention and deflection activities pre-event needs to focus on response scenarios, coordinated planning including establishment of a number of likely scenarios, establishing deflection capabilities, and planning for the contingency that deflection attempts may fail.

9. During the impact event communications with the public will be paramount, including status of deflection attempts, evacuation activities, and instructions to the public.

10. Post-event planning must take into account population return and/or relocation, rebuilding, and return to vigilance. Based on the experiences of the Indian Ocean tsunami and hurricane Katrina this will be a difficult and protracted period that only realistic planning and preparation can help to ameliorate.

Chapter 6: Behavioral factors and planetary defense

1. Empirical studies of human response to threat and disaster provide sound underpinnings for NEO disaster management. However different cultures are known to respond differently to disasters and this must be taken into account in the planning.

2. Even though the consequences could be terrible indeed, low probability events generate little worry and little action, and thus planning for NEO impacts is an extraordinarily difficult undertaking. The "giggle factor" associated with NEO impacts makes it even more difficult to plan responsibly.

3. Proper planning requires moving beyond widespread but erroneous stereotypes regarding human behavior in catastrophic situations. These stereotypes are that panic will be widespread, civility/looting commonplace, and that a pervasive feeling of helplessness/passiveness will prevail. While to a degree they will occur mutual assistance and support tends to be the rule rather than the exception.

4. Pre-impact phase: planning and rehearsals are crucial. The media must be involved, its workings understood, and an effective working relationship developed with it. Communications must either exist or be ready to be deployed, and must be adequate for the contemplated functions. An effective warning system must be in place, with different segments distributing coordinated messages

5. Impact phase: Large numbers of direct casualties as well as anxiety disorders will be ubiquitous. Disaster workers will be affected as much as the people who they are trying to help. Acute stress reactions and several forms of trauma must be expected, and psychological support prepared for addressing them, both for the injured and for the caregivers.

6. Recovery phase: Massive scale of triage, medical and psychological support and therapy, and long term post-traumatic effects should be expected. Some of the likely chaos should be ameliorated by proper planning for these activities. Population dynamics must be understood and planned for.

7. Five core values – empathy, trust, sensitivity to differences, openness and flexibility – provide a firm basis for protecting human life and welfare. These will be paramount when the scale of the disaster is such that human values or even the very survival of humanity are threatened.

8. National, international and regional agencies can and do play crucial roles in disaster management, but are likely to be the most effective when they coordinate with local authorities and encourage grass roots efforts.

Chapter 7: Policy Implications

1. Several nations/consortia have active programs toward discovery, cataloguing, and characterizing the NEO threat. The principal activities already have some international components.

2. The existing international policy is limited to a number of instruments calling upon states to consider adopting a range of voluntary measures related to the NEO issue.

3. In 1996 the Council of Europe recommended that ESA contribute to an international program to detect NEOs and development of a strategy for remedies against possible impacts.

4. In 1999 Unispace III urged international coordination and harmonizing efforts aimed at detection and orbit prediction, and consider developing a common strategy for future activities.

5. In 2003 the Organization for Economic Cooperation and Development recommended that governments explore strategies for mitigation of NEO threats, and established an advisory panel to work with ESA.

6. In 2007 the UN COPUOUS Action Team 14 recommended addressing the threat from smaller asteroids, augmentation of the Minor Planet center, and preparation of a draft NEO deflection protocol and international procedures.

7. An IADC analogue would be an appropriate way to move forward toward a coordinated international plan for dealing with NEOs.

Chapter 9:
RECOMMENDATIONS

The report's recommendations are intended to improve understanding of the threat, refine estimates of the impact risk and consequences, develop well-defined options for mitigation, and prepare a framework for appropriate international political and social response. These are presented organized by report chapter. In addition a potential role for the IAA is identified.

Detection, orbit determination, and impact warning

An effective surveillance infrastructure should be emplaced to expand the Spaceguard survey to catalogue 90% of those potentially hazardous objects no larger than 140 m diameter by 2020. Existing radars should be provided adequate resources to continue the search, while increasingly more capable ground based detection systems should be developed. Meter class space based sensors should be developed and orbited to accelerate the discovery and cataloguing of NEAs in the near term.

A serious effort should be begun to address detection, orbit determination, and impact warning for the long-period comet threat, which is much less well developed than for asteroids. To that end responsible definition of a large (10-20 m) new technology very lightweight and thus affordable optical space-based telescope should be performed.

Preventing or mitigating an impact

Detailed planning and mission design of both "slow" and "fast" deflection techniques must be undertaken. The mission designs should proceed using to the maximum extent existing vehicles and technologies. These mission designs must include all launches, sensors, communications, and command/control necessary to ensure deflection of a target NEO set with high probability. This probably means employing several different and/or redundant launchers, space vehicles, sensors, technologies, in campaigns designed to result in high confidence of mission success.

At least one non-nuclear kinetic mitigation and one slow deflection approach should be defined and designed so that a comparison of systems including complexity, life cycle cost, reliability, operations, and effectiveness can be made. The mission designs must include all systems and subsystems required to perform a mitigation mission after a threat has been identified, including precursor or follow-on missions for NEO characterization as required.

A separate system design of a nuclear interceptor should be made, with large NEOs or smaller NEOs with short warning time as intended targets. Non-nuclear laboratory and field experiments should be performed to fully understand the fragmentation issues involved in deflection attempts of various classes and compositions of NEOs.

Organizing for the task

Response plans for a number of impact scenarios must be developed. This includes near-miss as well as actual impacts on various geographic locations around the globe, should deflection attempts either not materialize or fail. Disaster planning must also include the post-impact phases in which recovery and return to normalcy will be the goals. These response plans should be carried out by international planning groups with the support of national resources. The planning could proceed by several groups in parallel initially to benefit from differing viewpoints, but eventually a truly international organization should be created to take the global leadership role in NEO response planning, probably coordinated under the auspices of the UN.

The response plans must draw upon experience gained in the course of hurricanes, earthquakes, tsunami and other relatively common disasters, even though they are imperfect analogues of NEO impacts, since evidence-based, policy-oriented research will provide crucial building blocks for managing NEO threats. Such planning will require the coordination of organizations and agencies at many different levels: international, national, regional, and local. An important function of higher-level organizations will be to facilitate the efforts of regional, local, and "grass roots" efforts.

Behavioral factors and planetary defense

Pre-impact activities, including preparation and issuance of effective warnings, and the staging of personnel, equipment, and supplies, will require rehearsal. It will be important to recognize the role of religion, superstition and myth to effectively communicate risk, to encourage people to take protective action; and to effectively employ post-disaster relief. In all phases of mitigation planning, it will be important to be mindful that not everyone subscribes to the Western scientific viewpoint.

Mass casualties will require psychological as well as medical assistance; however, it will be very important to recognize and plan for the fact that disasters have adverse effects on the disaster workers and their families as well. Residents of the disaster area will need both immediate assistance and the tools to rebuild their lives and infrastructure, and regain independence. Recovery efforts should extend well into the post-disaster phase and should be prepared to remedy long standing local problems as well as the direct consequences of the impact.

