NEO Mitigation and Coordination with the Disaster Management Community

1st IAA Planetary Defense Conference:
Protecting Earth from Asteroids

27-30 April 2009

Granada, Spain

Clark R. Chapman[1,2], Russell L. Schweickart[2]

[1] *Southwest Research Institute*
Suite 300, 1050 Walnut St.
Boulder CO 80302 USA
Email: cchapman@boulder.swri.edu

[2] *B612 Foundation*
760 Fifth St. East
Sonoma, CA 95476 USA
Email: info@B612Foundation.org

ABSTRACT

We now realize, from the case of 2008 TC_3's discovery and subsequent impact in Sudan, that it is ***much*** more likely that a Near Earth Object (NEO) large enough to cause damage on the ground will be found (by the current Spaceguard Survey telescopes) on its "death plunge," providing a couple weeks of warning, than that a dangerous NEO will be found years or decades before impact. We also understand that serious ground damage may be caused by smaller NEOs than previously thought, and these strike the Earth more frequently. Cases of final apparition "virtual impactors" also could result in a short-term impact warning. Thus civil defense measures, like issuing a short-term alert for impending impact of a modest-sized NEO and implementing evacuation of ground-zero, will be more crucial and relevant to public officials than plans for deflecting a larger NEO by a space mission. Unfortunately, little attention has been given to establishing communication channels for warning so that civil defense measures like evacuation can be successful. Development of national and international capabilities and infrastructure for handling the NEO hazard must include – beyond engineering design of deflection missions -- on-the-ground disaster management procedures. An integrated international framework for responding to the NEO threat has been put before the United Nations by the Association of Space Explorers International Panel on Asteroid Threat Mitigation, which constitutes a first step of engagement between NEO scientists and engineers and the international disaster management community.

INTRODUCTION

If a potentially damaging impact by a Near Earth Object (NEO) is to be evaluated seriously as a natural hazard to be mitigated, then we need systematic end-to-end planning for handling such a rare but possibly very dangerous threat. Currently, there is a systematic telescopic search effort, the "Spaceguard Survey," designed to detect NEOs > 1 km diameter, but which also detects numerous NEOs only hundreds of meters in size or smaller. (Nearly all NEOs are near-Earth *asteroids*, not *comets*, but we use "NEO" throughout this paper.) There is also considerable thinking, though based on almost no funding, about how we might deflect a threatening NEO if one is discovered to be on a trajectory that will impact Earth many years to decades later. However, major elements of a systematic approach to NEO hazard mitigation are missing, or nearly so, from current efforts. These include such disparate matters as (a) communications linkages between astronomers who discover and catalog potential NEO impacts and the emergency management agencies that will need to respond effectively in the unlikely case that a hazardous object is found and (b) consideration that the most likely NEO impact scenario to unfold in the next decades is a short-term (days to weeks) warning of an impact requiring evacuation of ground-zero rather than a long-term warning (a decade or longer) that can be addressed by launching a space mission to deflect the dangerous body. We address several of these issues in this paper.

Some pieces of the required infrastructure for handling the NEO hazard are in place, at least in rudimentary form. Of course, there are the Spaceguard Survey observatories [1], the asteroid data archival facility (Minor Planet Center) [2], and the two independent facilities that calculate and tabulate potential impacts (JPL Sentry and Univ. of Pisa NEODyS) [3,4]. There are also some information centers and websites (e.g. the U.K. Near Earth Object Information Centre [5]), but they are not updated frequently. In the United States, observers are expected to report NEO threats to the director of NASA's Near Earth Object Observations Program, who would try to inform relevant American emergency management agencies (e.g. Federal Emergency Management Agency); but it is not clear that recipients of such warnings have either the background knowledge or the established protocols for dealing with such information. We are not aware of robust links between astronomers and emergency management agencies in any other country. And there is, as yet, no international infrastructure for responding to an NEO threat, although a framework has been proposed by the Association of Space Explorers (ASE) to the United Nations through the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS) [6, 7]. As we will show below, the need to establish an end-to-end response system is more urgent than had been realized, because the chances that society will have to respond to one or more events in the next decade or two are higher than had been thought. That is because we now realize that smaller NEOs, once thought to be harmless, may be dangerous; also we now realize that small or moderate sized NEOs on an impact trajectory will be much more likely to be detected weeks before they impact than previously assumed, providing short-term warning.

WHAT IS THE SMALLEST NEO THAT IS DANGEROUS?

