Systems-Level Considerations for Mitigating the NEO Impact Hazard

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Systems-level issues are given in regards to the study, research, development, and deployment of a mitigation system for the protection of Earth against impacts by massive comets and asteroids, i.e., near-Earth objects (NEOs). A number of guiding considerations will define in the coming years the extent to which humankind prepares for protecting ourselves against the impact hazard. Topics to be discussed include: detection (in the context of hazard warning), warning time, threat definition, safety and safeguards, technical research and peer review, information exchange, international teaming, precursor mitigation missions, mitigating smaller NEO impactors (25-100 m), mitigation planning, system deployment, trends in technology and geopolitics, and cost.

Introduction

Compelling evidence of a catastrophic asteroid impact on the Earth 65 million years ago (Alvarez et al., 1980 and Sharpton and Ward, 1990) has given rise to international discussions about the probability and prevention of future impacts. As a result of several recent near-misses (Morrison, 1992 and Scotti et al., 1991) and the comet Shoemaker Levy-9 impact of Jupiter in July 1994, considerable international attention has focused on defining the impact threat and determining potential mitigation schemes for the protection of Earth against planetesimal impacts (Tedeschi, 1994). Because asteroid and comet impacts pose a grave danger to all humanity, preventive defensive measures should appropriately be based on international cooperation and action. Action may consist of detection research, experimentation to prevent the impact, public education on the issues, emergency planning, and actual protection if required. This paper provides background information on the impact threat posed by NEOs and discusses associated technical and geopolitical issues requiring attention.

Basic human instincts

The fundamental issue at stake here is the core human instinct of survival - the will to live both individually and collectively. We all obviously relate very well to the individual survival instinct, and we certainly understand the need for collective approaches to protect ourselves and social institutions from danger and the ways in which we acknowledge this in our social contracts. Good collective examples are the preamble of the U.S. Constitution which contains the phase, "provide for a common defense," and Article 51 of the United Nations Charter (Nijhoff, 1985) which gives member nations the inherent right of individual or collective defense against attack. The need and desire to defend ourselves against an urgent an obvious NEO impact threat in the future is quite clear. A problem arises in the case of when there is no urgent and obvious impact threat and we must therefore prioritize meeting this need with other competing needs, some of which are definitely much more urgent and obvious. However, as humans, we have the unique ability to understand our surroundings, rationalize our existence, balance our competing needs, and act accordingly.

Impact consequences

When a large NEO (10's of meters to kilometers in size) impacts the Earth at velocities in excess of 5-10 km/sec, massive amounts of energy (10's to greater than 10^8 MT of TNT equivalent) are explosively released on very short time scales (seconds), with a resultant potential to cause damage to the Earth's biosphere. Short-term effects (< 1 second to many seconds) can include blast waves, x-rays, thermal heating, crush, and cratering (Melosh, 1989; Chyba et al. 1993; and Chapman and Morrison, 1994). Long-term effects (minutes to years) can include dust and debris, fires, tsunamis, global cooling, atmospheric and oceanographic chemistry changes, and even global warming (Gehrels, 1994). All of these effects can lead to loss of human life on unprecedented scales, depending on the size of the impactor (see Fig. 1). The scientific evidence is undeniable that Earth has been and will continue to be impacted by comets and asteroids (Morrison, 1992). Space-based optical sensors looking downward toward Earth have detected a steady flux of smaller meteoroids impacting our atmosphere (Tagliaferri et al., 1994). Before we can hope to protect ourselves against such impacts we must be able to detect such threats with ample warning time to allow us to respond effectively. The key is to find the minimum impactor size which poses a threat under some set of particular circumstances and then assure protection against it. We also must learn more about past impacts and the resultant consequences, as this will allow us to more confidently assess future impacts.