Policy implications

An analogue of the Inter-Agency Space Debris Coordination Committee (IADC) would be an appropriate way to move forward toward a coordinated international plan for dealing with NEOs. This plan should include a number of specific policy statements and activities which include: establish the threshold of detection to NEOs which are not greater than 140 m in size; establish a facility with complementary capabilities to the Minor Planets Center (MPC); establish common and secure data management policy/protocols for the MPC "nodes; secure the long term operational status of an organization to coordinate NEO monitoring, including calculation of orbital elements, impact threat assessments, and issue warnings; identify the criteria and thresholds associated with a potential impact event requiring active communication through official channels; and identify the communication channels, both at national and international levels, for communication of the NEO risk.

An international technical forum should be organized and recognized globally as an impartial focus of technical excellence to provide informed support to decision-makers worldwide. This forum should undertake the tasks of risk estimation and the support for preparation of technically viable plans for mitigation and recovery options for a range of credible scenarios.

Among the support this forum could provide to international policy makers would be to: establish the risk threshold for conducting detailed assessment of the consequences of an impact threat; establish a methodology for assessing the consequences of a specific impact threat; develop a detailed protocol for the consideration of risk mitigation options and agree to criteria which will help to guide the choice and implementation of an appropriate response; develop a matrix of mitigation options and decision criteria to a level of maturation to permit reliable mission timelines to be mapped onto a decision timeline for the envisaged protocol; propose qualitative criteria to help to guide the choice and implementation of an appropriate response in situations where scientific evaluation of the consequences and likelihoods reveals such uncertainty that it is impossible to assess the risk with sufficient confidence to inform decision-making; and identify those aspects of existing legislation which require modification to permit agencies to mount a deflection mission, without fear of liability for the consequences when acting within agreed constraints.

Potential role of the IAA

The IAA should facilitate the process of dealing with the NEO threat, beyond the hoped-for contributions of this report, by supporting the international activities discussed above by organizing international workshops; and through the technical, policy, social, and legal expertise of its members serving on working groups and committees addressing the NEO threat.

Appendix

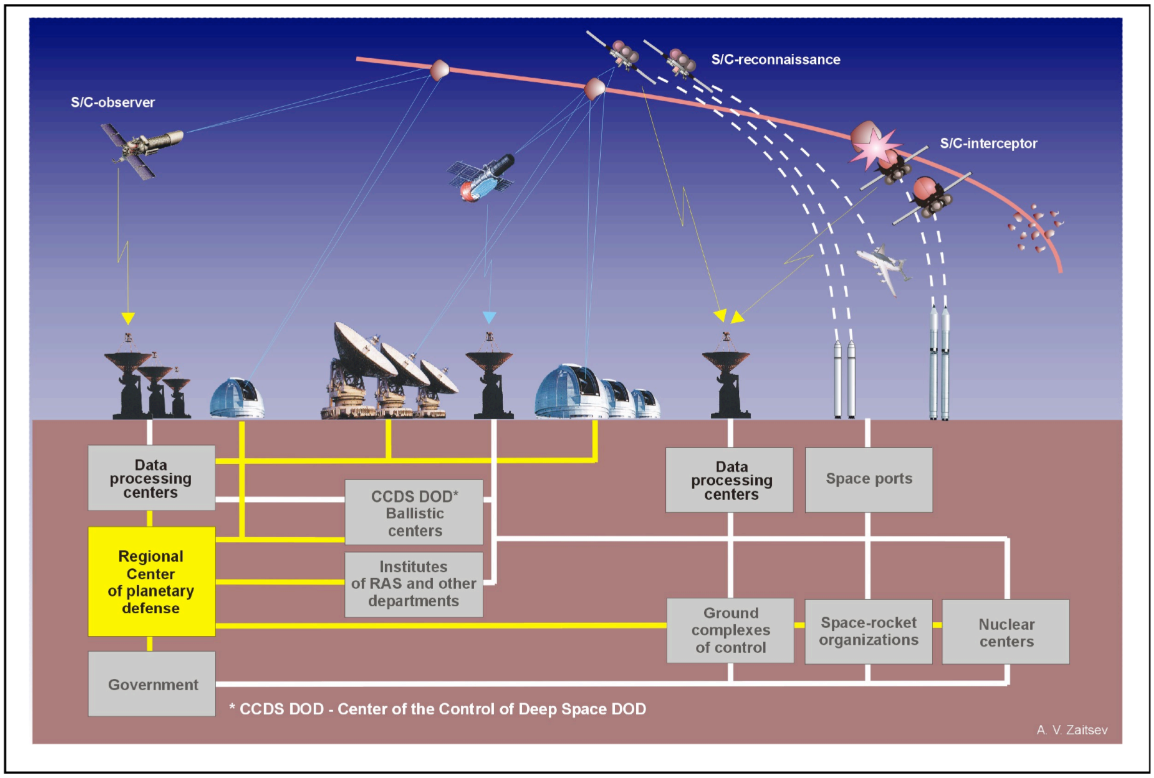
AN EXAMPLE PLANETARY DEFENSE SYSTEM: "CITADEL"

This appendix was contributed by Dr. Anatoly Zaitsev of Russia. It is being included as one of many possible examples of an ultimate and mature international planetary defense system, but it must be kept in mind that the form and content of such a system would likely be very different from that below when actually implemented. This system concept must thus be considered only an illustrative example, and not a recommended system concept. This concept description is based on Russian technologies, but clearly any real concept should be implemented with the best of all the world's technologies.

The minimum requirements for such a system would be that 1) the system implementation should be amenable to the defense of any country or region, and be amenable to exclusion of those that wish to be excluded from its action; 2) it must be designed to efficiently and rapidly provide notification to all that a threat exists, and to prevent data suppression by anyone; 3) it must guarantee that the system capabilities will not be used for military purposes; 4) it must provide maximum warning time and minimize damage from fragments of the NEO or the mitigation means themselves; and 5) it must allow for modernization as new technologies become available

Since it is unrealistic to initially deploy and operate continuously a system designed to mitigate large NEOs which occur very infrequently, the system concept envisions a two-tier structure in which a subset would operate continuously against NEOs of tens to hundreds of meters size, and the capabilities against larger NEOs brought into play if needed later upon detection of a viable threat. This latter capability, though designed and understood, can be established only when a real threat materializes and thus to some extent will exist initially in virtual form.

The small-NEO initial system is envisioned to have international ground and space surveillance means and two Planetary Defense Centers, a European/Asiatic one and an American one. The observation component would use optical and radar systems sited both on the ground and in space. The Planetary Defense Centers would include interception launch facilities with both non-nuclear and nuclear devices at the ready. The observation and interception means will be connected and netted as shown in the Figure below.



Notional future integrated and dedicated Planetary Defense System (Zaitsev, Russia)

A typical operation sequence could be as follows: Once a threat NEO/PHA has been detected the appropriate Control Center would issue a prediction concerning the expected place and time of impact as well as expected damage. Catastrophe prevention measures would be developed and an operations plan submitted to the hierarchy of nations/consortia/global entities comprising the management of the system. Once the plan has been proved at that intergovernmental level, launches of reconnaissance spacecrafts on Dnepr or Zenit launch vehicles and then interceptor spacecraft on Zenit or Proton launch vehicles can proceed. In the future multi-purpose launch/intercept systems could be developed and used.