The size distribution of NEOs is treated elsewhere in these Proceedings [8]. One of its salient features is that small NEOs are much more common than larger ones, hence they impact the Earth much more often. Because of the extraordinary destructive potential of impact by an NEO larger than 1 km diameter, we must continue to be aware of the possibility of such an extremely unlikely catastrophe, even though it is becoming even less likely as the Spaceguard Survey continues to discover remaining large NEOs that will not hit during the next century [8]. But the public can be expected to focus on *any* predicted future impact, no matter how modest the expected damage may be (consider the extreme example of public concerns about the re-entry of Spacelab in 1979). Generally, meteoroids (small asteroids) smaller than 10 or 20 m in size explode more-or-less harmlessly in the upper atmosphere; although they can rain meteorites onto the land below, there is no well documented case of anyone being killed by a meteorite. But somewhat larger NEOs explode with greater force and at lower altitudes, and their momentum can drive a dangerous shock wave down to the ground; this is apparently what happened at Tunguska, Russia, in 1908, when an object perhaps only 35 m in diameter exploded with a force of several megatons, with devastating effects on the fortunately unpopulated taiga forest below [9]. The serious NEO issue that is most likely to confront public officials in the near future is the predicted impact of the *smallest* NEO with a reasonable chance of having seriously destructive or even deadly consequences... because the smallest NEOs impact most frequently and hence are most likely to constitute the next threat.

Most considerations of the NEO hazard (e.g. attempts to design a deflection mission) have considered that a typical NEO is like Apophis, which is over 250 m in diameter. Such large NEOs are, of course, more dangerous than smaller ones, but they are also the ones that the current surveys find much more frequently than the actually more numerous small NEOs. As we write this in May 2009, one of only two NEOs with a non-zero threat rating on the Torino Scale is 2009 KK, with a close approach to Earth and possible impact on 29 May 2022; its estimated diameter is 270 m, similar to Apophis. Yet it is ~100 times more likely that the next impact will be by a 35 m Tunguska-like NEO than by an Apophis-sized NEO. (The other TS=1 NEO is also, at 130 m diameter, much larger than the low-end threshold size for damage.)

Therefore, a vital issue for decision makers is what is the smallest NEO that poses a credible threat, beyond a brilliant flash in the sky and some meteorite falls? Actually, strong metallic meteoroids can penetrate the atmosphere and crater the ground, but they constitute only ~3% of all NEOs; also, we may expect rare, anomalous cases of small stony meteoroids striking the ground at hypervelocity, like the 2007 impact near Carancas, Peru [10]. The SDT report [11] considered 50 m to be the minimum diameter for a typical, non-metallic NEO to have damaging consequences, but a consensus is developing (e.g. [9]) that NEOs as small as 35 m are probably dangerous. Should we then be unconcerned about 25 m bodies, which impact 10 times as frequently as 50 m bodies? Not really. One reason is because of the bimodal distribution of asteroid albedos (most NEOs are either very dark or moderately reflective); the actual size of an

NEO is quite likely to be either half as big or, more worrisomely, twice as big as the nominal diameter, which is usually based on optical magnitude only. So a prudent public official might take action (e.g. order an evacuation) if there is a predicted impact by an NEO that is nominally only 15 m in diameter...and there is a 20% chance of such an impact, somewhere on Earth, during the next ten years. As we show in the next section, there is a fair chance that the current Spaceguard Survey will actually discover such an NEO and provide warning just days or weeks before impact, so the scenario of public officials having to make decisions with little advanced notice is very plausible, indeed.

SHORT-TERM WARNING: THE MOST LIKELY NEO MITIGATION CASE

Current Surveys Warn of Final Plunges by Small NEOs

On 7 October 2008 the NEO designated 2008 TC_3 (hereafter TC3), discovered by the Catalina Sky Survey (part of the Spaceguard Survey) less than 20 hours earlier, crashed into the atmosphere above a remote part of Sudan, within kilometers of where JPL dynamicists had predicted it to impact [12,13,14]. Prior to the impact, several large telescopes were hastily rescheduled in order to observe the object before its demise. Two months later, attempts to find meteorites on the ground below the track of the disintegrating NEO were successful (they are ureilites, a rare type of achondrite); as of March 2009, nearly 300 fragments had been found. The impact was observed and measured in various ways. Evidently TC3 was about 4 m in diameter and exploded with an energy between 1 and 2 kT TNT equivalent. While many scientific insights will be gleaned from the resulting astronomical and cosmochemical data, TC3 has especially important implications for our understanding of, and response to, the NEO impact hazard.

