Final Report

NASA Workshop on Scientific Requirements for Mitigation Of Hazardous Comets and Asteroids

Held in Arlington, VA, September 3-6, 2002

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Michael J.S. Belton, Principal Investigator
Belton Space Exploration Initiatives, LLC. (HYPERLINK "mailto:belton@azstarnet.com)" belton@azstarnet.com)

Erik Asphaug (UCSC), Co-investigator
Walter Huebner (SWRI), Co-investigator
Donald K. Yeomans (JPL), Co-investigator

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1. EXECUTIVE SUMMARY AND RECOMMENDATIONS

Purpose of the workshop and primary conclusions:

The “Workshop on Scientific Requirements for Mitigation of Hazardous Comets and Asteroids,” supported by the NASA’s Office of Space Science, was held on September 3 – 6, 2002, at the Hyatt Hotel in Arlington, VA. Seventy-seven scientists, engineers and military experts from the United States, Europe, and Japan participated. Its purpose was to consider the *scientific requirements* for avoidance and mitigation of hazards to the Earth due to asteroids and comets, *i.e.,* what should be done to ensure that an adequate base of scientific knowledge is created that will allow efficient development of a reliable, but as yet undefined, collision mitigation system when needed in the future.

It became clear that *the prime impediment to further advances in this field is the lack of any assigned responsibility to any national or international governmental organization to prepare for a disruptive collision and the absence of any authority to act in preparation for some future collision mitigation attempt.*

Eighteen major conclusions (listed below) were formulated that provided the basis for five recommendations. In brief, these are:

That NASA be assigned the responsibility to advance this field,
That a new and adequately funded program be instituted at NASA to create, through space missions and allied research, the specialized knowledge base needed to respond to a future threat of a collision from an asteroid or comet nucleus,
That the Spaceguard survey be extended to cover the hazardous part of the population of possible impactors down to 200 m in size,
That the DoD more rapidly communicate surveillance data on natural airbursts,
That governmental policy makers formulate a chain of responsibility for action in the event a threat to the Earth becomes known.

A record of some of the workshop presentations can be found in a volume of extended abstracts on the web at: HYPERLINK "http://www.noao.edu/meetings/mitigation/eav.html" www.noao.edu/meetings/mitigation/eav.html. Other invited papers will be published by Cambridge University Press as a book entitled “Mitigation of Hazardous Impacts due to Asteroids and Comets,” in the spring of 2003.

What was discussed:

All aspects of near-Earth objects were discussed. These included the completeness of our knowledge about the population of potential impactors, their physical and compositional characteristics, the properties of surveys that need to be done to find hazardous objects smaller than 1 km in size, our theoretical understanding of impact phenomena, new laboratory results on the impact process, the need for space missions of specific types, education of the public, public responsibility for dealing with the threat, and the possible roles of NASA, the military, and other agencies in mitigating the threat.

Brief assessment of status and needs:

About 2,225 near-Earth objects are now known in the 10m to 30km size range out of a total population of about a million. Physical information exists only for a small number (~300) of these. *It is estimated that there are roughly 25,000 are larger than 150m in size (above which the potential exists for easy penetration of the Earth’s protective atmosphere) but it is estimated that only ~250 of these are potentially hazardous.* The number of objects larger than 1 km (i.e., objects capable of global scale catastrophe) is now estimated to lie between 900 and 1230 and about 55% of these have been found – none on Earth intersecting trajectories. *Without continuing improvements to existing survey equipment it is expected that ~70% will have been found by 2008. Extension of the Spaceguard survey may be needed to achieve its goal.*

To find a significant fraction of potentially hazardous objects between 100m and 1km in a reasonable time will require advanced telescopic capabilities (LSST, PanStarrs). Extensive follow-up astrometric observations including radar data will also be needed to confidently identify hazardous impactors with enough lead-time (decades) to allow effective mitigation.

New space and telescopic observations together with modeling indicate high internal porosity for many near-Earth objects and have resulted in changing views as to the nature of the surface processes on asteroids. Physical and compositional knowledge of the surface layers and interiors of near-Earth objects, given their diversity, is judged inadequate for mitigation purposes. Extensive observational and experimental studies from spacecraft, and Earth based telescopic systems, are required. Similarly laboratory and theoretical work is needed to clarify how porosity at the surface or in the interior of an object affects the outcome of a rapid application of large amounts of energy. *Modeling suggests that deep layers of porous surface materials may have a dramatic effect on mitigation using high-energy explosives so that previous estimates of requirements may have to be increased by factors of 100 or more.*

Substantial investment and time will be required to accomplish an adequate level of physical and compositional knowledge.

A roadmap for future advances:

A strawman roadmap suggests that $5-6B over 25yr (to keep total annual expenditures to <$300M/yr) involving a number of government agencies will be required. This roadmap also includes resources for in-space interaction experiments so that the process of *learning* how to apply possible mitigation techniques, and the rapid identification of the most effective techniques, can begin.

Major conclusions:

On the hazardous population –

A future collision of an asteroid or cometary nucleus with the Earth with catastrophic effects is inevitable unless technology is developed to modify the orbit of such bodies.

The most likely objects to collide with the Earth with catastrophic effects are 100 m or more in size and have a significant probability (20%) of colliding with the Earth over times of human interest (~100yr).

Excellent progress has been made in satisfying the congressional mandate charged to NASA to find 90% of near-Earth objects with H<18 (size greater than 1 km) by 2008. However, models indicate that completion by 2008 will require that technical improvements to the current discovery systems be made.

On the organization needed to respond to a threat -

There exists no government agency or international organization with the assignment or acceptance of responsibility for averting the threat of an impending collision.

Once an object is verified to be on an Earth-threatening trajectory, there is no identified organization responsible for the timely reporting of these events to the public or other nations

The NASA charter includes the goal of protecting our home planet, which is relevant to the mitigation problem.

The priorities of the technical and scientific objectives of space missions designed to acquire a relevant basis of knowledge for mitigation purposes may be distinct from those in other high priority space exploration programs which address the same class of targets (small planetary bodies) and that are already being pursued by NASA and other foreign space agencies.

The costs incurred by the above program of space and associated Earth-based research will be substantial, but possibly could eventually be offset by profitable activities in the low-gravity, resource-rich environment of asteroids and cometary nuclei.

An estimate of the time necessary to acquire this basis of knowledge is measured in decades.

The threat of catastrophic collisions with the Earth is global and any and all nations may be affected.

There is strong international interest in understanding the nature of this threat.

On what is required to respond to a threat –

The development of a relevant and adequate knowledge basis for future attempts to reliably mitigate an impending collision of an object greater than 100 m in size will require scientific proof of the efficacy of

a wide range of proposed techniques in the space environment, including ways to measure relevant physical and compositional properties.
A series of space missions is required in order to acquire a relevant and adequate basis of knowledge on which to base the future development of a reliable collision mitigation system.
A multifaceted program of Earth-based theoretical, experimental, observational, and interpretive research is necessary to support, complement, guide, and extend a program of space missions for mitigation purposes.
Relatively low-cost Earth-based surveys for NEOs are now technically feasible down to a size limit of about 200 m.
Committees of the National Research Council of the National Academy of Sciences have recommended the construction of a large-aperture synoptic survey telescope (LSST) that is capable of detecting 90% of near-Earth objects above the 200 m size limit within approximately a decade.

On concerns with current activities –

Department of Defense space surveillance programs regularly observe upper atmosphere airbursts with the release of 1 kT of energy and above caused by objects entering the Earth's atmosphere from space with typical sizes near 10 m.
The public and nations with nuclear capability outside the U.S. may not be aware of this continuing flux of extraterrestrial objects and their effects in the Earth's upper atmosphere.

Recommendations:

Based on the above conclusions, the members of the workshop's scientific and local organizing committees formulated the following *recommendations* that, when implemented, will lead to the acquisition of a relevant body of scientific knowledge on which a practical and reliable collision mitigation system could be developed at some time in the future.

Recommendation 1. That the National Aeronautics and Space Administration be assigned the responsibility to acquire relevant scientific knowledge on the compositional and physical properties of the diverse population of hazardous objects that may threaten the Earth and on which the future development of a reliable collision mitigation system could be based. In undertaking this responsibility, the interests and cooperative support of the international community should be welcomed.

Recommendation 2. That a new and appropriately funded program be instituted at the National Aeronautics and Space Administration, consistent with its mission to "Understand and protect our home planet," to create an adequate basis of scientific knowledge through space missions and supporting Earth-based research on which future attempts to reliably mitigate impending collisions of hazardous objects with the Earth can be founded.

Recommendation 3. That the congressionally mandated survey presently being pursued by the National Aeronautics and Space Administration to catalog near-Earth objects brighter than H~18 (~ 1 km in size), be extended to include 90% of hazardous near-Earth objects down to a size range of 200 m over the next decade.

Recommendation 4. That the Department of Defense increase the speed with which it makes information about natural airburst phenomena available to the public and other nations to prevent possible misinterpretations of these small, frequent events.

Recommendation 5. That government and international policy makers act now to formulate and publish an agreed upon chain of responsibility for action in the event that an Earth-threatening object is discovered.

2. INTRODUCTION.

The "Workshop on Scientific Requirements for Mitigation of Hazardous Comets and Asteroids" was held on September 3 – 6, 2002, at the Hyatt Hotel in Arlington, VA. The National Aeronautics and Space Administration through the Solar System Exploration Division of the Office of Space Science sponsored the workshop in response to a proposal "Scientific Requirement for Mitigation of Hazardous Comets and Asteroids" from the National Optical Astronomy Observatory (NOAO) with M.J.S. Belton of Belton Space Exploration Initiatives, LLC (BSEI), as Principal Investigator. In addition to this primary support, the workshop also received generous support from Science Applications International Corporation, Ball Aerospace and Technologies Corporation, Lockheed Martin Space Systems Company, and the University of Maryland. The rationale that was proposed for the workshop is described in Appendix A.