The reconnaissance spacecraft would approach the NEO as fast as possible and come to a minimum distance from the NEO. It would define the NEO’s trajectory, velocity of rotation, mass, mineralogical content and dimensions, and acquire a detailed panorama of its surface and download these data to the Planetary Defense Centers. A mission design would then be undertaken to determine the best means of intercepting and mitigating the NEO threat using nuclear or non-nuclear means as appropriate. Nuclear devices with yield of 1.5 - 5 MT would suffice to mitigate a stony NEO with diameter up to a few hundred meters. Several interceptor modules could be assembled in Earth orbit to implement a capability to mitigate substantially larger NEOs.

A number of steps would be necessary for its implementation, including:

1. Development of top-priority measures of population relocation and property recovery for potential areas subject to damage, including protection of property and cultural values. This should be done even before a defense system is developed

2. Perform experiments to understand the interaction between the interception means and the NEO to asses the practicality and effectiveness of the mitigation operation.

3. Demonstration projects to test methods and means of NEO interception and deflection, including development of kinetic and slow deflection interceptors.

4. Deployment of the short term system tier to respond to smaller threat NEOs, including all the surveillance, launch, communications and command/control systems required. This could use upgraded existing facilities, development of new ones, or both. It is estimated that the first such near term tier of a Planetary Defense System could be developed within 5-7 years from an international decision to do so.

5. Creation of a plan for development, deployment, and operation of the longer term tier to respond to much larger NEOs later in time. This could include development of new high energy launch vehicles and interceptors as needed. This plan would not be implemented until later.

6. Development of the legal regime addressing organizational, financial, political, juridical, ethical and other questions at national and international levels necessary to create and operate a Planetary Defense System.

7. Definition of a list of technologies designated as necessary for its successful operation, and available without restriction to all parties for the purpose

The problem of defense of the Earth against NEOs is common to all mankind and therefore it should be addressed as an international program of the whole world community. The importance of the problem and its global and complex nature require resources to be pooled and managed at the intergovernmental level. One major step forward to be taken in this direction would be the creation of a "Mankind Insurance Fund" for financing the development and operation of such a Planetary Defense System. Such a fund would be established by all the more developed countries of the world with participation of government resources, banks, organizations, and individuals. In addition to financial, pooling of intellectual, technical, and other world assets would be required. Specifically the objectives should include:

1. Establishing an International Coordination Council of heads of leading organizations, scientists and specialists in the NEO defense field in order to coordinate efforts to define and develop a Planetary Defense System proposal.

2. Drawing up a draft of constituent documents of the "Mankind Insurance Fund" intended to finance the project and forward them, together with the proposal, to major government organizations, banks, funds, individuals and others and solicit their participation in establishing the Fund.

3. To create the Mankind Insurance Fund and when financial resources become available to proceed with development and operation of the first phase of the "Citadel" Planetary Defense System.

4. Preliminary estimates for the costs of such a Planetary Defense System are USD 3-5 Billion. This equates to an annual cost of only 5-10 cents per human being on the planet.

In summary, exploration and development work already carried out show that there is a good chance that a first operational system can be developed in 3-5 years, and that it could operate successfully based on current technical assessments. The more difficult problems of organizational, political, and judicial problems need addressing, and hopefully can also be solved in this time frame. Thus, while there is little doubt that the solutions exist or can be created we need to overcome the main problem which is a moral one: to understand that there is a necessity for all mankind to realize a responsibility for its own preservation and that of the Earth biosphere, as well as that of cultural, material and other values that have been created for millennia by billions of human beings.

Thus the problem of NEO defense can be seen as a kind of test for mankind's ability to solve global problems which it faces. So this "Citadel" Planetary Defense System could become a model for the first global project of mankind in the third millennium, which could turn the Earth into an unassailable fortress with protection from space threats. This, in turn could become a catalyst for development of many industries and technologies that facilitate not only improvements in Planetary Defense but also further development facilitating unity of many nations. But to make that happen many countries will be required to pool their resources, including financial as well as specialists in both natural-science and humanitarian fields.

Glossary

AIAA	American Institute of Aeronautics and Astronautics
AU	Astronomical Unit
CNN	Cable News Network
COPUOUS	UN Committee on the peaceful uses of outer space
CSA	Canadian Space Agency
ECC	Earth Crossing Comets
ESA	European Space Agency
ESRIN	European Space Research Institute
GEO	Geostationary orbit
Gy	Giga-years
IAA	International Academy of Astronautics
IADC	Inter-Agency space debris coordination committee
IAU	International Astronomical Union
ICBM	Intercontinental Ballistic Missile
IEO	Inner Earth Objects
JAXA	Japan Aerospace Exploration Agency
JHU	Johns Hopkins University
JPL	NASA's Jet Propulsion Laboratory
JSGA	Japanese Spaceguard Association
LHB	Late Heavy bombardment
LINEAR	Lincoln Near-Earth Asteroid Research
LONEOS	Lowell Observatory Near-Earth Object Search
LPC	Long-period comet
MIT	Massachusetts Institute of Technology
MPC	Minor Planet Center
MT	Megatons of TNT
My	Mega-years
NASA	National Aeronautics and Space Agency
NEA	Near Earth Asteroid
NEAR	Near Earth Asteroid Rendezvous
NEAT	Near-Earth Asteroid Tracking
NEO	Near Earth Object
NEODyS	Near Earth Object Dynamics Site
OECD	Organisation for Economic Cooperation and Development
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PHA	Potentially Hazardous Asteroid
PHC	Potentially hazardous long period comet
PHO	Potentially Hazardous Object
SDT	NASA's Science Definition Team
SPC	Short period comet
UN	United Nations
WHO	World health Organization

References

Chapter 2: The problem

[1] Z. Ceplecha, *Meteoroids: an item in the inventory*, in: T.W. Rettig & J.M. Hahn (Eds.), Completing the Inventory of the Solar System, Astron. Soc. Pacific Conf. Ser. 107, 1996, pp. 75-84.

[2] S.J. Weidenschilling, *Formation of planetesimals and accretion of the terrestrial planets*, Space Sci. Revs. 92 (2000) 295-310.

[3] Chambers, J.E., Wetherill, G.W. 1998.*Making the Terrestrial Planets: N-Body Integrations of Planetary Embryos in Three Dimensions.* Icarus 136, 304-327.

[4] Canup, R.M., Asphaug, E. 2001. *Origin of the Moon in a giant impact near the end of the Earth's formation.* Nature 412, 708-712.

[5] Morbidelli, A., Petit, J.M., Gladman, B., Chambers, J. 2001. *A plausible cause of the late heavy bombardment*. Meteoritics and Planetary Science 36, 371-380.

[6] G. Ryder, *Mass flux in the ancient Earth-Moon system and benign implications for the origin of life on Earth*, J. Geophys. Res. 107 (E4) (2002), 5022, doi: 10.1029/2001JE001583.

[7] Gomes R., Tsiganis, K., Morbidelli, A., Levison, H.F., 2005. *The cataclysmic Late Heavy Bombardment triggered by a delayed start of planet migration*. Nature, submitted.

[8] W.K. Hartmann, *Megaregolith evolution and cratering cataclysm models--Lunar cataclysm as a misconception (28 years later), Meteoritics & Planet*. Sci. 38 (2003) 579-593.