Impacts of ~5 m objects exploding in the atmosphere with 1 or 2 kT are expected to be roughly an annual event on our planet [8, 15]. However, in treatments of the NEO impact hazard, the canonical statement has been that “a short lead time for an NEO is extremely unlikely – we can expect either decades of warning or none at all” [16]. The concept of warning times less than 1 year is not even mentioned in the 272-page NASA report [17]. It has also been estimated that the current Spaceguard Survey will find less than 1-in-a-million of the more than 100 million NEOs around 5 m diameter. Even the “next generation” surveys by large telescopes like Pan-STARRS and LSST, planned for completion in the mid-2020s, would be expected to find a fraction of 1% of 5-m NEOs. So how is it possible that what may have been the largest NEO to impact Earth during 2008 actually was found beforehand by a small Spaceguard telescope?

It turns out that, because it is so close to the Earth, a small NEO heading straight for impact is actually *much* brighter than typical NEOs of that size orbiting around the inner solar system. Indeed, an object the size of TC3 can be detected one or even two days before impact by the larger Spaceguard Survey telescopes. And the Survey searches a large fraction of the night-time sky every week or two. So the pre-detection of an annual impactor during a decade of systematic searching is not especially unexpected [7]. Indeed, larger, potentially damaging NEOs (e.g. 15 - 35 m in diameter) -- which would be brighter and detectable farther out than TC3 on their final plunge -- might be detected one-third of the time, or even more completely if current observing protocols were extended to cover more of the southern hemisphere and the pre-dawn and post-twilight parts of the sky. Such substantial detectability of NEOs during their final plunge contrasts sharply with the 0.1% of total 30 m objects nominally expected to be cataloged by the current Spaceguard Survey. Since the goal of an NEO survey is supposed to be to find an NEO that is *going* to impact *before* it hits, clearly the previously unappreciated short-term warning capability of the Spaceguard Survey has a dramatically larger chance of meeting that primary goal than finding, with very low probability, an impact of similar magnitude that may occur decades from now.

TC3 forces us to think about short-term warning. On the one hand, it remains unlikely (say around 5%) that a >30 m object will strike in the next 15 years. But if it does strike in the next 15 years, it is *very much more likely* to be found on its final plunge to Earth, providing maybe a couple of weeks' warning, than that it will be found in the traditional way, during a moderately close passage to Earth one or more orbits before its actual impact. This results from (a) the previously unappreciated high short-term discovery effectiveness of the current survey for the numerous small NEOs compared with (b) the inherent rarity of Apophis-sized NEOs, even though the latter are cataloged with fairly good efficiency by the current survey. In fact, the current Spaceguard Survey does such a poor job of cataloging small NEOs that it is about 100 times more likely that it will find a >30 m impactor on its final plunge than long beforehand.

The next generation survey, employing larger telescopes, will do a much better job cataloging small NEOs. Still, a short-warning case involving a >30 m NEO is at least as likely as the discovery of a >30 m NEO that will impact decades in the future. And there remains a similar chance that a 30 m object will strike the Earth without ever having been detected in advance, either short- or long-term. So by the mid-2020s there will be roughly equal chances of long-term warning, short-term warning, and no warning. It should be noted that the LSST and Pan-STARRS surveys, as presently designed, actually cannot provide short-term warning for sub-30 m NEOs because of a combination of [a] the observing cadence, which is designed for long-term warning and for other astrophysical goals, and [b] the data reduction software and reporting protocols currently being designed. While, in principle, the newly appreciated value of short-term warning, both for enabling evacuation and for TC3-like meteoritical research, might motivate changes to the observing cadence, it is more likely that software and reporting protocols can be changed for the better during the many years it will take for these surveys to be fully implemented. In any case, simple continuation into future decades of the current, rather inexpensive Spaceguard Survey could provide adequate short-term warning capability.