Seventy-seven scientists, engineers and military experts from the United States, Europe, and Japan participated in the workshop (Attachment B), which was organized around a program of 25-invited presentations, 25 posters, and 2 panel discussions (Attachment C).

E. Asphaug (UCSC) chaired the Scientific Organizing Committee (Attachment D) and was responsible for the scientific program. M.F. A'Hearn (U. Maryland) chaired the Local Organizing Committee (Attachment D) and was responsible for all logistical arrangements. Travel grants were provided to selected participants to ensure the presentation of invited papers. Twenty-three members of the international press and media corps attended the workshop, which resulted in considerable media coverage of the proceedings (Attachment E). D. Isbell (NOAO) coordinated arrangements for press activities. A web site for the workshop was provided by NOAO (HYPERLINK "http://www.noao.edu/meetings/mitigation" http://www.noao.edu/meetings/mitigation) and coordinated by N.H. Samarasinha (NOAO).

The proceedings of the workshop are being documented in two ways. A book based on the proceedings at the workshop entitled "Mitigation of Hazardous Impacts due to Asteroids and Comets" edited by M.J.S. Belton, D.K. Yeomans (JPL), and T.H. Morgan (NASA) will be published by Cambridge University Press in 2003. An outline of the book is in Appendix F. Secondly, a volume of extended abstracts (Appendix G), edited by E. Asphaug and N. Samarasinha, is available on the Internet at HYPERLINK "http://www.noao.edu/meetings/mitigation/eav.html" http://www.noao.edu/meetings/mitigation/eav.html.

3. BACKGROUND AND GOALS OF THE WORKSHOP.

Background:

Scientific and, to some extent, public interest in the effects of collisions between objects in space and the Earth and the possible consequences of these collisions for life and society was rekindled when Alvarez *et al.* (1980) showed that the mass extinctions that mark the boundary of the cretaceous and tertiary were likely the result of the collision of a large asteroid with the Earth. Since that time the world has witnessed some of the awful power of such impacts with the collisions of numerous fragments of comet Shoemaker-Levy 9 with Jupiter, and the finding of the remains of the massive crater associated with the cretaceous/tertiary layer near Chicxulub, Mexico.

With the publication of "Hazards due to Asteroids and Comets" (Gehrels, 1994), the scientific community began detailed documentation of the nature of the hazard to the Earth, what is known of the population of potential asteroidal and cometary impactors, and to understand the nature of the tools that might be used to mitigate future collisions.

In response to the argument that a collision with a near-Earth object larger than 1 km in size could cause global catastrophe that would put the entire human specie at risk, the Spaceguard goal (Morrison, 1992) was mandated by Congress in 1994 and implemented by NASA in 1998. In parallel with this initiative, work in the United States and other nations has led to several international workshops, the institution of monitoring efforts to alert the public to possible future collisions, and a governmental task force on NEOs in the United Kingdom (Atkinson, 2001). As a result of these activities there also has arisen increasing interest in the effects of collision of the Earth with objects of much smaller than 1 km in size. Such collisions, which are more frequent, can cause substantial regional devastation either by direct impact on land or through the medium of tsunamis caused by ocean impacts. It is this interest that led to the present workshop (Appendix A).

Current activities at NASA, NSF, and the DoD:

A new statement of the NASA mission includes the goal "To understand and protect our home planet." However, most of the emphasis towards this goal appears to be protection of the environment, safer air transportation, and homeland security (O'Keefe, 2002); there is apparently no focus, at least to our knowledge, on hazards to the planet due, for example, to near-Earth objects that might find themselves on a collision course. In the Office of Space Science substantial sums have been and continue to be invested in space mission projects to explore asteroids and comets with the objective of understanding their physical and compositional nature and what they can tell us about the origin and evolution of the planetary system. However, there is little emphasis in these widely supported and scientifically important solar system exploration projects on problems associated with the mitigation of collisions of such objects with the Earth. Roughly $3-4M is spent annually on research and analysis programs on near-Earth objects – with the majority of these funds being invested in searches for NEOs to fulfill the congressionally mandated Spaceguard goal of finding 90% of NEOs with $H < 18$ (size greater than ~ 1 km) by 2008. Only a small fraction of these funds are spent to address the physical and compositional characterization of NEOs with the result that we remain ignorant of even the crudest indications of the nature of most of the objects that have now been found. Recently a Science Definition Team (SDT) has been formed within the Solar System Exploration Program to understand how the current Spaceguard survey might be extended to near-Earth objects of sizes less than 1 km in diameter and to define a size cutoff where a cost/risk benefit study would suggest that an advanced warning only is appropriate, instead of a mitigation attempt.

At the NSF a small grant program for solar system research is supported. However, there is no specific focus on the collision mitigation problem.

As part of their duties to the nation, the DoD maintains a program of space surveillance that detects energetic upper atmospheric airbursts caused by random objects that originate from near-Earth space. There are roughly 30 of these airburst each year that typically release ~1kT TNT equivalent energy and are caused by objects primarily in the 1-10 m size range. The DoD does not support, at least to our knowledge, any programs that specifically address mitigation of collisions of objects from space with the Earth.

Goals of the workshop:

Given the above background, in particular the absence of any government supported programs or defined responsibility to deal with inevitable future collisions of serious consequence, the following initial goals were set for the workshop:

Determination of the scientific requirements for those collision avoidance and impact mitigation technologies that are considered viable. This includes identification of what measurements are needed and the accuracy that should be attained.
Determination of what mission models and instrumentation developments are needed to make these measurements.
Construction of a mission and research roadmap for achieving an adequate level of knowledge on which to base the future development of practical and reliable collision avoidance and impact mitigation systems.

4. SYNOPSIS OF PROCEEDINGS

Modeling of the population of possible impactors:

Bottke (SwRI) discussed the sources of NEO and their dynamical properties and showed how these sources could be linked with the observed population thus providing a quantitative estimate of observational selection effects. Coupling their model with the properties of active survey systems they estimated that the Spaceguard goal of finding 90% of objects brighter than H=18 (roughly 1 km across) could be achieved as early as 2013. The Spaceguard goal is to reach 90% by 2008 – Bottke *et al.,* predict ~ 70% completion by then. However, with continuing improvements to the current discovery systems, 90% completion by 2008 may be within reach.

Chesley (JPL) argued that detection of NEOs was not enough and it is the detection of the hazardous impactor population itself that counts. He discussed his results on the modeling of the impactor population (*i.e.,* those virtual objects in the Bottke *et al.,* model that actually could impact the Earth) in order to find out how many impactors could actually be recognized and with what advance notice. The somewhat disquieting result indicates that, unless a great deal of information on a discovered impactor is acquired just after discovery, the potential for impact might not be recognized until it is too late. Chesley also pointed out that whereas the current NEO discovery surveys most often search near opposition, most hazardous objects, one kilometer in diameter and larger, would be more efficiently found at relatively low solar elongation angles away from the opposition point.

The discussion of possible impactors generally concentrated on NEOs and, while recognizing the small contribution of the flux of long period comets to the impact hazard, did not consider the latter objects in detail.

Physical characteristics of the population of possible impactors:

Harris (DLR) outlined what is known about the physical properties of NEOs and emphasized the diversity of objects that exist. Recent discoveries include the identification of numerous binary systems that have yielded an array of bulk densities. These suggest that the population is characterized by a wide range of bulk porosity (0 – 80%). Other advances suggest large ranges of albedo (with implications for the inferred size of the objects), a dependence of albedo on size (smaller objects tend to be brighter), and a marked change in spin properties at a size of about 200 m. Asteroids smaller than this often spin faster than the gravitational stability limit suggesting considerable internal strength.

Harris (JPL) described the known properties of the NEO population and argued that rendezvous missions will be a necessity for the application of viable mitigation strategies and pointed out that objects on near impact trajectories are amongst the most difficult targets for which this can be accomplished, requiring on average the same Δv required to send a payload to Pluto.

Binzel (MIT) presented a review of the known properties of NEOs pointing out that we now have some physical information about some 300 objects. In his presentation he focused on how these, largely ground- and orbital-based observations, provide information on some of the properties that are of interest to the basis of mitigation technologies.

Ostro (JPL) reviewed the abilities of the Arecibo and Goldstone radars to give precise information on the orbits of NEOs and comets as well as define their sizes, shapes, spin states, and surface roughness. Accurate orbits are needed to make accurate prediction of the possibility of impact with long (decades) lead times. He pointed out that future radar capabilities could also be critical in determining the precise orbits of hazardous long period comets.

Chapman (SwRI) reviewed what is known about the physical and compositional properties of the surfaces of asteroids pointing out that many of the suggested techniques, particularly those employing low-thrust propulsion, for deflecting asteroids depend on anchoring to the surface or removal of surface materials. Is a regolith layer present? Is it deep or superficial? These are the questions to be addressed and a diversity of situations is expected. Recent results from the NEAR mission showing boulder fields and ponding of fine materials have exploded the idea that the better-known properties of the lunar regolith could be used as reliable surrogates for asteroidal surface properties. He stressed that an intensified phase of surface science exploration as well as interior explorations of an adequate sample of the diverse NEO population will be necessary to lay a firm scientific basis for future mitigation technology.

Di Martini (Torino Observatory) discussed observations of fireballs and their interpretation in terms of physical properties. These observations are an effective means to understand the physical properties of impacting objects at the limit of small sizes, *e.g.,* the fragmentation of objects with sizes less than ~100 m. He pointed out that ESA's future Galileo Constellation mission could be an important tool for surveillance of small NEOs entering the atmosphere.

Theory:

Melosh (U. Arizona) pointed out that the reason why we see a relatively large fraction of binaries in the NEO population may be the number of close tidal encounter interactions that these objects had during their dynamical evolution. If these objects are intrinsically weak, *e.g.,* rubble piles, the formation of a binary system during a close planetary encounter maybe a likely outcome. Evidence of such processes can be seen in the Jupiter system where crater chains are seen of the surface of the icy satellites.