[9] W.F. Bottke Jr., D. Vokrouhlický, D.P. Rubincam, M. Brož, *The effect of Yarkovsky thermal forces on the dynamical evolution of asteroids and meteoroids, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (Eds.), Asteroids III,* Univ. Arizona Press, Tucson, 2002, pp. 395-408.

[10] T.S. Culler, T.A. Becker, R.A. Muller, P.R. Renne, *Lunar impact history from* $^{40}Ar/^{39}Ar$ *dating of glass spherules,* Science 287 (2000) 1785-1788.

[11] H. Atkinson, C. Tickell, D. Williams (Eds.), *Report of the Task Force on Potentially Hazardous Near Earth Objects, British National Space Centre*, London, 2000, 54 pp.

[12] F. Watson, *Between the Planets, The Blakiston Co.,* Philadelphia, 1941, 222 pp.

[13] R.B. Baldwin, *The Face of the Moon,* Univ. Chicago Press, Chicago, 1949, 239 pp.

[14] E.J. Öpik 1998, *On the catastrophic effect of collisions with celestial bodies*, Irish Astron. J. 5 (1958) 36.

---

[15] E.M. Shoemaker, *Impact mechanics at Meteor Crater, Arizona*, in: B.M. Middlehurst & G.P. Kuiper (Eds.), The Moon Meteorites and Comets, Univ. Chicago Press, Chicago, 1963, pp. 301-336.

[16] R.B. Leighton, B.C. Murray, R.P. Sharp, J.D. Allen, R.K. Sloan, *Mariner IV photography of Mars: initial results,* Science 149 (1965) 627-630.

[17] L.W. Alvarez, W. Alvarez, F. Asaro, H.V. Michel, *Extraterrestrial cause for the Cretaceous-Tertiary extinction,* Science 208 (1980), 1095-1108.

[18] A.R. Hildebrand, W.V. Boynton, *Proximal Cretaceous-Tertiary boundary impact deposits in the Caribbean*, Science 248 (1990) 843-847; see also, A.R. Hildebrand, W.V. Boynton, Cretaceous ground zero, Natural History (6) (1991), 47-53 and G.T. Penfield, Pre-Alvarez impact, Natural History (6) (1991), 4.

[19] *Proceedings of the Planetary Defense Workshop*, Lawrence Livermore Natl. Lab. CONF-9505266, Livermore CA, 1995, 513 pp.

[20] D. Morrison (Ed.), *The Spaceguard Survey: Report of the NASA International Near-Earth Object Detection Workshop*, NASA, Washington D.C., 1992, http://impact.arc.nasa.gov/reports/spaceguard/index.html.

[21] E.M. Shoemaker (Ed.), *Report of the Near-Earth Objects Survey Working Group*, NASA, Washington D.C., 1995, http://impact.arc.nasa.gov/reports/neoreport/index.html.

[22] *T. Gehrels (Ed.), Hazards due to Comets & Asteroids*, Univ. Arizona Press, Tucson, 1994, 1300 pp.

[23] C. Koeberl, K.G. MacLeod (Eds.), *Catastrophic Events and Mass Extinctions: Impacts and Beyond*, Geological Soc. America, Boulder CO, Special Paper 356, 2002, 746 pp.

[24] W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (Eds.), *Asteroids III,* Univ. Arizona Press, Tucson, 2002, 785 pp.

[25] Stuart, J.S. 2001. *A Near-Earth Asteroid Population Estimate from the LINEAR Survey*. Science 294, 1691-1693.

[26] W.F. Bottke, A. Morbidelli, R. Jedicke, J-M. Petit, H.F. Levison, P. Michel, T.S. Metcalfe, *Debiased orbital and absolute magnitude distribution of the Near-Earth Objects*, Icarus 156 (2002) 399-433.

[27] P. Brown, R.E. Spalding, D.O. ReVelle, E. Tagliaferri, S.P. Worden, *The flux of small near-Earth objects colliding with the Earth*, Nature 420 (2002) 294-296.

[28] Wiegert, P., Tremaine, S. 1999. *The Evolution of Long-Period Comets*. Icarus 137, 84-121.

[29] Levison, H.F., Morbidelli, A., Dones, L., Jedicke, R., Wiegert, P.A., Bottke, W.F.2002. *The Mass disruption of Oort Cloud Comets.* Science 296, 2212-2215.

---

[30] Jedicke, R., Morbidelli, A., Spahr, T., Petit, J., Bottke, W.F. 2003. *Earth and space-based NEO survey simulations: prospects for achieving the Spaceguard goal*. Icarus 161, 17-33.

[31] C.R. Chapman, *Space weathering of asteroid surfaces*, Ann. Revs. Earth & Planet. Sci., 2004, in press.

[32] S.J. Bus, F. Vilas, M.A. Barucci, *Visible-wavelength spectroscopy of asteroids*, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (Eds.), Asteroids III, Univ. Arizona Press, Tucson, 2002, pp. 169-182.

[33] S.J. Ostro, R.S. Hudson, L.A.M. Benner, J.D. Giorgini, C. Magri, J-L. Margot, M.C. Nolan, *Asteroid radar astronomy*, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (Eds.), Asteroids III, Univ. Arizona Press, Tucson, 2002, pp. 151-168.

[34] R.P. Binzel, D.F. Lupishko, M. DiMartino, R.J. Whiteley, G.J. Hahn, *Physical properties of near-Earth objects*, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (Eds.), Asteroids III, Univ. Arizona Press, Tucson, 2002, pp. 255-271.

[35] Morbidelli, A., Jedicke, R., Bottke, W.F., Michel, P., Tedesco, E.F. 2002. *From Magnitudes to Diameters: The Albedo Distribution of Near Earth Objects and the Earth Collision Hazard*. Icarus 158, 329-342.

[36] Stuart, J.S., Binzel, R.P. 2004. *Bias-corrected population, size distribution, and impact hazard for the near-Earth objects.* Icarus 170, 295-311

[37] V.R. Oberbeck & M. Aoyagi, *Martian doublet craters,* J. Geophys. Res. 77 (1972) 2419-2432.

[38] C.M. Cook, H.J. Melosh, W.F. Bottke Jr., *Doublet craters on Venus*, Icarus 165 (2003) 90-100

[39] W.J. Merline, S.J. Weidenschilling, D.D. Durda, J.L. Margot, P. Pravec, A.D. Storrs, *Asteroids do have satellites*, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (Eds.), Asteroids III, Univ. Arizona Press, Tucson, 2002, pp. 289-312.

[40] E. Asphaug, W. Benz, *Size, density, and structure of Comet Shoemaker-Levy 9 inferred from the physics of tidal breakup,* Icarus 121 (1996) 225-248.

[41] D.C. Richardson, Z.M. Leinhardt, H.J. Melosh, W.F. Bottke Jr., E. Asphaug, *Gravitational aggregates: evidence and evolution, in*: W.F. Bottke Jr., A. Cellino, P. Paolicchi & R.P. Binzel (Eds.), Asteroids III, Univ. Arizona Press, Tucson, 2002, pp. 501-515

[42] C.R. Chapman, *The evolution of asteroids as meteorite parent-bodies,* in: A.H. Delsemme (Ed.), Comets Asteroids Meteorites: Interrelations, Evolution and Origins,
Univ. of Toledo Press, Toledo OH, 1977, 265.