Search for Virtual Impactors on Final Plunge

At any time, there are numerous low-probability impact predictions on, for example, the JPL Sentry website [3]. In some cases, especially for small NEOs, there may be no opportunities for further observations until the NEO is on its final plunge. If the impact is predicted for a date within the next decade, the ultimate mitigation approach most likely will be evacuation rather than deflection, but only if it can be determined that the NEO will actually hit. Any such impact prediction, because of the large uncertainties resulting in the low probability for the impact, will have numerous "virtual NEOs" representing the range of plausible trajectories for the actual NEO [18]. As demonstrated in the case of AL0067 [19], telescopic observers can search the portion of the sky for virtual impactors (the virtual NEOs that would actually impact the Earth), and either rule out or, less likely, rule *in* an impact during the days and weeks before the possible impact. This situation resembles the short-term warning case discussed earlier, with two differences: (a) observers know where to look for the incoming NEO, if it is really going to hit, but (b) there is a low probability (whatever it is) of actually finding the NEO there. Another difference concerns virtual impactors coming from the general direction of the Sun, so that optical telescopes would be incapable of searching for an incoming NEO. In such cases, ground-based radar facilities could be utilized, but because of the strong dependence of radar detectability on distance, the warning time might be very short – hours to days.

For optical or radar observers to be motivated to make the effort to search for such virtual impactors, the predicted impact probability cannot be too small and/or the potential impacting NEO must be unusually and dangerously large. Otherwise, there are too many low probability impacts to be studied to reward an observer for finding an actual case meriting a warning. More study of such final-plunging virtual impactors is necessary before we can assign priorities for systematically looking for virtual impactors that exceed some thresholds for size and impact probability. Note that the "risk corridor" for the dangerous virtual impactors (the path across the Earth where the NEO would hit, if it does hit) will be reasonably well known even if the impact probability is low, and that knowledge might also affect the priority of searching for the dangerous virtual impactors.

Mitigating Short-Term Warnings

This new gestalt on the likely short-term warnings changes the way we must think about mitigating the NEO impact hazard. Prior to now, most attention has been given to deflecting the threatening NEO so that it will not hit the Earth. Debate has surrounded which technique, or combination of techniques, is most appropriate/sufficient/effective in accomplishing the required deflection. Civil defense measures, like evacuation of ground-zero, were hardly considered in the 1990s and have remained in the background. One of us (CRC) has advocated [20] thinking about evacuation to deal with two unlikely situations: (a) very unlikely impacts by comets too large (or with too little warning time) to deflect and (b) as back-up in case deflection attempts were to fail. Of course, it had been considered that there was a small chance that any large NEO headed for Earth impact, and a very good chance that any small NEO headed for Earth (for which the surveys were assumed to be very incomplete), would slip through undetected so that our first knowledge of it would be the explosion, in which case post-disaster rescue and recovery operations would be employed similar to those following an earthquake [21].

It is now clear that civil defense must play a much larger role in NEO mitigation than we had been expecting. The good news is that, with a couple weeks of warning, the opportunity to save lives (though not most property) is greatly enhanced compared with after-the-disaster recovery operations...for, even now with our current Spaceguard telescopes, we can predict a *far* larger fraction (tens of percent) of impending impacts than had been supposed. Evacuation and other civil defense measures can be planned and implemented, if necessary, with plausible chances for success. Another lesson is that we really must optimize the current search procedures to find incoming NEOs and we must establish rapid communication channels to inform the emergency response community about an impending impact in ways that enable first responders to be effective.

RELATIVE FREQUENCY AND IMPORTANCE OF NEO IMPACT SCENARIOS

There has been no definitive study of the likelihood that society, and public officials, will have to respond to various scenarios, and there should be. But based on our analysis above and previous evaluations, we offer the following tentative, qualitative list of scenarios, in decreasing order of likelihood. Each scenario is summarized, followed by an underlined description of the importance of the scenario if it were to occur, followed by a very crude estimate of the likelihood (at the present, then during the final years of the next-generation surveys).

- Hyped or unreliable media news stories. *Officials are irritated but must do nothing.* Annual → more often?
- Predicted impacts during future decades requiring analysis, but leading to no action. 20%/decade → several per year.
- Short-term impact warning for a ~15 m NEO. *Immediate evacuation would be prudent.* 7%/decade → 15%/decade.
- Prediction of an impact during the next 50 years *eventually requiring launching of a transponder mission* (for NEOs > 100 m). 1% chance → 15% chance.
- Short-term impact warning for a >40 m NEO. *Immediate evacuation required* (by ships or from ground-zero). 0.3%/decade → 1%/decade.
- Detection of an NEO >100 m that would ultimately impact during next 50 years *and would be very destructive if deflection isn't successful or even attempted.* 0.01% → 0.2%.
- Detection of a civilization-threatening NEO that will strike in the next 50 years. 0.001% → 0.0003% chance.