Holsapple (U. Washington) discussed impact (cratering) theory in light of the new information that indicates high porosity for many NEOs and the unexpected properties of the large craters that were observed on Mathilde by the NEAR Shoemaker spacecraft. He showed that in such situations the process of compaction must play a significant role in the dynamics of cratering. He concluded that early estimates of the ability of mitigation strategies using high-energy explosions to deflect an asteroid might be insufficient by up to four orders of magnitude.

Kofman (LPG Grenoble) presented the theoretical basis for low frequency radio reflection (radar) tomography, a technique that can sense complex permittivity gradients, boundaries, and discontinuities in the interior of small asteroidal and cometary bodies. This technique should make future exploration of the interior structure of such objects possible a reality.

Missions:

Dissly (Ball Aerospace) reviewed various spacecraft and technology issues surrounding small body missions.

Conway (U. Illinois) discussed the theory behind the optimization of low-thrust propulsion and ways of efficiently maximizing orbital deflection strategies.

Kahle (Dresden U. Tech) discussed the general science requirements for proposed mitigation strategies and focused on two systems that should work given enough warning time: Ablation (sublimation) of asteroidal surface material by use of a solar concentrator and induced magnetospheric propulsion using an electromagnetic coupling to the solar wind flow. These systems have the advantage of relying minimally upon the specific properties of the asteroid; however, development of such systems is still decades away and each technique will present major technical challenges.

Yano (ISAS) described the goals and status of the MUSES-C mission emphasizing the relevance of its mobile surface exploration experiment to the mitigation problem.

Scheeres (U. Michigan) pointed out that in cases like the MUSES-C mission where the mass of the target object is small and the shape irregular, spacecraft motion may be far from Keplerian. Motion of artifacts on the surface may be very hard to predict unless the internal mass distribution is well understood. Transient dust atmospheres and unpredictable regolith motion may also represent hazards to operations.

Schweickart (B612 foundation) briefed the workshop on of the goal of the newly formed B612 foundation "to significantly alter the orbit of an asteroid in a controlled manner by 2015." More details can be found at HYPERLINK "http://www.B612Foundation.org" http://www.B612Foundation.org.

Experimentation:

Sears (U. Arkansas) described laboratory and near zero gravity airborne experiments to simulate taking of samples from an asteroidal surface. The experience clearly demonstrates that many problems face the experimentalist for even this apparently simple task. Sears advocated intensive preflight experimentation with emphasis on practice and realistic simulations.

Ball (Open University, UK) gave a review of available technologies for exploring upper surface layers by means of landed instrumentation, penetrators, and "moles." He advocated early stress on investigation of the utility of tomographic techniques, both seismic and radio reflection, and investigations of mechanical and thermal properties to create a basis for mitigation technology.

Walker and Huebner (SwRI) reviewed lunar seismology and the possible application of miniaturized seismometers on NEOs for the exploration of internal structure. They emphasized the uncertainties of the NEO situation and advocated exploratory experiments in order to learn how to apply this technique to small cometary and asteroidal bodies.

Durda (SwRI) spoke on the experience and benefits of using humans in the space environment to do geological exploration and on the dual purpose such missions would serve in getting humans to Mars.

Organization:

Worden (USAF) outlined work ongoing in the space surveillance command. The detection of small impactors, generally less than 10 m in size, is a regular occurrence and is of considerable interest for national security. About 30 impacts per year occur in the 1 kT TNT equivalent energy range. The details of these activities are classified and he described efforts to release information on natural impact events more rapidly to the interested scientific community. He recommended that mitigation efforts concentrate on small objects in the 10 – 500m range. He also noted that there was an exploratory role for military microsatellites in Earth-lunar, weakly bound orbits, in the reconnaissance of small bodies passing close to the Earth. He expects that the military will want to focus on "Command and Control" functions in future mitigation efforts.

Asphaug (UCSC) discussed tsunamis as a natural analog for NEO impact into ocean basins. He pointed out that objects near 250 m in size are most efficient in producing wave energy and that there is a convergence of interests in objects of this size. He pointed out that "predictability" is, unlike the case for volcanic landslides, earthquakes, and other natural phenomena, a unique property of the NEO hazard, and that precise early warning can of itself be an effective means of mitigation for small asteroids.

In a panel discussion, Morrison (Ames RC) pointed out that dual functions for mitigation and research are common. Solar system exploration is coupled to the scientific exploration of small bodies for purposes of mitigation but has separate goals and priorities. He also advocated that, while other government agencies might play a role, NASA is the most appropriate agency to carry out mitigation studies until a specific threat is identified. He also stressed that the international aspects of mitigation must be seriously addressed.

Belton (BSEI) addressed the problems associated with creating and costing a roadmap to achieving the goal of preparing a sound scientific basis for some future mitigation technology. He concluded that a multifaceted national program, separate from solar system scientific exploration, is needed. It should involve detection to sizes as small as 100 m, an impact amelioration activity in case of an unpredicted event, a strong research program including physical characterization (radar, IR, and optical observations), theory and laboratory experimentation, a flight program at NASA involving several substantial rendezvous missions (to sample the diversity of internal and near surface structure and composition, of all major classes of NEOs) and a series of small, microsatellite missions, to characterize the diversity of the surfaces of NEOs. He also advocated that the military undertake the responsibility to conduct space missions with the purpose of beginning the process of *learning* how to interact with small NEOs under operational conditions, *i.e.,* hovering and landing operations, applications of energetic devices, *etc*. He estimated that such a program would probably take about 25 years to accomplish and cost in the vicinity of $5– 6B. Johnson (USAF) pointed out that the USAF prepared a similar plan/roadmap in 1997 but no action had yet been taken. Action within the military would require direction from the highest levels of government.

5. PRIMARY CONCLUSIONS

On the population of potentially hazardous objects:

About 2,225 NEOs are now known in the 10 m – 30 km size range, some physical information is available on about 300 objects, and 110 of these have now been studied in some detail by radar. This is a fraction of a percent of the total population that probably exceeds a million objects. There is some evidence that smaller NEOs are systematically brighter than their larger brothers so that there may be fewer large ones in total population that is currently estimated. Only 1 in about 4000 of the total NEO population is hazardous, suggesting that a total of ~250 potentially hazardous objects currently exist over the entire size range.

The number of objects larger than 1 km is estimated to be between 900 and 1230. About 55% of these objects have now been found and none of these appears to be hazardous. The contribution of dormant comets to NEOs larger than 1km is about 60 although this number is very uncertain (+/- 40).

There was a sense at the workshop that we have not yet seen every animal in the zoo! What has been missed? What surprises are in store?

On NEO detection strategies:

NASA is well on its way to meeting the Spaceguard goal of discovering 90% of the NEOs larger than 1 km. However, we're only beginning to think of how to efficiently find the smaller potentially hazardous objects and how to deal with the long-period comets. Roughly ten discoveries per lunation of NEOs larger than 1 km is required to meet the Spaceguard goal if the total population is 1000. The current discovery rate is about 9 per lunation.

Continued detection of objects in still the highest priority activity and a strong case can be made for parallel detection systems. The easy ones are found first with those NEOs with relatively large orbital size, eccentricity, and inclination (*a, e,* and *i)* being the most difficult to locate, but these are also the least hazardous. Some 10 - 15% of the population will be extremely hard to find - but this is not seen as a major drawback.

At present we know of no NEO-Earth encounters in the next few centuries whose impact risk should be of concern to the public and, more likely than not, that situation will continue for some time. However, there is a serious question, addressed in detail by Chesley (JPL), as to whether we would recognize an impactor even if such an object had been detected. Finding objects that have a high probability of impact, or getting reliable lead times for these after their detection, will not be easy. Rapid follow up observations are critical for identifying a potential impactor. With present capabilities, the smaller hazardous objects may not be recognized until a few weeks before impact.

Future NEO discovery strategy should be to search deeper (greater limiting magnitude). Future application of the proposed Large-aperture Synoptic Survey telescope (LSST), which was recently recommended for construction by two independent committees of the National Research Council, should make it possible to detect ~ 90% of NEOs down to 200-300 m in size (~24^{th} mag.) in ~10 years after the telescope is put into operation. It should also give us 40% of the Tunguska class (10 – 100 m) impactors. Such large search telescopes will also need to do the follow-up observations that are required to secure accurate orbits. Currently, amateurs do some of this follow-up with relatively small telescopes, but once the search for NEOs goes down to 20 - 21 mag. (and deeper), this follow-up activity will have to be done with the same telescopes that provide the discoveries. To some extent, this is already beginning to happen since LINEAR, NEAT, LONEOS, and Spacewatch surveys already provide follow-up for one another.

Finally, there is no search activity in the southern hemisphere: As a result, at least 20% of the sky remains unsearched. However, objects currently in the southern hemisphere should eventually be discoverable in the northern hemisphere and it will simply take longer to find them without a southern hemisphere search site.

On theoretical and laboratory research:

The importance of including the process of compaction in models of impact cratering is now evident with the new results on asteroidal densities. These indicate that high internal porosity is a common attribute. A program of laboratory experiments and allied theoretical investigations to understand the effects of porosity on impact cratering is needed. Impact experiments and modeling efforts must be continued in an effort to resolve significant differences in opinion on which mitigation techniques are viable for rubble pile asteroids and comets. In addition, a comprehensive database of physical properties needs to be developed for near-Earth objects. This would assist in more clearly identifying what has been done and what needs to be done in the area of physical characterization.

On observational studies general:

It continues to be important to probe the range of diversity in the NEO population. Only when the full range of properties is understood can mitigation techniques be devised to cover all reasonable possibilities. The current search metric (Spaceguard Goal) for finding NEOs should be reconsidered and it was proposed that a new goal to find 90% of the large ***hazardous*** objects (i.e. that part of the population of NEOs that can actually collide with the Earth) by the end of 2008 rather than simply 90% of the large (D > 1 km) NEOs should be recommended.