---

[43] R.J. Whiteley, D.J. Tholen, C.W. Hergenrother, *Lightcurve analysis of four new monolithic rapidly-rotating asteroid*s, Icarus 157 (2002) 139-154.

[44] C.R. Chapman, W.J. Merline, P.C. Thomas, J. Joseph, A.F. Cheng, N. Izenberg, *Impact history of Eros: craters and boulders*, Icarus 155 (2002) 104-118.

[45] C.R. Chapman, *What we know and don't know about surfaces of potentially hazardous small bodies*, in: M.J.S. Belton (Ed.), Mitigation of Hazardous Comets and Asteroids, Cambridge Univ. Press, Cambridge, 2004, in press.

[46] *Earth Impact Database*, http://www.unb.ca/passc/ImpactDatabase/, accessed 12 Dec. 2003.

[47] K.A. Maher, D.J. Stevenson, *Impact frustration of the origin of life*, Nature 331 (1988) 612-614.

[48] N.H. Sleep, K.J. Zahnle, J.F. Kasting, H.J. Morowitz, *Annihilation of ecosystems by large asteroid impacts on the early Earth,* Nature 342 (1989) 139-142.

[49] N.H. Sleep, K. Zahnle, *Refugia from asteroid impacts on early Mars and the early Earth*, J. Geophys. Res. 103 (1998) 28529-28544.

[50] J.C. Armstrong, L.E. Wells, G. Gonzalez, *Rummaging through Earth's attic for remains of ancient life*, Icarus 160 (2002) 183-196.

[51] P.F. Hoffman, A.J. Kaufman, G.P. Halverson, D.P. Schrag, *A Neoproterozoic snowball Earth*, Science 281 (1998) 1342-1346.

[52] P.F. Hoffman, D.P. Schrag, *The snowball Earth hypothesis: testing the limits of global change*, Terra Nova 14 (2002) 129-155.

[53] D.H. Erwin, S.A. Bowring, J. Yugan, *End-Permian mass extinctions*: a review, in: C. Koeberl, K.G. MacLeod (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond, Geological Soc. America, Boulder CO, Special Paper 356, 2002, pp. 363-383.

[54] O.B. Toon, K. Zahnle, D. Morrison, R.P. Turco, C. Covey, *Environmental perturbations caused by the impacts of asteroids and comets,* Revs. Geophysics 35 (1997) 41-78.

[55] D.S. Robertson, M.C. McKenna, O.B. Toon, S. Hope, J.A. Lillegraven, *Survival in the first hours of the Ceno*zoic, Geol. Soc. Am. Bull., 2004, in press.

[56] D.A. Kring, *Environmental consequences of impact cratering events as a function of ambient conditions on Earth*, Astrobiology 3 (2003) 133-152.

[57] C.R. Chapman, *Impact lethality and risks in today's world: lessons for interpreting Earth history*, in: C. Koeberl, K.G. MacLeod (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond, Geological Society of America, Boulder CO, Special Paper 356, 2002, pp. 7-19.

---

[58] D.M. Raup, *Bad Genes or Bad Luck*?, Norton, New York, 1991, 210 pp.

[59] J.G. Hills, C.L. Mader, *Tsunami produced by the impacts of small asteroids*, in: J.L. Remo (Ed.), Near-Earth Objects: The United Nations International Conference, Annals of the New York Academy of Sciences, Vol. 822, 1997, 381-394.

[60] S.R. Chesley, S.N. Ward, *A quantitative assessment of the human and economic hazard from impact-generated tsunami,* Natural Hazards, in press 2005.

[61] D.M. Morrison, C.R. Chapman, D. Steel, R. Binzel, *Impacts and the public: communicating the nature of the impact hazard*, in: M.J.S. Belton (Ed.), Mitigation of Hazardous Comets and Asteroids, Cambridge Univ. Press, Cambridge, 2004, in press.

[62] C.R. Chapman, D. Morrison, *Impacts on the Earth by asteroids and comets: assessing the hazard*, Nature 367 (1994) 33-40.

[63] J.G. Hills, M.P. Goda, *The fragmentation of small asteroids in the atmosphere,* Astron. J. 105 (1993) 1114-1144.

[64] P.A. Bland, N.A. Artemieva, *Efficient disruption of small asteroids by Earth's atmosphere*, Nature 424 (2003) 288-291.

[65] D. Morrison, C.R. Chapman, P. Slovic, *The impact hazard*, in: T. Gehrels (Ed.), Hazards due to Comets & Asteroids, Univ. Arizona Press, Tucson, 1994, 59-91.

[66] R.P. Binzel, *The Torino impact hazard scale*, Planet. Space Sci. 48 (2000) 297-303.

[67] C.R. Chapman, *The asteroid/comet impact hazard: Homo sapiens as dinosaur?,* in: D. Sarewitz et al.(Eds.), Prediction: Science, Decision Making, and the Future of Nature, Island Press, Washington D.C., 2000, pp. 107-134.

[68] D. Rabinowitz, E. Helin, K. Lawrence, S. Pravado, *A reduced estimate of the number of kilometer-sized near-Earth asteroids*, Nature 403 (2000) 165-166.

[69] K.O. Pope, *Impact dust not the cause of the Cretaceous-Tertiary mass extinction*, Geology 30 (2002) 99-102.

[70] L. Clarke, *Panic: myth or reality*, Contexts (American Sociological Association, Univ. Calif. Press) v. 1 #3 2002 (http://www.contextsmagazine.org/content_sample_v1-3.php)

Chapter 3: detection, orbit prediction, and warning

[1] Morrison, D., Chairperson: *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop*. Jet Propulsion Laboratory, Pasadena, CA, Jan. 25, 1992.

---

[2] http://neo.jpl.nasa.gov/faq, accessed December 23, 2008.

[3] http://neo.jpl.nasa.gov/programs, accessed December 23, 2008.

[4] http://sscws1.ipac.caltech.edu/Imagegallery/image.php?image_name=ssc2006-13a, accessed December 23, 2008.

[5] Hildebrand A.R., et al., *The Near Earth Object Surveillance Satellite (NEOSSsat) Mission Enables An Efficient Space-Based Survey (NESS Project) of Interior-To-Earth-Orbit (IEO) Asteroids*. Lunar and Planetary Science XXXVIII, March 12-16, 2007, League City, TX. No. 2372.

[6] http://www.cfa.harvard.edu/iau/mpc.html, accessed December 23, 2008.

[7] http://cfa-www.harvard.edu/iau/NEO/ToConfirm.html, accessed December 23, 2008.

[8] http://ssd.jpl.nasa.gov/?horizons, accessed December 23, 2008.

[9] http://newton.dm.unipi.it/cgi-bin/neodys/neoibo, accessed December 23, 2008.

[10] *Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters: Report of the Near-Earth Object Science Definition Team (SDT),* National Aeronautics and Space Administration (NASA) Office of Space Science Solar System Exploration Division, August 2003.

[11] *Space Mission Priorities for Near-Earth Object Risk Assessment and Reduction: Recommendations to ESA by the Near-Earth Object Mission Advisory Panel (NEOMAP*), European Space Agency (ESA), July 2004.