Despite the new emphasis we must give to short-term warning and evacuation, we should not forget the importance of the rarer long-term warnings required for generally larger NEOs (the last two bullets above). After all, despite their rarity, they could be vastly more destructive, there would be greater motivation to deflect them, and there very likely would be time to mount a deflection mission. Besides those considerations, once the next generation survey is well underway a decade from now, the chances that a > 30 m NEO will be found years or decades before its final plunge will grow to be more comparable with the chances of a short-warning discovery, and such a threat may well merit a deflection campaign. Moreover, public officials will have to *make decisions* about initiating a deflection campaign *much* more frequently than actual strikes will happen, as demonstrated in the ASE report to the U.N. [7].

WHAT DOES "MITIGATION" MEAN FOR THE NEO HAZARD?

The word "mitigation" has a common meaning of "lessening unfavorable consequences" in many societal contexts (e.g. engineering, economics, environmental impacts, medical care) and the concept is especially central to emergency management. Naturally, we should want to mitigate the NEO impact hazard using any and all of the most effective tools available. In 2005 the Congress used the well-known word "mitigation" when it changed the Space Act of 1958 to read:

The Congress declares that the general welfare and security of the United States require that the unique competence of the National Aeronautics and Space Administration be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide ***warning and mitigation*** *of the potential hazard of such near-Earth objects to the Earth.* [Emphasis added]

Yet, in the world of NEO threat reduction, the word "mitigation" has come to mean, in most quarters, simply "deflection". Why is this? The book "Hazards Due to Comets & Asteroids" [22], based on meetings held in 1991-1993, has a whole section entitled "Hazard Mitigation," yet all chapters deal solely with interception (for purposes of NEO deflection or fragmentation). The reason for this is probably because the NEOs then given primary attention were those > 1 km diameter, potential civilization-destroyers for which "taking the hit" is a very bad option. As the Spaceguard Survey was designed, mandated by Congress, and implemented, >1 km diameter remained the focus. Although Tunguska-sized impacts were often discussed, we find no published analysis of the Survey's capabilities for short-term warning. For example, the Shoemaker Committee's report [23], issued in the wake of the Shoemaker-Levy 9 impacts on Jupiter, did not analyze the committee's proposed survey's capability for short-term warning, except for comets. The SDT [11] report did evaluate short-term warning, but only in the context of the next generation surveys; it found that ground-based or near-Earth observatories could provide short-term warning, but it concluded that such warnings would just be a by-product of running the long-term cataloging effort, which would also eventually reach down to most NEOs >50 m diameter (their estimate of lower limit for damage). Thus the effectiveness of the *current* Spaceguard Survey for short-term warning has simply been overlooked...and so attention has remained on deflection.

In its 2006/2007 report to Congress [17], NASA explicitly recognized the more encompassing meaning of the word "mitigation" but explicitly chose to ignore any mitigation option other than deflection. (It even chose not to evaluate fragmentation and the report never mentions evacuation.) The NASA report ignores the SDT study [11] of short-term warning and defines short-term warning to mean 1 to 20 years before impact, generally in a cometary context; warning times of less than 1 year are never mentioned. One might surmise that it is in the interests of the space agency, and of its aerospace constituents, to emphasize mitigation techniques involving space missions rather than civil defense. But rather than imputing biased motives, we prefer to conclude that asteroid astronomers are responsible for de-emphasizing or simply overlooking the short-term warning capability of the current survey.

We must change our view about mitigation strategies. Surely the Congress wants to mitigate the NEO hazard, in whatever way possible (if Congress has emphasized deflection, it is only because astronomers have told it to do so). We now must proceed with an understanding that, during the next decade, it is ~100 times more likely that a small-but-still-dangerous NEO >30 m diameter will be found on its final plunge, requiring evacuation, than that the cataloging effort will find a probably larger, Apophis-sized NEO eventually requiring deflection. Thus any future consideration of NEO mitigation *must* consider issues such as optimization of short-term warning, developing communications channels and protocols between optical/radar astronomers and the public and emergency managers, and determining whether there are NEO-specific attributes of civil defense that should be studied. One useful proposal to enhance effective management of the NEO hazard is that of the ASE's International Panel on Asteroid Threat Mitigation [7], which recommends formation, within the U.N., of an "Information Gathering, Analysis, and Warning Network," which would implement the integrated process beginning with telescopic searches for threatening NEOs through coordination with national and international disaster management agencies.