On ground-based observations:

Many uncertainties have been introduced into the interpretation of asteroid spectroscopy with the recognition that optical space weathering of surface materials is a factor. Modeling NEO surfaces with analogues such as meteorites or the lunar regolith may therefore lead to misinterpretations. Ground based radar investigations should help in understanding the diversity of surface properties, and there is a sense that radar needs to focus more on this observational aspect. The Yarkovsky effect – a subtle force caused by an asteroid's re-radiation of solar energy - needs to be understood quantitatively and radar clearly has an important role to play in improving the accuracy of asteroidal orbits.

Increased access to 4-meter and larger class telescopes for ground-based spectroscopic and infrared investigations is needed to advance physical studies. It is regarded as critical that radar studies of NEOs continue uninterrupted at both the planetary radar facilities (*i.e.,* Goldstone and Arecibo) both for the powerful astrometric data and physical characterizations these data provide.

On space observations:

A more detailed geophysical understanding of small NEOs will be required before technologies for impact mitigation via diversion or disruption are viable. This means that interior properties throughout the body of potential impactors must be studied as well as the state of their surface materials. Seismic and radio reflection tomography investigations can get us deep into the interior and yield complementary information. For example, radio wave tomography can detect differences in the complex permittivity of various materials but only over scales the size of the wavelength (typically 5 - 50 m). The technique can detect changes in ice/rock layers but only if there are fairly large contrasts. For example, the application of this technique (at 10 MHz) may not be able to detect a one meter-thick mantle on a comet. On the other hand seismic techniques should provide excellent information on the structure of surface layers. In both seismology and microwave tomography we need to experiment and incrementally 'learn' how to best apply the techniques in this strange new environment.

Inevitably, contact with the surface will be needed in order to understand its structural and compositional properties well enough for mitigation purposes. In addition, it may be necessary to perform in situ experiments and to study the effects of small-scale high-energy explosions on the surfaces of asteroids and comets.

These geophysical data, once acquired, can be used to construct comprehensive models for stimulating the effects of specific mitigation strategies on asteroids and comets.

On scientific requirements:

Mitigation techniques will require detailed knowledge of the target object including its size, shape, mass, mass distribution, topology of the object's external gravitational-field, its spin state, its possible multiplicity, the composition and state of the surface material and interior structure. Each hazardous object may have a very different set of these parameters that characterize it. This suggests that a precursor rendezvous mission may be needed to obtain this information before mitigation is attempted. Potentially hazardous objects with a particularly high probability of colliding with the Earth may need to have transponders attached to their surfaces so that they can be tracked thereafter to a few kilometers accuracy.

Knowledge of the bulk density of asteroids has exploded with the recent discovery of several binary asteroid systems. A wide range of porosity is indicated and there is a need to characterize the complete geology of these objects. Porosity, in turn, points to learning about internal structure of potentially hazardous objects, a topic that is not adequately addressed by current exploration missions. Also, it is believed that deep layers of porous surface materials may have a dramatic effect on mitigation using high-energy explosives so that previous requirements may have to be increased by factors of 100 or more.

On education:

The effects of an NEO impact with the Earth are not presently in anyone's realm of experience. As a result there is a need for better education of the public on the nature of the threat and they need assurance that mitigation of collisions with small bodies can actually be accomplished. Similarly the arcane subject of orbital dynamics of a hypothetical threat for which no one has personal experience needs to be better explained; until this is done NASA faces a difficult situation explaining why it occasionally appears to "cry wolf" over impactors that follow-up observations rule out. Moreover, a public which does not understand the threat is unlikely to be motivated by an early warning system. An ultimate goal in this regard might be to one day have the NEO impact hazard issue lucidly explained in High School textbooks. Efforts should be increased to educate the public on the nature of the NEO population, impact probabilities and uncertainties. Potential damage to societal infrastructure and associated costs also needs to be better understood and explained.

On organization:

At present there is no governmental assigned responsibility for dealing with an impending collision of the Earth with an object from space. If such a hazardous object were found today there is no person or assigned organization that is directly charged with the responsibility to initiate further action. NASA does have a mandate to find the larger objects, but if a high-probability hazard were found as a result of this program, currently there is no plan or, apparently, authority to do anything about it. Since it is part of NASA's newly stated mission "to understand and protect our home planet," is seems obvious that this responsibility should reside in NASA, and, for the subject to advance, a strategic roadmap leading towards a mitigation capability, with identifiable intermediate goals and milestones, needs to be developed.

At some level it seems clear that military involvement in the task to mitigate a specific and proven hazard will be necessary. However, with the present inadequate state of knowledge about the physical and compositional properties of the potential impactor population, the development of a specific hazard mitigation system is obviously premature. We first need to learn and understand what we are mitigating against, and to what extent it is feasible in terms of physics, politics and economics. Ultimately it seems clear that action within the military will require direction from the highest levels of government and, in the absence of an imminent threat, this may take some time to plan and accomplish. In addition, we anticipate that an in-space learning and practice phase will be important in developing a reliable system. Those responsible must "learn" how to deal with various possible targets. However, only if a high–probability threat is verified should a program gear-up to acquire a full-blown mitigation system.

The current goal should be to assign organizational responsibility to NASA, with adequate funding authority, to pursue a scientific program so that, hopefully no more than 30 years from now, the United States will be in a position where adequate knowledge is available to pursue the development of an active mitigation technology that is safe, reliable, affordable, and beneficial to both humanity and solar system exploration.

On missions:

No support surfaced at the workshop for attempting to build a serious mitigation system at the present time. However, it is considered appropriate to go beyond detection of potentially hazardous objects to begin to establish a relevant scientific basis for such a mitigation system. The focus should be the implementation of space missions and associated ground based activities that will allow us to learn enough about potential targets to enable a mitigation system to be developed perhaps twenty to thirty years from now. To this end a program of detailed interior and surface science exploration is needed. Development of enabling technologies is also a key element. For example, the development of asteroidal seismology, radio wave tomography, and emplacement of accurate radio Doppler transponders on all asteroids thought to be potentially hazardous are high-priority. Other enabling technologies like active orbit control, stability in hovering, mission operations in a binary-asteroid environment, and testing material sampling instruments in near zero-g environments need serious attention. Several rendezvous missions with advanced high-energy propulsion systems will probably be required for mitigation related projects, particularly where it is necessary to deliver payloads to the surface of target asteroids. MUSES-C is expected to be very informative in these studies since particles and dust kicked off a low mass NEO could form a transient "atmosphere" that might interfere with mitigation operations.

6. STRAWMAN ROADMAP

Part of the workshop was devoted to the development of a strawman roadmap towards the goal of achieving a basis of knowledge, both scientific and operational, to allow the start of the development of a reliable mitigation system sometime in the not to distant future. It should be understood that the purpose of the roadmap was *not* to create an actual mitigation system but to simply create the knowledge base that will be needed when the development of such a system becomes a priority. Also this strawman roadmap is not included in the workshop recommendations. It is meant simply as a preliminary guide to those agencies who may be called upon to implement the workshop recommendations given above.

Based on a proposal made by the organizers and suggestions from the workshop floor the proposed roadmap is outlined schematically in Table 1. The time duration of the roadmap is shown as 25 years, which is judged as roughly appropriate if the maximum annual expenditures are to be kept less than $300M/yr. A shorter program, advocated by some at the workshop, would be possible if a higher maximum expenditure rate is deemed appropriate. A crude estimate for the total cost of the work outlined in the roadmap is between $5 and 6B over the 25-year span.

Elements of the Roadmap:

Five primary elements are identified in the roadmap, which should be pursued in parallel:

Survey to detect and obtain accurate orbits for hazardous objects
Amelioration and public education
Detailed physical and compositional characterization of hazardous objects
Supporting theoretical and laboratory research
Preliminary Interaction system development

Survey to detect and obtain accurate orbits for hazardous objects:

The purpose of this element is to extend the current survey aimed at detecting 90% of near-Earth objects brighter than H ~ 18 mag (roughly 1 km in size) to achieving a similar completeness factor for objects of 200m size within a decade and detect as many objects down to 100m in size as possible within the time frame of the roadmap. This objective is believed to be within the capability of the proposed Large-aperture Synoptic Survey telescope (LSST). The PanStarrs (USAF/University of Hawaii) telescope system currently underdevelopment and current NASA supported survey telescopic programs are also seen as contributors to this goal.

The radar systems at Arecibo and Goldstone are seen as a critical contributor to the acquisition of orbital information of the highest accuracy on many hazardous objects during this period. We envision that the extension of the current survey and support of radar observations would continue to be the responsibility of NASA.

Amelioration and public education:

This element is included to support the education of the general public on the nature of the asteroid/comet nucleus collision threat and to provide for training and identification of needs for personnel in public disaster response organizations on how to deal with an unpredicted collision of regional consequence that could possibly occur during the timeframe of the roadmap. The organization (*e.g.,* FEMA) that would undertake the responsibility for this element needs further discussion.

Detailed physical and compositional characterization of hazardous objects:

This element has two components: investigations in space and investigations using ground-based and Earth-orbital astronomical techniques. For investigations in space we again envision two parts: a survey program of small low-cost missions, similar to that recommended by the UK Task force, to visit as many NEOs as possible to increase our knowledge on the origin of the diversity of the physical and compositional properties of these objects. We have included a series of 7 such missions in the roadmap that might investigate as many as 14 targets of different character. These missions would be in the $200M class. Secondly, we include a program of missions designed to investigate the diversity of interior structures that may exist within a selection of NEOs. These latter missions would be extended rendezvous missions with multiple targets carrying novel, synergistic payloads in the $500M cost class involving landed equipment. In the strawman roadmap we have suggested 4 such missions with 8 targets as a minimum requirement. To ensure maximum benefit from these missions we advocate comprehensive data analysis, interpretation, and modeling programs be funded to underlie the flight program and that can, through peer review, involve the entire research community.