[12] http://pan-starrs.ifa.hawaii.edu/public/design-features/ps1-prototype.html, accessed December 23, 2008.

[13] http://www.lowell.edu/media/content/general/DCT_fact_sheet_0307.pdf, accessed December 23, 2008.

[14] *Testimony of LSST Director J. Anthony Tyson, Hearing on Near-Earth Objects: Status of the Survey Program and Review of NASA's 2007 Report to Congress.* http://democrats.science.house.gov/media/File/Commdocs/hearings/2007/space/08nov/Tyson_testimony.pdf, accessed December 23, 2008.

[15] *Near-Earth Object Survey and Deflection Analysis of Alternatives - Report to Congress.* March 2007. http://www.nasa.gov/pdf/171331main_NEO_report_march07.pdf, accessed December 23, 2008.

[16] Hirata, N., et al., *Survey of Craters and Impact Structures on the Asteroid Itokawa.* Lunar and Planetary Science XXXVIII, March 12-16, 2007, League City, TX. No. 1572.

---

[17] Shinsuke Abe, et. al., *Mass and Local Topography Measurements of Itokawa by Hayabusa*. *Science*, vol. 312, June 2, 2006, no. 5778, pp. 1344–1347.

[1] Gold, R. E., Principal Investigator: *SHIELD—A Comprehensive Earth Protection System. A Phase I Report to the NASA Institute for Advanced Concepts.* The Johns Hopkins University Applied Physics Laboratory, 1999.

[2] Ivan Bekey: *"Very large yet extremely lightweight space imaging systems"*. Presented at the SPIE Astronomical Telescopes and Instrumentation Conference, Hawaii, 22-28 August 2002.

[3] Ivan Bekey: *"Extremely large yet very low weight and low cost space-based telescopes for detection of 140 meter diameter asteroids at 5.7 AU, and obtaining 6 year warning times for 1 km diameter comets"*. White Paper and presentation at NASA workshop on NEOs, Vail, Colorado, June 26-29, 2006.

[4] Lodders, K. and Fegley, B., Jr.: *The Planetary Scientist's Companion.* Oxford Univ. Press, New York, 1998.

[5] http://seds.lpl.arizona.edu/nineplanets/nineplanets/kboc.html, accessed December 23, 2008.

[6] http://neo.jpl.nasa.gov/risk/doc/palermo.html, accessed December 23, 2008.

[7] http://neo.jpl.nasa.gov/risk/doc/sentry.html, accessed December 23, 2008.

[1] L.W. Alvarez, W. Alvarez, F. Asaro, H.V. Michel, *Extraterrestrial cause for the Cretaceous-Tertiary extinction*, Science 208 (1980), 1095-1108.

[2] David Morrison, Alan W Harris, Geoff Summer, Clark R. Chapman, & Andrea Carusi: *Dealing with Impact Hazard*, 2002 technical summary

[3] David Morrison, *Is the Sky Falling?,* Skeptical Inquirer 1997

[4] Robert B. Adams, Jonathan W. Campbell, Randall C. Hopkins and W. Scott Smith, et.al., "*Near Earth Object (NEO) Mitigation Options Using Exploration Technologies."* Paper presented at the 2007 Planetary Defense Conference, Washington, DC.

[5] D. Izzo, A. Bourdoux, R. Walker, and F. Ongaro; *"Optimal Trajectories for the Impulsive Deflection of NEOs"*; Paper IAC-05-C1.5.06, 56th International Astronautical Congress, Fukuoka, Japan, (October 2005) available in www.esa.int/gsp/ACT/studies_publications.htm

[6] Keith A. Holsapple "*Existing methods of asteroid deflections will work: Impacts and nuclear bombs",* A white paper for NASA NEO Detection, Characterization, and Threat Mitigation Workshop, Vail, Colorado, June, 2006

---

[7] Dr Harry Atkinson, (Chair) Sir Crispin Tickell and Professor David Williams, "*Report of the Task Force on Potentially Hazardous Near Earth Objects*", BNSC Sept 2000

[8] John S Lewis "*Mining The Sky"* Perseus Books 1996

[9] Ivan Bekey, "*Obtaining long warning times on long-period comets and small asteroids: extremely large yet extremely lightweight space telescope systems",* AIAA Planetary Defense Conference: Protecting Earth from Asteroids, Feb 23-26, 2004, Garden Grove, California, USA**.**

[10] Ivan Bekey, "*Extremely large yet very low weight and low cost space-based telescopes for detection of 140 meter diameter asteroids at 5.7 AU, and obtaining 6 year warning times for 1 km diameter comets*". White Paper and presentation at NASA workshop on NEOs, Vail, Colorado, June 26-29, 2006.

[11] Ivan Bekey, "*Very short reaction time, low* ΔV*, non-nuclear mitigation of some NEOs: a case study*". Paper presented at the 2007 Planetary Defense Conference, Washington, DC.

[12] Russell L. Schweickart, Edward T. Lu, Piet Hut and Clark R. Chapman; *"The Asteroid Tugboat"*; Scientific American (November 2003).

[13] Roger Walker, Dario Izzo, Cristina de Negueruela, Leopold Summerer, Mark Ayre and Massimiliano Vasile, **"***Concepts for Near-Earth Asteroid Deflection using Spacecraft with Advanced Nuclear and Solar Electric Propulsion Systems***"** Journal of the British Interplanetary Society July/August 2005 Vol. 59 7/8

[14] Jonathan W. Campbell, *MFS-31408 - Solar Wing And Tether Mechanisms For Asteroid Uncooperative Docking And Asteroid Orbit Adjustments* - U.S. Patent Awarded to NASA.

[15] Ed Lu. *The Gravity Tractor.* Presentation at the Planetary Defense Conference, March 6, 2007, Washington, DC. Also at: http://www.b612foundation.org/papers/AT-GT.pdf

[16] Jonathan W. Campbell, *Laser Prevention of Earth Impact Disasters*, IAF-01-C.2.09 published in the proceedings of the 53d International Astronautical Congress, World Space Congress, Houston, TX, Oct. 2002

[17] Clark R. Chapman, Daniel D. Durda & Robert E. Gold (February 24, 2001) *Impact Hazard, a Systems Approach*, white paper on public policy issues associated with the impact hazard, at http://www.boulder.swri.edu/clark/neowp.html

[18] John Olds, SpaceWorks Engineering. *Multiple Mass Drivers as an Option for Asteroid Deflection Missions.* AIAA Planetary Defense Conference, Washington, DC, March 6, 2007

[19] Donald W. Cox, and James H. Chestek. 1996. *Doomsday Asteroid: Can We Survive?* New York: Prometheus Books. ISBN 1573920665.

Chapter 5: Organizing for the task

[1] *Centre for Research on the Epidemiology of Disasters (CRED) World Disasters Report Emergency Events Database (EM-DAT)* http://www.em-dat.net/documents/PRDISASTERS2005final.pdf

[2] http://www.moroccotimes.com/paper/article.asp?idr=2&id=14935

[3] For more details, see Steven Chesley, *Potential Impact Detection for Near-Earth Asteroids: The Case of 99942 Apophis (2004 MN4),* Proceedings IAU Symposium No 229, 2005.