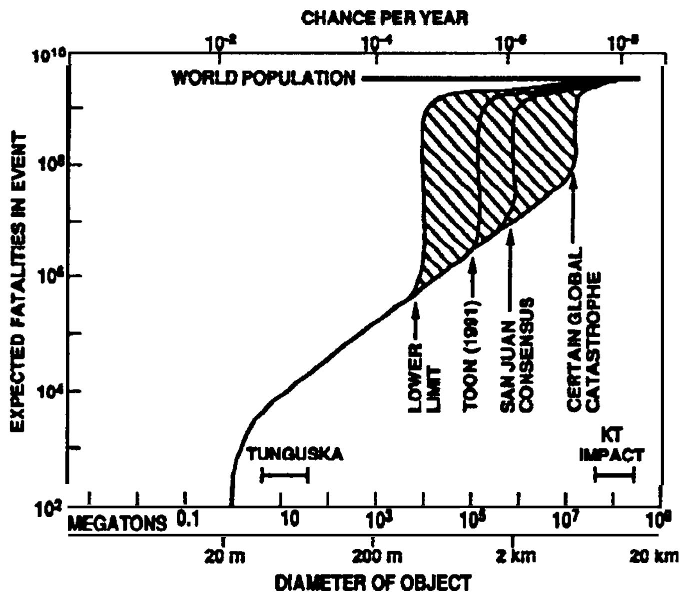

Figure 1. Estimate of expected human fatalities in an impact event versus impactor diameter (Morrison, 1992).

Detection

For any NEO protection system (detection and mitigation) to be effective, adequate warning of an Earth-approaching NEO is absolutely necessary. Currently, warning times for some small- to medium-sized NEOs, which have recently passed by Earth, are woefully short to nonexistent (Morrison, 1992 and Scotti et al., 1991). Some detections are made only hours to days before closest approach, other detections of passing NEOs have occurred only *after* closest approach with Earth. Of course, trajectories of already discovered and catalogued objects can be (and are routinely) projected forward to predict possible future close-approaches with Earth. It would seem that existing worldwide observational facilities (telescopes and radars) would be ideally suited for this mission of detection, and that the need for new facilities might only be required to ensure suitable coverage, e.g., in the Southern hemisphere or daytime sky, or establish a new type of detection capability. Once detections are made and orbit determinations made, the information must be placed in a catalog for use in refining the impact flux estimates on Earth and learning more about the threat.

Warning Time

Upon detection of an approaching NEO impactor of consequence, rapid dissemination of warning information is absolutely essential, especially for smaller objects and newly discovered long-period comets and larger asteroids. For smaller NEOs < 200 m in size, weeks of warning at the very minimum are required, however months would be preferable. For large NEOs > 1000 m in size, a year of warning at the very minimum is required, while multiple years of warning would be preferable. The size and composition of the impactor and amount of warning time available will determine which mitigation technology (or technologies) is (are) used. Currently there are a number of existing formal (e.g., International Astronomical Union Central Bureau for Astronomical Telegrams) and informal (e.g., telephone and internet) networks for reporting and learning of NEO discoveries. Warning must be timely and open. An alternative complimentary approach may be worthy of consideration. Some of the more advanced militaries of the world have observational sensors, both optical and radar, and communication networks which might add to our ability to detect NEOs and increase the warning time provided. A U.S. Air Force optical site has several 1+ meter telescopes which are now being used to detect and characterize orbital debris (Nordwell, 1993), and the Russians are devoting some of their assets to similar missions (Batyr et al., 1993). It has been postulated (Tedeschi and McKnight, 1995) that a worldwide integrated surveillance system should be considered for detecting and warning of NEO impact threats, in addition to performing other useful functions (see Tab. 1 and Fig. 2).

Table 1. Postulated worldwide integrated surveillance system (Tedeschi and McKnight.1995).

ID	TITLE	TARGETS TO SURVEIL	SUPPORTING SENSORS	COMMENTS
NDISS	National Defense ISS	Ballistic Missiles and ASATs	Ground: Radar, optical, and electro-optical Space: IR and possibly coronograph, UV, and IR/optical	National Defense
CISS	Civil ISS	LEO and GEO man-made objects	Ground: Radar, optical, and electro-optical Space: Possibly coronograph, UV, and IR/optical	For manned space safety, hazardous reentries, and GEO traffic management
IISS	Interplanetary ISS	Comets and asteroids	Ground: Optical, electro-optical, and radar Space: IR	To detect incoming natural objects and support basic research