For investigations using ground-based and Earth-orbital astronomical techniques the goals again divide into two parts: first, to provide physical, orbital, and compositional information in direct support of the space missions described above, and second to provide support for investigation of the physical and compositional characteristics of the near-Earth objects and potentially hazardous cometary nuclei that have been found in the congressionally mandated survey and any future extension of this effort.

The responsibility for the space based components and allied supporting research of this element should be clearly at NASA. The ground-based activities using astronomical techniques are probably best handled as a separately and newly funded extension of the planetary astronomy program already established at NASA.

Supporting theoretical and laboratory research:

There are many significant scientific issues on how mitigation might be accomplished and these need to be addressed in parallel with the above described program of physical and compositional characterization. A prime issue involves an orders of magnitude uncertainty in the effectiveness of the most obvious and easiest mitigation methods, including nuclear explosives and other methods of rapid energy deposition. Many, perhaps all, of these issues could be resolved in small-scale laboratory experiments using impactors, explosives, and other methods of energy deposition. Theoretical studies especially numerical code calculations could be particularly effective, if models of material behavior and basic geophysics of asteroids can be improved. These could be a natural extension of existing efforts (e.g., DOE-ASCI) geared towards modeling the detailed effects of nuclear explosions. These and other theoretical studies would be used to extrapolate experimental result to test conditions out of reach of laboratory methods.

Preliminary interaction system development:

Prior to the development and application of a specific mitigation attempt it is clear that the organization responsible will need to *learn* how to accomplish its goals and this will take some time and substantial resources. Small-scale, in-space interaction experiments will need to be planned, developed and executed and tests performed to achieve an adequate understanding of the pluses and minuses of possible intercept technologies. These issues were not discussed in any detail at the workshop, however they were recognized as an important element in the roadmap based on an earlier report that was done by military personnel (Naka, 1996). The strawman roadmap contains a first effort to chart a course of action in this area. Presumably the responsibility for this element would lie in the domain of the Department of Defense.

TABLE 1

7. RECOMMENDATIONS

Given that:

the future collision of an asteroid or cometary nucleus with the Earth with catastrophic effects is, without intervention, inevitable,

the most likely objects to collide with the Earth with catastrophic effects are 100 m or more in size and have a significant probability of colliding with the Earth over times of human interest (~100yr),

there exists no other government agency with the assignment or acceptance of responsibility for averting the threat of an impending collision, numerous space missions will be required to acquire a relevant and adequate basis of knowledge on which to base the future development of a reliable collision mitigation system,

estimates of the time necessary to acquire a relevant and adequate basis of knowledge on which to base the future development of a reliable collision mitigation system is measured in decades,

there is strong international interest in understanding the nature of this threat,

the NASA charter includes the goal of protecting our home planet,

We recommend that the National Aeronautics and Space Administration be assigned the responsibility to acquire relevant scientific knowledge on the compositional and physical properties of the diverse population of hazardous objects that may threaten the Earth and on which the future development of a reliable collision mitigation system could be based. In undertaking this responsibility, the interests and cooperative support of the international community should be welcomed.

Given that:

The development of a relevant and adequate knowledge basis for future attempts to reliably mitigate an impending collision of an object greater than 100 m in size will require scientific proof of the efficacy of a wide range of proposed techniques in the space environment including ways to measure relevant physical and compositional properties,

the priorities of the technical and scientific objectives of space missions designed to acquire a relevant basis of knowledge for mitigation purposes may be distinct from the priorities in other high priority space exploration programs already being pursued by NASA and other foreign space agencies,

a multifaceted program of allied Earth-based theoretical, experimental, observational, and interpretive research is necessary to support, complement, guide, and extend a program of space missions for mitigation purposes,

estimates of the costs incurred by such a program will be substantial,

We recommend that a new and appropriately funded program be instituted at the National Aeronautics and Space Administration, consistent with its mission to "Understand and protect our home planet," to create an adequate basis of scientific knowledge through space missions and supporting Earth-based research on which future attempts to reliably mitigate impending collisions of hazardous objects with the Earth can be founded.

Given that:

excellent progress has been made in satisfying the congressional mandate charged to NASA to find 90% of near-Earth objects with size greater than 1 km by 2008,

the objects capable of causing widespread destruction range down to 100 m in size,

relatively low-cost Earth-based surveys are now technically feasible down to a size limit of about 200 m.

committees of the National Research Council of the National Academy of Sciences have recommended the construction of a large-aperture synoptic survey telescope (LSST) that is capable of detecting 90% of near-Earth objects above the 200 m size limit within approximately a decade,

We recommend that the congressionally mandated survey presently being pursued by the National Aeronautics and Space Administration to catalog near-Earth objects brighter than H~18 (~ 1 km in size), be extended to include 90% of hazardous near-Earth objects down to a size range of 200 m over the next decade.

Given that:

Department of Defense space surveillance programs regularly observe upper atmosphere airbursts with the release of 1 kT of energy and above caused by extraterrestrial objects,

the public and other nations with nuclear capability may not be aware of this continuing flux of extraterrestrial objects and their effects in the Earth's upper atmosphere,

there is no organization responsible for timely reporting these events to the public or other nations,

We recommend that the Department of Defense increase the speed with which it makes information about natural airburst phenomena available to the public and other nations to prevent possible misinterpretations of these events.

Given that:

the threat of catastrophic collisions with the Earth is global and that any and all nations may be affected,

there is no national or international organization or unit with the responsibility for dealing with the threat of an impending collision with the Earth in the event that an Earth-threatening object is discovered,

We recommend that government and international policy makers act now to formulate and publish an agreed upon chain of responsibility for action in the event that an Earth-threatening object is discovered.

8. REFERENCES.

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APPENDIX A: RATIONALE FOR THE WORKSHOP
(taken from the original proposal)

One hundred years is approximately the time scale for an Earth impact, at 20% probability, by a 100-meter sized near-Earth asteroid, one capable of causing substantial regional destruction. This is also the estimated time (~70 years) necessary to assure the development of an appropriate mitigation technology and learn how to apply it to the Earth threatening object (Belton *et al*, 2001). This timescale is also similar to the typical lifetime of a family from birth through the death of grandchildren and therefore can be expected to be of particular interest to contemporary civilized society.

This confluence of timescales gives some present urgency and special interest to consideration of the scientific foundations on which NEO collision avoidance and impact mitigation technologies must be based. While programs for the detection of possible impactors are well in hand and ideas on how to apply the energy required to either disrupt or deflect an incoming impactor abound (*e.g.* in *Hazards due to Comets & Asteroids*, T. Gehrels, Ed., 1994), little published work exists that addresses the detailed *scientific (or technical) requirements* for avoidance and mitigation technologies and whether an adequate knowledge base exists.

In this context, the need for space exploration of NEOs is widely recognized (*e.g.,* in the *Spaceguard Survey* report, Morrison, 1992; or in *Space Surveillance, Asteroids and Comets, and Space Debris,* USAF Science Advisory Board report, 1997). More recently, a UK Task Force on NEOs has recommended that an international approach be considered that employs a coordinated set of rendezvous missions based on "inexpensive" micro-satellite technology (Atkinson, 2001).

However, even with the publication of such recommendations it is not clear to us from what has been published that they are offered on a secure scientific and technical basis. For example, we are aware of Discovery mission proposals that have been considered that employ micro-satellite class spacecraft, which seems to indicate that they may indeed have an important role to play in the future *scientific exploration* of NEOs, *i.e.,* to discover their origins, evolutionary history, or interrelationships between them by using comparative imaging, various kinds of spectroscopy of their surfaces, and sample return techniques.

On the other hand, we (Belton *et al*, 2001) have shown, in a preliminary analysis, that for impact mitigation or collision avoidance technologies to be successful a much higher priority must be placed on other kinds of scientific investigations, *i.e.,* those more intimately associated with the deep interior structure and special material properties of these objects. Beyond revealing fundamental clues to the origins of planets, knowledge of the deep interior structure of asteroids and comets is a requirement if one means to apply whole-body forces to them and achieve predictable results.

It seems clear to us that to measure and characterize internal properties such as detailed internal mass distribution, internal fracture state, composition, material strength, *etc,* novel kinds of spacecraft investigations will be required. Locally, drilling and digging from the surface can provide some of these data, but will probably be restricted to a limited depth. Globally, new and as yet unproven kinds of radio and seismic wave propagation and scattering approaches with active sources may be necessary to provide adequate information throughout the entire body with sufficient detail and accuracy. To be able to adequately address such objectives as these, mission concepts much more substantial than micro-satellites may be needed.

Belton, M.J.S., Asphaug, E., Huebner, W., and Yeomans, D.K. (2001) Scientific Requirements for NEO Impact Mitigation. Presented at the *Asteroid 2001 Meeting*, Palermo, Italy.