[4] http://www.cfa.harvard.edu/iau/mpc.html

[5] http://neo.jpl.nasa.gov/faq/#purpose

[6] http://131.114.72.13/cgi-bin/neodys/neoibo

[7] http://www.cfa.harvard.edu/iau/NEO/ToConfirm.htm

[8] See for example: http://131.114.72.13/cgi-bin/neodys/neoibo?objects_list:0;main

[9] See for example: http://131.114.72.13/cgi-bin/neodys/neoibo?quicksearch:0;main

[10] http://neo.jpl.nasa.gov/cgi-bin/neo_ca

[11] *National Response Plan,* http://www.dhs.gov/interweb/assetlibrary/NRP_FullText.pdf, December 2004, released January 6, 2005

[12] *Federal Response to Hurricane Katrina, Lessons Learned*, February 2006.

[13] http://neo.jpl.nasa.gov/missions/

[14] http://www.lpl.arizona.edu/impacteffects/

[15] See for example, Galen Gisler, Robert Weaver, Charles Mader, Michael Gittings, *Two- And Three-Dimensional Simulations Of Asteroid Ocean Impacts* Los Alamos, NM, USA

[16] *NASA Research Announcement, Call For Papers: Near-Earth Object Detection, Characterization, and Threat Mitigation, Solicitation*: NNH06ZAE001R

[17] The B612 Foundation and the Association of Space Explorers are vocal advocates of action to establish an internationally coordinated operational mitigation capability

Chapter 6: Behavioral factors and planetary defense

[1] Helsloot, I., and Ruitenberg A., *"Citizen Response to Disasters: A Survey of Literature and Some Practical Implications,"* Journal of Contingencies and Crisis Management, Vol. 12, No. 2, 2004, pp. 98-111.

[2] Auf der Heide, E., "Common Misconceptions about Disasters: 'Panic', 'the Disaster Syndrome', and 'Looting.' In M. O'Leary, ed., *The First 72 Hours: A Community Approach to Disaster Preparedness*, iUniverse, New York, 2004, pp. 340-380.

[3] Dwyer, J., and Flynn, K., *102 Minutes: The Untold Story of the Fight to Survive Inside the World Trade Center*, Times Books, New York, 2005.

[4] Dynes, R. R., "Finding Order in Disorder: Continuities in the 9/11 Response." Invited Paper, Mid-South Sociological Society, Memphis, TN, 2002.

[5] Quantrelli, E. L., "The Origins and Impact of Disaster Research," In M. O'Leary, ed., *The First 72 Hours: A Community Approach to Disaster Preparedness*, iUniverse, New York, 2004, pp. 321-339.

[6] Cross, J. A., "Megacities and Small Towns: Different Perspectives on Hazard Vulnerability," *Experimental Hazards*, Vol. 3, 2001, pp. 63-80.

[7] Allen, B. P., "After the Missiles: Sociopsychological Aspects of Nuclear War," *American Psychologist*, Vol. 40, No. 8, 1985, pp. 927-937.

[8] Taylor, A. J. W., "Value Conflict Arising from a Disaster," *The Australasian Journal of Disaster and Trauma Studies*, Volume 2, 1999. http:www.massey.ac.nz/trauma/issues /1999-2/taylor.htm. Accessed 4.3.2005.

[9] Chester, D. K., "Theology and Disaster Studies," *Journal of Volcanology and Geothermal Research*, Vol. 146, 2005, pp. 319-328.

[10] Garshnek, V., Morrison, D. L., and Burkle, F. M., Jr., "The Mitigation, Management and Survivability of Asteroid/Comet Impact with Earth." *Space Policy*, Vol. 16, 2000, pp. 213-222.

[11] Birkland, T. A. *After Disaster: Agenda Setting, Public Policy, and Focusing Events*. Georgetown, DC: Georgetown University Press, 1997.

[12] Solecki, W. D., and Michaels, S., "Looking Through the Post disaster Policy Window," *Environmental Management*, Vol. 16, No. 4, 1994, pp. 587-595.

[13] Janis, I. L., and Mann, L. *Decision Making: A Psychological Analysis of Conflict, Choice and Commitment*, The Free Press, New York, 1977

[14] Larson, E., *Isaac's Storm: A Man, a Time, and the Deadliest Hurricane in History*, Vintage Books, New York, 1999.

---

[15] Beevor, A., *Stalingrad: The Fateful Siege, 1942-1943*, Penguin, New York, 1997.

[16] Kolata,, G. *Flu: The Story of the Great Influenza Pandemic*, New York, Touchstone, 1999.

[17] Mason, R. O., "Lessons in Organizational Ethics from the Columbia Disaster: Can a Culture be Lethal?," *Organizational Dynamics*, Vol. 33, No. 2, 2004, pp. 128-142.

[18] Dynes, R. R., "Noah and Disaster Planning: The Cultural Significance of the Flood Story," *Journal of Contingencies and Crisis Management*, Vol. 11, No. 4, 2003, pp. 170-177.

[19] Milleti, D. S., and Peek, L., "The Social Psychology of Public Responses to Warnings of a Nuclear Power Plant Accident," *Journal of Hazardous Materials*, Vol. 75, 2000, pp. 181-194.

[20] Mulilis, J-P., Duval, T. S., and Rombach, D., "Personal Responsibility of Tornado Preparedness: Commitment or Choice?," *Journal of Applied Social Psychology*, Vol. 31, No. 8, 2001, pp. 1659-1688.

[21] Dudley-Grant, G. R., Mendez, G. L., and Zinn, J., *"*Strategies for Anticipating and Preventing Psychological Trauma of Hurricanes Through Community Education," *Professional Psychology: Research & Practice,* Vol. 31, No. 4, 2000, pp. 387-392

[22] De Man, A. F., and Simpson-Housley, P., "Factors in Perception of Earthquake Hazard", *Perceptual and Motor Skills*, Vol. 64, No. 3, Pt. 1, 1987, 64 pp. 815-820.

[23] Shalev, A. Y., "Debriefing Following Traumatic Exposure." In Ursano, Robert J., et. al., Eds, *Individual and Community Responses to Trauma and Disaster: The Structure of Human Chaos*, Cambridge, Cambridge University Press, 1994, pp. 201-219.

[24] Ursano, R.J., Tzu-Cheng, K., and Fullerton, C.S., "Posttraumatic Disorder and Meaning: Structuring Human Chaos," *Journal of Nervous & Mental Disease*, Vol. 180, No. 12, 1992, pp. 756-759.

[25] Ursano, R.J., McCaughey, B. G, and Fullerton, C. S., "Trauma and Disaster," in R. J. Ursano, et. al., Eds, *Individual and Community Responses to Trauma and Disaster: The Structure of Human Chaos*, Cambridge, Cambridge University Press, 1994, pp. 3-31.

[26] Hodgkinson, P. E. and Stewart, M., *Coping with Catastrophe: A Handbook of Post-Disaster Psychosocial Aftercare*, Routledge, New York, 1998.

[27] American Red Cross, "Emotional Health Issues for Families of Disaster Workers," http:www.trauma-pages.com/arcwkfm.html. Accessed 9/08/08.

[28] Swenson, C. et. al., "Impact of a Natural Disaster on Preschool Children: Adjustment 14 Months After a Hurricane," *American Journal of Orthopsychiatry*, Vol. 66., No. 1, 1996, pp. 122-130.