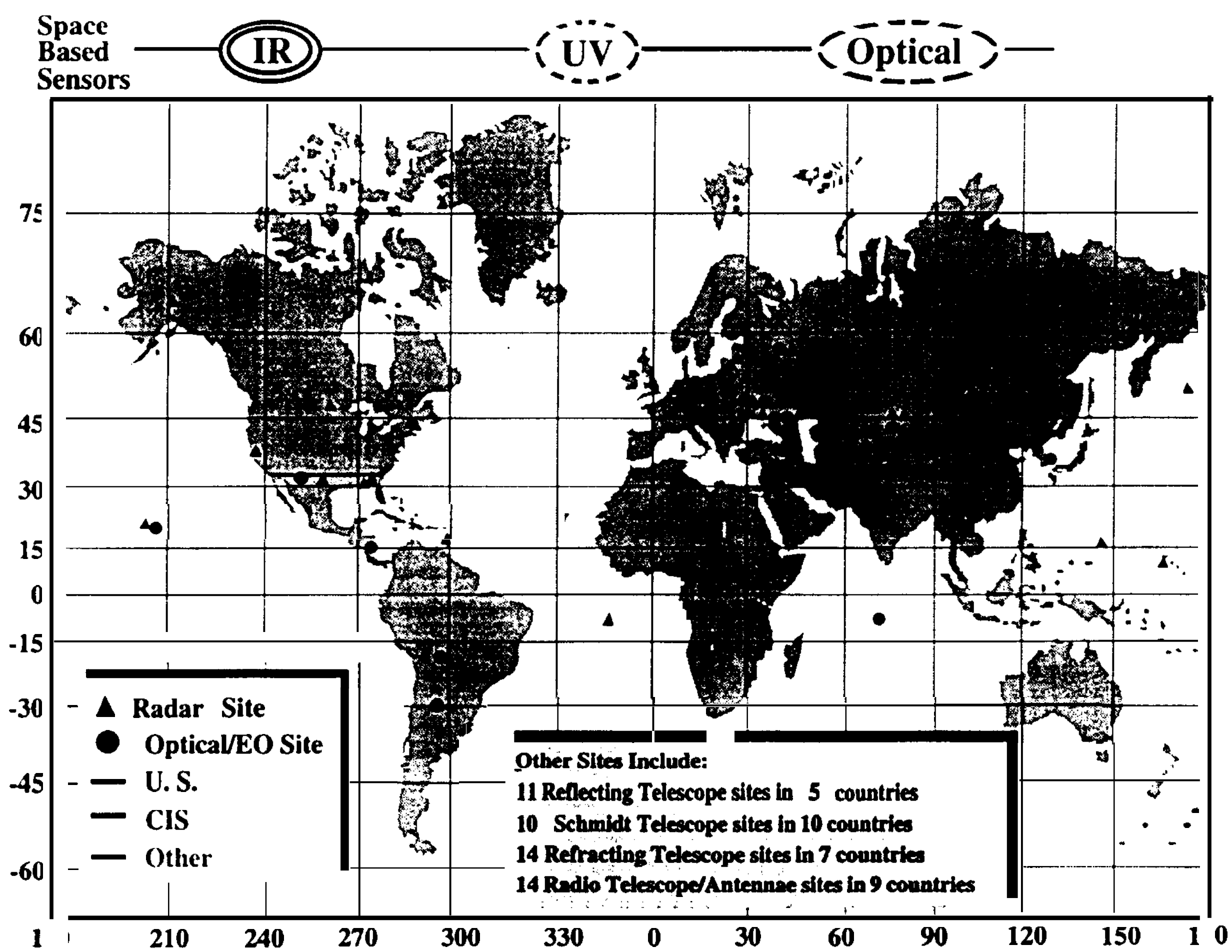

Figure 2. Worldwide Surveillance sensors ideal for NEO and orbital debris observations (Tedeschi and McKnight, 1995).