APPENDIX B: PARTICIPANTS IN THE WORKSHOP

Abell, Paul	RPI Science Center	abellp@rpi.edu
A'Hearn, Michael	University of Maryland	ma@astro.umd.edu
Asphaug, Erik	University of California	asphaug@es.ucsc.edu

Avery, Don	NASA	d.e.avery@larc.nasa.gov
Ball, Andrew	The Open University, UK	a.j.ball@open.ac.uk
Belton, Mike	Belton Space Exploration	belton@azstarnet.com
Bennett, Keith	Washington University	bennett@seas.wustl.edu
Binzel, Richard P.	MIT	rpb@mit.edu
Bottke, William	Southwest Research Institute	bottke@boulder.swri.edu
Bussolino, Luigi	Alenia Spazio - Italy	lbussoli@to.alespazio.it
Campbell, Jonathan	MFSC	
Cellino, A.	Astronomical Obs. of Torino	cellino@to.astro.it
Chamot, Joshua	National Science Foundation	jchamot@nsf.gov
Chapman, Clark R.	Southwest Research Institute	cchapman@boulder.swri.edu
Cheng, Andrew	JHU/APL	andrew.cheng@jhuapl.edu
Chesley, Steve	JPL	steve.chesley@jpl.nasa.gov
Cline, Tim	University of Maryland	tcline@astro.umd.edu
Conway, Bruce	University of Illinois Urbana	bconway@uiuc.edu
Dahlstrom, Eric L.	International Space	eric.dahlstrom@internationalspace.com
DI Martino, Mario	Oss. Astronomico Di Torino	dimartino@to.astro.it
Diamond, Linda	University of Maryland	linda@astro.umd.edu
Dissly, Richard	Ball	rdissly@ball.com
Dupree, Samuel	Lockheed Martin	sdupree@computational-astronomer.com
Durda, Dan	Southwest Research Institute	durda@boulder.swri.edu
Egan, Michael P.	Air Force Research Lab	michael.egan@mda.osd.mil
Frisbee, Joseph H.	United Space Alliance - JSC	oe.h.frisbee@usahg.unitedspacealliance.com
Giorgini, Jon	JPL	jon.giorgini@jpl.nasa.gov
Greczyn, Warren	AIAA Space System Tech.	warren.greczyn@anser.org
Harris, Alan	Jet Propulsion Laboratory	Alan.W.Harris@jpl.nasa.gov
Harris, Alan W.	DLR	Alan.Harris@dlr.de
Holsapple, Keith	University of Washington	holsapple@aa.washington.edu
Huebner, W.F.	Southwest Research Institute	whuebner@swri.edu
Johnson, David	Stellar Research Group	starmanus@earthlink.net
Johnson, Lindley	US Air Force	lindley.johnson@pentagon.af.mil
Kahle, Ralph	Tech. Universitaet Dresden	Ralph.Kahle@mailbox.tu-dresden.de
Knight, Matthew	University of Maryland	mnk8a@astro.umd.edu
Kofman, Wlodek	Planetologie CNRS/UJF/OSUG	wlodek.kofman@obs.ujf-grenoble.fr
Lisse, Carey	University of Maryland	lisse@astro.umd.edu
Lu, Edward	Johnson Space Center	edward.t.lul@jsc.nasa.gov
Maccone, Claudio	Int. Acad.Astronautics	clmaccon@libero.it
Malay, Jonathan T.	Ball Aerospace	jmalay@ball.com
Mazanek, Daniel	Langley Research Center	d.d.mazanek@larc.nasa.gov
McFadden, Lucy	University of Maryland	mcfadden@astro.umd.edu
Meech, Karen	University of Hawaii	meech@ifa.hawaii.edu
Melosh, Jay	University of Arizona	jmelosh@lpl.arizona.edu
Merline, William	Southwest Research Institute	merline@boulder.swri.edu
Mink, Ron	Goddard Space Flight Center	rmink@pop500.gsfc.nasa.gov
Mitchell, Drake	Planetary Defense	PlanetaryDefence@Netscape.Net
Monet, Alice	US Naval Observatory	alice@nofs.navy.mil
Morgan, Thomas	NASA Hdqts	tmorgan@hq.nasa.gov
Morrison, David	NASA Astrobiology Institute	dmorrison@arc.nasa.gov
Muinonen, Karri	University of Helsinki	Karri.Muinonen@helsinki.fi
Ostro, Steve	JPL	ostro@reason.jpl.nasa.gov
Pawlowski, James F.	Johnson Space Center	jpawlows@ems.jsc.nasa.gov
Pelczynski, Gabrielle	SAIC	Gabrielle.D.Pelczynski@saic.com
Pervan, Sherry L.	SAIC	pervan@interaccess.com
Pierce, Donna	University of Maryland	pierce@astro.umd.edu
Price, Robert	Lockheed Martin	stephen.price@lmco.com
Reinert, Richard	Ball Aerospace	rreinert@ball.com
Reitsema, Harold	Ball Aerospace	hreitsema@ball.com
Safaeinili, Ali	Jet Propulsion Laboratory	ali.safaeinili@jpl.nasa.gov

Samarasinha, Nalin	NOAO	nalin@noao.edu
Scheeres, Dan	University of Michigan	scheeres@umich.edu
Schweickart, Russell L.	B612 Foundation	rs@well.com
Sears, Derek	University of Arkansas	dsears@uark.edu
Steel, Duncan	University of Salford	D.I.Steel@salford.ac.uk
Sunshine, Jessica	SAIC	jess@stillwater.saic.com
Tholen, David J.	University of Hawaii	tholen@ifa.hawaii.edu
Valentine, Lee	Space Studies Institute	lsvalentine@attn.net
Valsecchi,G.B.	ISAF-CNR	giovanni@rm.iasf.cnr.it
Walker, James	Southwest Research Institute	jwalker@swri.edu
Warner, Elizabeth	University of Maryland	warnerem@astro.umd.edu
Whiteley, Robert	University of Arizona	whiteley@hindmost.lpl.arizona.edu
Wick, John	SAIC	John.A.Wick@SAIC.com
Worden, Simon P.	USAF	simon.worden@peterson.af.mil
Yano, Hajime	Inst. of Space & Astronautical Sci.	yano@planeta.sci.isas.ac.jp
Yeomans, Donald K.	JPL	donald.k.yeomans@jpl.nasa.gov

APPENDIX C: INVITED PRESENTATIONS

A geophysical understanding of small Near-Earth Objects is required before we can meaningfully pursue technologies for impact mitigation via diversion, disruption, or resource exploitation. The goal of this workshop was to lay out the scientific and technological requirements for spacecraft and ground based reconnaissance, for laboratory research and theoretical modeling, and in situ exploration of near-Earth comets and asteroids. It concluded with a recommended timeline for satisfying those requirements by 2030.

TUESDAY 9/3/2002

8:00 Registration

9:00 Welcome
T. Morgan (NASA) and E. Asphaug (UCSC)

9:30 **Orbits, sizes and provenances of near-Earth asteroids and comets**
Bill Bottke (SwRI)

10:15 **Scientific requirements for understanding the NEO population**
Alan Harris (DLR)

10:45 **What we know and don't know about asteroid surfaces**.
Clark Chapman (SwRI)

11:30 Press Event

12:00 POSTER SESSSION

2:00 **Sizes and structures of comets and asteroids: What is worth mitigating and how?**
Erik Asphaug (UCSC)

2:45 **The scientific requirements of future mitigation technology**.
Ralph Kahle (Dresden Univ. Technology)

3:30 **Scientific requirements for enabling future technologies.**
Alan Harris (JPL)

4:00 POSTER SESSION

5:00 **A geophysical assessment of NEO mitigation requirements.**
Jay Melosh (U. Arizona)

WEDNESDAY 9/4/2002

9:00 **Fancy maneuvers: hopping, hovering and tethering.**
Dan Scheeres (U. Michigan)

9:45 **Mission operations in low gravity regolith and dust.**
Derek Sears (U. Arkansas)

10:30 **Exploratory mission architectures, from small-scale to large.**
Richard Dissly (Ball Aerospace)

11:15 **Optimizing the orbital interception and deflection of hazardous NEOs.**
Bruce Conway (U. Illinois)

12:00 POSTER SESSION

2:00 **Advances in ground-based characterization of NEOs.**
Rick Binzel (MIT)

2:45 **Radar reconnaissance of potentially hazardous asteroids and comets.**
Steve Ostro (JPL)

3:30 **NSF Leadership Presentation**
Wayne van Citters (NSF)

4:00 POSTER SESSION

5:00 **Workshop Panel: Science and public perception: our responsibilities "back home".**
Dave Morrison (NASA Ames), Clark Chapman (SwRI), and Duncan Steel (U. Salford)

THURSDAY 9/5/2002

9:00 **Peering inside of NEOs with microwave tomography.**
Wlodek Kofman (LPG Grenoble)

9:45 **Military perspectives on asteroid impact mitigation.**
Pete Worden (USAF)

10:30 **NASA Leadership presentation.**
Ed Weiler and Colleen Hartman (NASA Headquarters)

11:00 **Techniques for the structural investigation of aggregate bodies.**
Hajime Yano (ISAS)

12:00 POSTER SESSION

1:30 **Penetrator and lander technology.**
Andrew Ball (Open Univ., UK)

2:10 **Seismic investigations of asteroid and comet interiors.**
James Walker (SwRI)

2:50 **Geology of asteroids: implications of spin states.**
Keith Holsapple (U. Washington)

3:30 **Thermophysical properties of comets and asteroids inferred from fireball observations.**
Mario Di Martino (Obs. Torino)

4:00 POSTER SESSION

5:00 **Elements of a national program to mitigate impacts.**
Mike Belton (BSEI)

FRIDAY 9/6/2002

9:00 **Impact probabilities and lead times.**
Steve Chesley (JPL)

9:45 **Human exploration of near-Earth objects.**
Dan Durda (SWRI)

10:30 **Workshop Panel: The next steps: Development of a roadmap towards a practical and reliable impact mitigation system.**
Don Yeomans (JPL), Mike Belton (BSEI), Tom Morgan (NASA)

12:00 Final Business / Press Event

1:00 Adjourn

APPENDIX D: SCIENTIFIC AND LOCAL ORGANIZING COMMITTEES

Members of the Scientific Organizing Committee:

Michael A'Hearn, *University of Maryland*
Erik Asphaug (Scientific Prog. Chair), *University of California at Santa Cruz*
Harry Atkinson, *Bampton, United Kingdom*
Michael Belton (Chair; Proceedings Editor)), *Belton Space Exploration Initiatives, LLC*
Alberto Cellino, *Oss. Astronomico di Torino, Italy*
Clark Chapman, *Southwest Research Institute, Boulder*
Keith Holsapple, *University of Washington*
Walter Huebner (Participant Chair), *Southwest Research Institute, San Antonio*
Wlodek Kofman, *University of Grenoble, France*
Tim McCoy, *National Museum of Natural History*
Lucy McFadden, *University of Maryland*
Jay Melosh, *University of Arizona*
Tom Morgan (Proceedings Co-editor), *NASA Headquarters*
Dan Scheeres, *University of Michigan*
Derek Sears, *University of Arkansas*
Nalin Samarasinha, *National Optical Astronomy Observatory*