In designing appropriate plans for NEO mitigation, we must consider evacuation (and other disaster preparation and recovery procedures) on an equal footing with deflection. *Deflection* is important for it is the only responsible way to prevent an enormous NEO-caused regional or global catastrophe from happening. There are conundrums facing deflection, such as the obligation to make early decisions when the need to deflect is still uncertain. Moreover, a deflection mission may be regarded as too expensive, especially in a context where the need to deflect remains uncertain. But *evacuation* is an equally important element of mitigation, for it is by far the most likely case we are facing. Evacuation is comparatively inexpensive and it is familiar: in many ways, we need only apply the usual "all hazards" emergency procedures. But it requires further development of infrastructure, so that emergency managers and first responders know how to react effectively to an impact prediction for which there has been no precedent.

ACKNOWLEGEMENTS

We thank Mark Boslough, David Morrison, and Alan Harris for discussions.

REFERENCES

[1] http://neo.jpl.nasa.gov/programs/
[2] http://www.cfa.harvard.edu/iau/mpc.html
[3] http://neo.jpl.nasa.gov/risk/
[4] http://newton.dm.unipi.it/neodys/index.php?pc=4.0
[5] http://www.spacecentre.co.uk/neo/
[6] R.L. Schweickart, "Decision program on asteroid threat mitigation," *Acta Astronautica*, doi:10.1016/j.actaastro.2009.03.069, 2009.
[7] ASE (Association of Space Explorers International Panel on Asteroid Threat Mitigation), "Asteroid Threats: A Call for Global Response," 54 pp., 2008, http://www.space-explorers.org/ATACGR.pdf.

[8] A.W. Harris, "Estimating the NEO population and impact risk: past, present, and future," this volume, 2009.
[9] M. Boslough, "Computational modeling of low-altitude airbursts," *Eos Trans. AGU*, vol. 88(52), Fall Meet. Suppl., Abstract U21E-03, 2007.
[10] P. Brown *et al.*, "Analysis of a crater-forming meteorite impact in Peru," *J. Geophys. Research*, Vol. 113 (E9), 2009, doi: 10.1029/2008JE003105.
[11] SDT (Near-Earth Object Science Definition Team), *Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters*, NASA, 2003, http://neo.jpl.nasa.gov/neo/neoreport030825.pdf.
[12] S. Chesley, P. Chodas, D. Yeomans, "Asteroid 2008 TC3 strikes Earth: predictions and observations agree," 2008, http://neo.jpl.nasa.gov/news/2008tc3.html.
[13] R. Kwok, "The rock that fell to Earth," *Nature*, Vol. 458, pp. 401-403, 2009.
[14] P. Jenniskens *et al.*, "The impact and recovery of asteroid 2008 TC_3," *Nature*, Vol. 458, pp. 485-488, 2009.
[15] 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*, Vol. 420, pp. 294-296, 2002.
[16] D. Morrison, A.W. Harris, G. Sommer, C.R. Chapman, A. Carusi, "Dealing with the impact hazard," In *Asteroids III*, W.F. Bottke *et al.*, Eds. Tucson: Univ. Ariz. Press, pp. 739-754, 2002.
[17] NASA (Office of Program Analysis and Evaluation), *2006 Near-Earth Object Survey and Deflection Study: Final Report*, 272 pp., 2006.
[18] A. Milani, S.R. Chesley, A. Boattini, G.B. Valsecchi, "Virtual impactors: search and destroy," *Icarus*, Vol. 145, pp. 12-24, 2000.
[19] C.R. Chapman, "NEO Impact Scenarios," AIAA Paper 17184, 2004 Planetary Defense Conference, Garden Grove CA, 2004, http://www.b612foundation.org/papers/Chapman_AIAA.pdf.
[20] C.R. Chapman, "The asteroid impact hazard and interdisciplinary issues," In *Comet/Asteroid Impacts and Human Society*, P. Bobrowski & H. Rickman, Eds. Berlin: Springer, 145-162, 2007.
[21] V. Garshnek, D. Morrison, F.M. Burkle Jr., "The mitigation, management, and survivability of asteroid/comet impact with Earth," *Space Policy*, Vol. 16, 213-222, 2000.
[22] T. Gehrels, Ed., *Hazards Due to Comets & Asteroids*, Tucson: Univ. Ariz. Press, 1300 pp., 1995.
[23] NASA, *The Near-Earth Objects Survey Workgroup Report*, 1995, http://impact.arc.nasa.gov/downloads/neosurvey.pdf.