---

[29] Ruestemli, A, and Karanci, A. N., "Distress Reactions and Earthquake-Related Cognitions of Parents and their Adolescent Children in a Victimized Population," *Journal of Social Behavior and Personality*, Vol. 11, No. 4, 1996, pp. 767-780.

.

[30] Ursano, R J., and McCarroll, J E., "Exposure to Traumatic Death: The Nature of the Stressor.," R. J. Ursano et al., eds., *Individual and Community Responses to Trauma and Disaster: The Structure of* Human Chaos, Cambridge University Press, Cambridge, 1994pp. 46-72.

[31] Keller, R.T., and Bobo, W.V. "Handling Human Remains Following the Terrorist Attack on the Pentagon: Experiences of 10 Uniformed Health Care Workers," *Military Medicine*, Vol. 17, Suppl. 4, 2002, pp. 8-11.

[32] Stehr, S., and Simpson, D., *Victim Identification and Management Following the Collapse of the World Trade Center Towers*, Quick Response Report # 148. Boulder, Colorado: Natural Hazards Research and Applications Information Center, University of Colorado.

[33] McCarroll, J. E., Ursano, R. J., Wright, K. M., and Fullerton, C. S., "Handling Bodies After Violent Death: Strategies for Coping," *American Journal of Orthopsychiatry,* Vol. 63, No. 2, 1993, pp. 209-214.

[34] Ursano, R. J., McCaughey, B. G., and Fullerton, C. S., *Individual and Community Responses to Trauma and Disaster: The Structure of Human Chaos*. Cambridge, Cambridge University Press, 1994.

[35] Chochinov, H. M., "Vicarious Grief and Response to Global Disasters." *Lancet,* Vol. 266, 2005, pp. 697-698.

[36] Kennedy, C., Charlesworth, A., and Chen, J-Y, "Disaster at a Distance: Impact of 9.11.01 Televised News Coverage on Mothers' and Children's Health," *Journal of Pediatric Nursing*, Vol. 19, No. 5, 2004, pp. 329-339.

[37] Myers, D, and Wee, D. F., *Disaster Mental Health Services*, Bruner Routledge, New York, 2005.

[38] Frykberg, E. R., "Disaster and Mass Casualty Management: A Commentary on the American College of Surgeons Position Statement," *Journal of the American College of Surgeons*, Vol. 197, 2003, pp. 857-859.

[39] World Health Organization, "Mental Health in Emergencies: Mental and Social Aspects of Health of Populations Exposed to Extreme Stressors," Department of Mental Health and Substance Dependence, Geneva, 2003.

[40] Kaniasty, K., and Norris, F. H., "Mobilization and Deterioration of Social Support Following Natural Disaster," *Current Directions in Psychological Science*, Vol. 3, 1995, pp. 94-98.

[41] Raphael, B., and Wooding, S., "Debriefing: Its Evolution and Current Status," *Psychiatric Clinics of North America*, Vol. 27, 2004, pp. 407-423.

---

[42] Stuster, J. W., *Bold Endeavors*, Naval Institute Press, Annapolis, 1996.

[43] Harrison, A. A., *Spacefaring: The Human Dimension*. The University of California Press, Berkeley. 2001.

[44] Harrison, A. A., "New Directions in Spaceflight Behavioral Health: A Workshop Integrating Research and Application," *Aviation, Space and Environmental Medicine*, No. 6, Section II Supplement, 2005, B3-B12.

[45] Finney, B. R., and Jones, E. M., eds., *Interstellar Migration and the Human Experience,* Berkeley, University of California Press, 1984.

[46] Birdsell, J. B., "Biological Foundations of Small, Human Founding Colonies," in B. R. Finney and E. M. Jones, eds., *Interstellar Migration and the Human Experience*, Berkeley, University of California Press, 1985, pp. 110-119.

[47] Wachter, K., "Predicting Demographic Contours of an Interstellar Future," in B. R. and E. M. Jones, eds., *Interstellar Migration and the Human Experience,* Berkeley, University of California Press, 1984, pp. 120-133.

[48] Hodges, W. A., "The Division of Labor: A Response to Demographic Contours," in B. R. Finney and E. M. Jones, eds., *Interstellar Migration and the Human Experience* Berkeley, University of California Press, 1984, pp. 134-151.

Chapter 7: Policy implications

[1] Australia, Belgium, Canada, the Czech Republic, Denmark, the European Commission, France, Germany, Italy, Japan, Korea, Norway, South Africa, the United Kingdom, the United States

[2] Australia, Belgium, Canada, the Czech Republic, Denmark, the European Commission, France, Germany, Italy, Japan, Korea, Norway, South Africa, the United Kingdom, the United States

[3] ESA has 17 Member States; the national bodies responsible for space in these countries sit on ESA's ruling Council: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Norway, Portugal Spain, Sweden, Switzerland and the United Kingdom. Canada also sits on the Council and takes part in some projects under a Cooperation Agreement. The Czech Republic, Hungary, Romania and Poland are participating in the Plan for European Cooperating States (PECS).

[4] The Inter-Agency Space Debris Coordination Committee (IADC) is an international governmental forum for the worldwide coordination of activities related to the issues of man-made and natural debris in space. The primary purposes of the IADC are to exchange information on space debris research activities between member space agencies, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperative activities, and to identify debris mitigation options. The IADC member agencies include the following: ASI (Agenzia Spaziale Italiana), BNSC

(British National Space Centre), CNES (Centre National d'Etudes Spatiales), CNSA (China National Space Administration), DLR (German Aerospace Center), ESA (European Space Agency), ISRO (Indian Space Research Organisation), JAXA (Japan Aerospace Exploration Agency), NASA (National Aeronautics and Space Administration), NSAU (National Space Agency of Ukraine), ROSCOSMOS (Russian Federal Space Agency)

[5] UN document A/AC.105/890 describes the guidelines adopted by the Scientific and Technical Subcommittee (STSC) of the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) in February, 2007. The guidelines were developed via consensus within the Scientific and Technical Sub-Committee and endorsed by the full COPUOS in June, 2007. These guidelines are consistent with the IADC Space Debris Mitigation Guidelines.

Useful Links:

ASE	http://www.space-explorers.org/committees/NEO/neo.html
IADC	http://www.iadc-online.org/index.cgi?item=home
UK	http://www.nearearthobjects.co.uk/report/resources_task_intro.cfm
Council of Europe	http://www.astrosurf.com/luxorion/impacts-resolution.htm
ESA	http://www.esa.int/gsp/NEO/doc/NEOMAP_report_June23_wCover.pdf
USA	http://impact.arc.nasa.gov/gov_asteroidperils_1.cfm
	http://impact.arc.nasa.gov/gov_earthasteroids_1.cfm
	http://impact.arc.nasa.gov/gov_cong_hearings_1.cfm
	http://www.hq.nasa.gov/office/pao/FOIA/NEO_Analysis_Doc.pdf
	http://impact.arc.nasa.gov/gov_threat_2002.cfm
OECD	http://www.oecd.org/dataoecd/39/40/2503992.pdf
UN	http://www.unoosa.org/oosa/COPUOS/stsc/2007/index.html
	http://www.unoosa.org/oosa/SpaceLaw/outerspt.html