Vadim Simonenko, *Inst. for Technical Physics, Chelyabinsk*
Jessica Sunshine (LOC), *Science Applications International*
Simon P. Worden, *USAF*
Hajime Yano, *Institute of Space and Astronautical Science, Japan*
Donald Yeomans (Proceedings Co-Editor), *Jet Propulsion Laboratory*

Members of the Local Organizing Committee:

Michael A'Hearn (Chair), *University of Maryland*
Lucy McFadden, *University of Maryland*
Tim McCoy, *National Museum of Natural History*
Jessica Sunshine, *Science Applications International*
Tom Morgan, *NASA Headquarters*

APPENDIX E: REGISTERED MEDIA ATTENDANCE AND WORKSHOP PRESS RELEASE

Beatty, Kelly	Sky and Telescope	kbeatty@SkyandTelescope.co
Brown, Bill	Press	wfbrown@mrcbroadcast.com
Capobianco, Michael	Free-Lance	michael16@crosslink.net
Chandler, David	Free Lance Science Writer	candler@nasw.org
Chong, Wayne	Canadian Broadcasting Corp.	wayne_chong@cbc.ca
Dambeck, Thorsten	Free-Lance Science Writer	tdambeck@web.de
Fountain, Henry	New York Times	fountain@nytimes.com
Foust, Jeff	Space Today	jeff@spacetoday.net
Gruber, Dr. Peter	FOCUS Magazine	pgruber@erols.com
Isbell, Douglas	NOAO Press Office	disbell@jupiter.tuc.noao.edu
Kaleghi, Yazdi	Dialogue Productions	yazdi@yazdi.com
Kerr, Richard	Press	rkerr@aaas.org
Moidel, Mark	Space Viz Productions	info@spaceviz.com
Morton, Oliver	Free Lance Science Writer	abq72@dial.pipex.com
Murray, Colin	BBC	collin.murray-GW@bbc.co.uk
Recer, Paul	The Associated Press	precer@ap.org
Reddy, Vishnu	The Asian Age	vishnureddy@hotmail.com
Reed, Christy	Geotimes	car@agiweb.org
Regalado, Antonio	Wall Street Journal	antonio.regalado@wsj.com
Salla, Michael	Dialogue Productions	msalla@american.edu
Samuel, Eugenie	New Scientist	eugenie.samuel@newscientist.com
Shactman, Noah	Wired News	noahmax@inch.com
Zabarenko , Deborah	Reuters	deborah.zabarenko@reuters.com

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Science workshop reveals evolving perspective on asteroid threat

For more information:

Douglas Isbell
Public Information Officer
National Optical Astronomy Observatory
Phone: 520/318-8214
E-mail: HYPERLINK "mailto:disbell@noao.edu" disbell@noao.edu

Prof. Erik Asphaug
University of California at Santa Cruz
Phone: 831/459-2260
E-mail: HYPERLINK "mailto:asphaug@es.ucsc.edu" asphaug@es.ucsc.edu

Direct measurements of the surface properties and interior structures of asteroids and comets should be fundamental elements of future spacecraft missions to these primitive solar system bodies, according to participants in a scientific workshop held in Arlington, VA, from September 3-6. Such information is vitally important for preparing a variety of approaches for the diversion of Near-Earth Objects that may someday threaten Earth. Evidence presented at the workshop suggests that gentle thrusts applied for decades, rather than traditional explosives, are likely to be needed to change their orbital paths. This will require early detection together with knowledge of their geologic properties.

Sponsored by NASA, the workshop was designed to find common ground among researchers on the reconnaissance and exploration of Near-Earth Objects. "Unlike volcanoes or earthquakes, the NEO hazard was only recently identified, and we have just begun to understand its implications," said meeting organizer Erik Asphaug of the University of California at Santa Cruz. "This is the only major natural hazard which can, in principle, be made predictable and even eliminated if we find the dangerous ones and learn how to modify their orbits over time."

Astronomers have determined precise orbits and estimated the sizes of approximately 1,500 near-Earth objects (NEOs), according to conference presentations. More than 600 of the estimated 1,000 asteroids larger than one kilometer in diameter (a size that could cause widespread calamity on Earth) have been detected so far. This represents good progress toward the goal mandated by Congress for NASA to discover 90% of these objects by 2008. While no known asteroid is on collision course with Earth, ongoing detection should alert us to serious threats.

Significant topics of discussion at the workshop included large uncertainties in the state of scientific knowledge of asteroid surfaces, despite great advances in recent years. There is increasing evidence that most asteroids larger than a few hundred meters have complex interiors and may be loosely bound conglomerates that might resist explosive diversion. To almost everyone's surprise, about a sixth of NEOs are now observed to have moons, which would complicate any effort to change their orbits. While scientific goals of researching the early history of the solar system and mitigation goals of protecting the Earth are very different, the kinds of asteroid studies needed to address both goals are largely identical, several participants noted. "Learning more about them is the first step," Asphaug said. Gathering a wide variety of measurements is critical for fully understanding the history and properties of NEOs, given their great diversity and their many observed dissimilarities from presumed analogues like the surface of the Moon.

Because we know so little, researchers saw physical characterization as going hand-in-hand with potentially useful technological developments. For example, a large, lightweight solar concentrator was discussed that could vaporize a small surface area for measurements of composition; thrust from the escaping material could be measured to test concepts for solar-powered asteroid deflection. Because close calls are far more likely than actual impacts, attendees also discussed the deployment of radio transponders for precision tracking of dangerous objects. Many researchers expressed the need for high-performance propulsion systems that could power a spacecraft to a rapid rendezvous with an NEO. Ground-based observatories such as the proposed 8.4-meter Large Synoptic Survey Telescope (a high priority in the most recent Decadal Survey of astronomy by the National Academy of Sciences) can be effective tools to detect 80-90% of the NEO population down to a diameter of 300 meters within about a decade of full-time operations. A spacecraft orbiting close to the Sun and looking outward in tandem with such a telescope might reduce this time to five years. NEOs in this size range can cause widespread regional damage on Earth, although the workshop scientists agreed that the detailed effects of impacts of any size remain poorly understood. Ground-based radar observations of close-approaching NEOs will also remain a uniquely important and flexible method to study a variety of objects, attendees agreed. Radar is capable of imaging and accurately tracking the closest Earth-approachers. Few countries outside of the United States are spending significant resources on the NEO hazard, and this international imbalance must be remedied if the threat is to be fully understood within the next few decades, according to several speakers. For example, there are currently no active ground-based NEO searches in the

Southern Hemisphere. Despite the spectacular success of NASA's recently concluded Near Earth Asteroid Rendezvous mission, and excitement surrounding Japan's upcoming MUSES-C mission (the first-ever sample return from an asteroid, to be launched in December), researchers agreed that more substantial investigations are required if we are to learn how to change an asteroid's orbit. Scientists must take better advantage of opportunities to explain new detections and their related risks to the media and the public, attendees agreed. With advanced search systems coming on line, asteroids will be discovered at an increasing rate, with orbits that may initially appear dangerous. Only detailed follow-up on a case-by-case basis can prove each new discovery to be non-threatening. This process must be communicated more carefully, scientists agreed, in the manner that hurricanes are tracked by the weather service until the "all-clear" is announced.

Seventy-seven scientists attended the workshop from the United States, Australia, Europe and Japan. It was co-sponsored by Ball Aerospace, Science Applications International Corp., Lockheed Martin Corp., the National Optical Astronomy Observatory and the University of Maryland. A formal report on the workshop will be submitted to NASA by the end of 2002. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation. Last updated 6 September 2002.

APPENDIX F: OUTLINE OF THE WORKSHOP PROCEEDINGS.

The workshop proceedings are to be published under the title *"Mitigation of Hazardous Impacts due to Asteroids and Comets"* by Cambridge University Press in 2003.

The editors for the book are: M.J.S. Belton (BSEI), D.K. Yeomans (JPL), and T.H. Morgan (NASA Hdqts). An outline of the book follows:

Foreword
E. Weiler (proposed)
3 pages / 1500 words

Preface
M.J.S. Belton, D.K. Yeomans, & T.H. Morgan
3 pages / 1500 words

Acknowledgements
M.J.S. Belton
1 page / 500 words

Chapter 1. The near-Earth object population: Orbits, sizes, impact frequencies, and survey simulations
W. Bottke, A. Morbidelli, and R. Jedicke
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 2. Interior structures for asteroids and cometary nuclei
E. Asphaug
28 pages/ 14500 words / 3 B&W figures or tables)

Chapter 3. The physical nature of asteroid surfaces
C. Chapman
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 4. Radar reconnaissance of potentially hazardous asteroids and comets
S.J. Ostro and J.D. Giorgini

28 pages/ 14500 words / 3 B&W figures or tables

Chapter 5. Physical properties of comets and asteroids inferred from fireball observations
M. Di Martino and Alberto Cellino
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 6. Scientific requirements for understanding the near-Earth asteroid population
A.W. Harris (DLR)
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 7. Earth impactors: Orbital characteristics and warning times
S. R. Chesley and T. B. Spahr
28 pages/ 14500 words / 8 B&W figures or tables)

Chapter 8. The deflection of menacing rubble pile asteroids
K. Holsapple and K. Housen
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 9. Techniques for the structural investigation of aggregate bodies
H. Yano, J. Terazono, H. Akiyama, T. Kobayashi, T. Maruki, and K. Yoshida
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 10. Peering inside NEOs with radio tomography
W. Kofman and A. Safaeinili
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 11. Seismic investigations of asteroid and comet interiors
J.D. Walker and W. Huebner
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 12. Future mitigation technologies and their scientific requirements
C. Gritzner and R. Kahle
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 13. Lander and penetrator science for NEO mitigation studies
A.J. Ball, P. Lognonné, T. Spohn, K. Seiferlin, S.F. Green, and J.C. Zarnecki
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 14. Optimal interception and deflection of Earth-approaching asteroids using low-thrust electric propulsion
B.A. Conway
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 15. Close proximity operations at small bodies: Orbiting, hovering, and hopping
D. J. Scheeres
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 16. Mission operations in low gravity regolith and dust
D. Sears, M. Franzen, S. Moore, S. Nichols, M. Kareev and P. Benoit
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 17. Towards a program to remove the threat of hazardous NEOs

M.J.S. Belton
28 pages/ 14500 words / 3 B&W figures or tables

Chapter 18. Impacts and the public: Communicating the nature of the impact hazard
D. Morrison, R. Binzel, C. Chapman, and D. Steel
28 pages/ 14500 words / 3 B&W figures or tables

References
M.J.S. Belton, D.K. Yeomans, & T.H. Morgan to be compiled with professional help from the chapter authors.

Glossary
M.J.S. Belton, D.K. Yeomans, & T.H. Morgan with professional help.

Index
M.J.S. Belton, D.K. Yeomans, & T.H. Morgan with professional help.

APPENDIX G: TITLES OF EXTENDED ABSTRACTS

The Extended Abstracts are on the web at HYPERLINK "http://www.noao.edu/meetings/mitigation/eav.html" http://www.noao.edu/meetings/mitigation/eav.html. The titles are as follows:

SIZES AND STRUCTURES OF COMETS AND ASTEROIDS: WHAT IS WORTH MITIGATING, AND HOW?
Erik Asphaug, Earth Sciences Dept., University of California, Santa Cruz CA 95064 USA

LANDER AND PENETRATOR SCIENCE AT NEOS.
A. J. Ball, Planetary and Space Sciences Research Institute, The Open University, Walton Hall, Milton Keynes MK7 6AA, U.K.

UNDERSTANDING THE DISTRIBUTION OF NEAR EARTH OBJECTS.
W. F. Bottke, Southwest Research Institute, Boulder, CO 80302, USA, A. Morbidelli, Observatoire de la Cote d'Azur, Nice, France, R. Jedicke, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

IMPACT: AN INTEGRATED APPROACH (Space and Ground) FOR MONITORING THE THREAT OF EARTH ORBIT CROSSING CELESTIAL BODIES
L. Bussolino, Alenia Spazio S.p.A. Strade Antica di Collegno 253, 10146 Torino (TO), Italy

PHYSICAL CHARACTERIZATION OF NEOs BY MEANS OF REMOTE OBSERVATIONS FROM SPACE.
A. Cellino 1, M. Delbò 1, K.Muinonen 2, E.F. Tedesco 3, S.D. Price 4, M. Egan 4, M. Ragni 5, L. Bussolino 6. 1 INAF-Torino Astronomical Observatory, 2 Observatory, University of Helsinki, 3 TerraSystems, Inc., 4 Air Force Research Laboratory, 5 University of Perugia, 6Alenia Spazio.

WHAT WE KNOW AND DON'T KNOW ABOUT ASTEROID SURFACES.
Clark R. Chapman (Southwest Research Inst., Boulder), USA

IMPLICATIONS OF THE NEAR MISSION FOR INTERNAL STRUCTURE.
A. F. Cheng, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA

EARTH IMPACTORS:ORBITAL CHARACTERISTICS AND WARNING TIMES.

S. R. Chesley, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA , T. B. Spahr, Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA.

OPTIMAL INTERCEPTION AND DEFLECTION OF EARTH-APPROACHING ASTEROIDS USING LOW- LOWTHRUST THRUST ELECTRIC PROPULSION.

B. A. Conway, Dept. of Aeronautical & Astronautical Engineering, University of Illinois, Urbana, IL 61801, USA.

PHYSICAL PROPERTIES OF COMETS AND ASTEROIDS INFERRED FROM FIREBALL OBSERVATIONS.

M. Di Martino, INAF - Osservatorio Astronomico di Torino, 10025 Pino Torinese, Italy,

MASS DRIVERS, A ROBUST SOLUTION FOR PLANETARY DEFENSE.

Freeman Dyson, George Friedman, and Lee Valentine, Space Studies Institute P.O. Box 82, Princeton, NJ 08540, USA.

ASTEROID 1950 DA'S ENCOUNTER WITH EARTH IN A.D. 2880.

J. D. Giorgini, S. J. Ostro, L. A. M. Benner, P. W. Chodas, S. R. Chesley, (Jet Propulsion Laboratory, Pasadena CA 91109, USA), R. S. Hudson,(Washington State University, USA), M. C. Nolan, (Arecibo Observatory, Puerto Rico, 00612), A. R. Klemola, (Lick Observatory,
Santa Cruz CA 95064, USA), E. M. Standish, R. F. Jurgens, R. Rose, D. K. Yeomans, (JPL), J.-L. Margot, (California Institute of Technology, Pasadena CA 91125, USA).

SCIENTIFIC REQUIREMENTS FOR UNDERSTANDING THE NEAR-EARTH ASTEROID POPULATION.

A. W. Harris**,** DLR Institute of Space Sensor Technology and Planetary Exploration, Rutherfordstr. 2, 12489 Berlin, Germany.

SPEED LIMITS OF RUBBLE PILE ASTEROIDS: EVEN FAST ROTATORS CAN BE RUBBLE PILES.

K. A. Holsapple, University of Washington, Box 352400, Seattle, WA 98195, USA.

THE DEFLECTION OF MENACING RUBBLE PILE ASTEROIDS.

Keith A. Holsapple, University of Washington, Box 352400, Seattle, WA, 98195, USA.

THE SCIENTIFIC REQUIREMENTS OF FUTURE MITIGATION TECHNOLOGY.

R. Kahle1, and Ch. Gritzner 2, 1 German Aerospace Center, Institute of Space Sensor Technology and Planetary Exploration, Rutherfordstrasse 2, 12489 Berlin, Germany, 2 Dresden University of Technology, Institute for Aerospace Engineering, Mommsenstrasse 13, 01062 Dresden, Germany

HOW WELL DO WE UNDERSTAND THE COMETARY HAZARD?

Matthew Knight, Michael A'Hearn, Department of Astronomy, University of Maryland, College Park MD 20742, USA.

RESULTS FROM AN ONGOING IR SURVEY OF COMETARY DUST AND NUCLEI.

C.M. Lisse 1, M.F. A'Hearn , 1, Y.R. Fernandez , 2. 1 University of Maryland, Department of Astronomy, College Park, MD 20742, 2 Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA.

DEFLECTING IMPACTORS AT 90°.

Claudio Maccone, Via Martorelli 43, I-10155 Torino (TO), Italy

COMET/ASTEROID PROTECTION SYSTEM (CAPS): A SPACE-BASED SYSTEM CONCEPT FOR REVOLUTIONIZING EARTH PROTECTION AND UTILIZATION OF NEAR-EARTH OBJECTS.
D. D. Mazanek, NASA Langley Research Center, MS 328, Hampton, VA 23681-2199, USA.

INITIAL ORBITS FOR NEAR EARTH OBJECTS FROM HIGH PRECISION ASTROMETRY.
K. Muinonen, Observatory, University of Helsinki, P.O. Box 14, FIN00014 U. Helsinki, Finland , J. Virtanen, Observatory, University of Helsinki, P.O. Box 14, FIN00014U. Helsinki, Finland, F. Mignard, Observatoire de la Cote d'Azur, CERGA, UMR CNRS 6527, av. Copernic, F06130 Grasse, France.

COMMUNICATING ABOUT COSMIC CATASTROPHES.
Brendan M. Mulligan, CIRES, Univ. Colorado (Boulder) & Queen's Univ. (Hamilton), Clark R. Chapman, Southwest Research Inst. (Boulder), USA

RADAR RECONNAISSANCE OF POTENTIALLY HAZARDOUS ASTEROIDS AND COMETS.
S.J. Ostro, Jet Propulsion Laboratory, California Institute of Technology Pasadena, CA 91109-8099, USA.

USING A SOLAR COLLECTOR TO DEFLECT A NEAR EARTH OBJECT.
James F. Pawlowski, Human Exploration Science Office, Johnson Space Center, Houston, TX. 77058, USA

IMAGING THE INTERIORS OF NEAR-EARTH OBJECTS WITH RADIO REFLECTION TOMOGRAPHY.
Ali Safaeinili and Steven J. Ostro, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099, USA.

INFERRING INTERIOR STRUCTURES OF COMETS AND ASTEROIDS BY REMOTE OBSERVATIONS.
Nalin H. Samarasinha, National Optical Astronomy Observatory, Tucson, AZ 85719, USA

CLOSE PROXIMITY OPERATIONS AT SMALL BODIES: ORBITING, HOVERING, AND HOPPING.
D.J. Scheeres, Department of Aerospace Engineering, The University of Michigan, Ann Arbor, MI 48109-2140, USA.

NEO IMPACT HAZARD: THE CANCER METAPHOR.
Duncan Steel, Joule Physics Laboratory, University of Sal Salford, Greater Manchester M5 4WT, UK.

EDDY CURRENT FORCE ON METALLIC ASTEROIDS.
Duncan Steel, Joule Physics Laboratory, University of Salford, Salford M5 4WT, England, UK

NEA DEFLECTION: SOMETIMES RESONANT RETURNS ARE OF NOT MUCH HELP.
G.B. Valsecchi, A. Carusi, *IASFCNR,Roma, Italy, and SCN, ESA/ESRIN, Frascati, Italy.*

SEISMIC INVESTIGATIONS OF ASTEROID AND COMET INTERIORS.

J. D. Walker and W. F. Huebner, Southwest Research Institute, P. O. Drawer 28510, San Antonio, TX 78228-0510, USA.

MILITARY PERSPECTIVES ON THE NEAR-EARTH OBJECT (NEO) THREAT.
S.P. Worden, United States Space Command, Peterson Air Force Base, CO 80914, USA.