Threat Definition

Once an approaching NEO is detected and before an effective defense could be mounted, it would be necessary to know as many specifics as possible about its physical characteristics, e.g., geometry, mass, dynamic state, elemental and molecular composition, macro- and micro-structure, and material properties. The detection community has the ability now to ascertain a NEO's simple spatial and temporal characteristics, i.e., dimensions, shape, and trajectory dynamics. The bodies optical and radar returns can be used to provide information on its surface characteristics, e.g., mineral composition and geometry, but not the internal composition and structure of the body. The NEO's internal state will be a driving factor in determining its response to a particular mitigation fluence. The threat definition issue, therefore, speaks directly to the need to conduct exploratory missions to NEOs beforehand or, as a last resort, to have the ability to send precursor spacecraft to a particular approaching NEO to probe and characterize it so that a follow-on spacecraft can deploy our mitigation response of choice. The ability to perform high-speed rendezvous' with comets and asteroids has already been demonstrated successfully, e.g., by U.S. (ICE) to comet Giacobini-Zinner; by Russia (Vega), the Europeans (Giotto), and Japan (Suisei) to comet Halley; and U.S. (Galileo) to asteroids Gaspra and Ida. The technology to rendezvous with other planets, to go into orbit and even soft-land on some of them has also been demonstrated. The follow-on Clementine mission to another Near-Earth asteroid is considering probing the surface with a small kinetic energy impactor to help assay its surface composition. What is also required are missions to either rendezvous and soft-land on a NEO and assay its surface, i.e., the canceled Comet Rendezvous and Asteroid Flyby (CRAF) mission which would have been a great start - however it was canceled, but the upcoming Rosetta and Near-Earth Asteroid Rendezvous (NEAR) missions may provide additional information, or penetrate a passing NEO to probe its internal characteristics (Tedeschi and Allahdadi, 1995 and Wood et al., 1995).

Treaties, agreements, and understandings

Several international treaties, agreements, and understandings exist which may someday limit or possibly even preempt our ability to do mitigation (see Tab. 2), e.g., the 1967 Outer Space Treaty prohibits the placement of weapons of mass destruction in orbit, in space, or on other celestial bodies. It may be necessary, therefore, to discuss the creation of new agreements (treaties, conventions, resolutions, protocols, etc.) or the modification of existing instruments to legally and morally allow NEO mitigation schemes to be someday conceptualized, developed, built, and used in space - if required. This is necessary for two reasons: 1) it allows all nations of the world to understand and participate in the process leading to a defensive mitigation action and 2) it allows us to carefully plan for and respond to a detected NEO threat so that the likelihood of misuse or accidental use of powerful mitigation devices is minimized and our chances of success are maximized. At a minimum it has been proposed that some discussion is warranted on how a mitigation process might unfold from a legal perspective (Tedeschi and Teller, 1994).

Table 2. International agreements and resolutions affecting our mitigation response.

Agreement	When	What
Threshhold Test Ban Treaty	1963	Prohibits atmospheric testing, even in outer space.
Outer Space Treaty	1967	Prohibits weapon placement in orbit, in space, or on other celestrial bodies, including the moon.
Nuclear Non-Proliferation Treaty	1970	Prohibits transfer of weapons or devices.
Convention on International Liability for Damage Caused by Space Objects		Prescribes liability protocol for damage caused by man-made space objects.
Convention on Registration of Objects Launched into Outer Space		Prescribes registration protocol for space launches.
Convention on Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques	1978	Prohibits certain environmental modification techniques
Convention on Prohibitions/Restrictions on Certain Conventional Weapons	1979	Prohibits certain weapons with indiscriminant effects.
Resolution on Prohibition on Development of New Weapons of Mass Destruction and New Systems	1985	UN resolution prohibiting development and manufacture of weapons of mass destruction.

Mitigation Technologies and Research

An effective NEO protection scheme for use against an approaching object would ideally require extensive study and research *a priori* to determine the best way to safely deliver and couple a given amount of mass, momentum, and/or energy into an approaching body to either fragment or deflect it. Experimentation might include not only laboratory experiments and simulations, but also the study of actual deflection or disruption of NEOs in non-menacing orbits. Doing so would provide an increased level of confidence in the effectiveness of a particular mitigation scheme against some future NEO impactor. Such means of mitigation could include: conventional and unconventional rockets, high explosives, nuclear explosives, robotic mass drivers, high-velocity kinetic energy impacts, solar sails, or lasers (Canavan et al., 1992 and Tedeschi, 1994). Figure 3 shows a compilation of different possible mitigation fluence coupling schemes into NEOs.

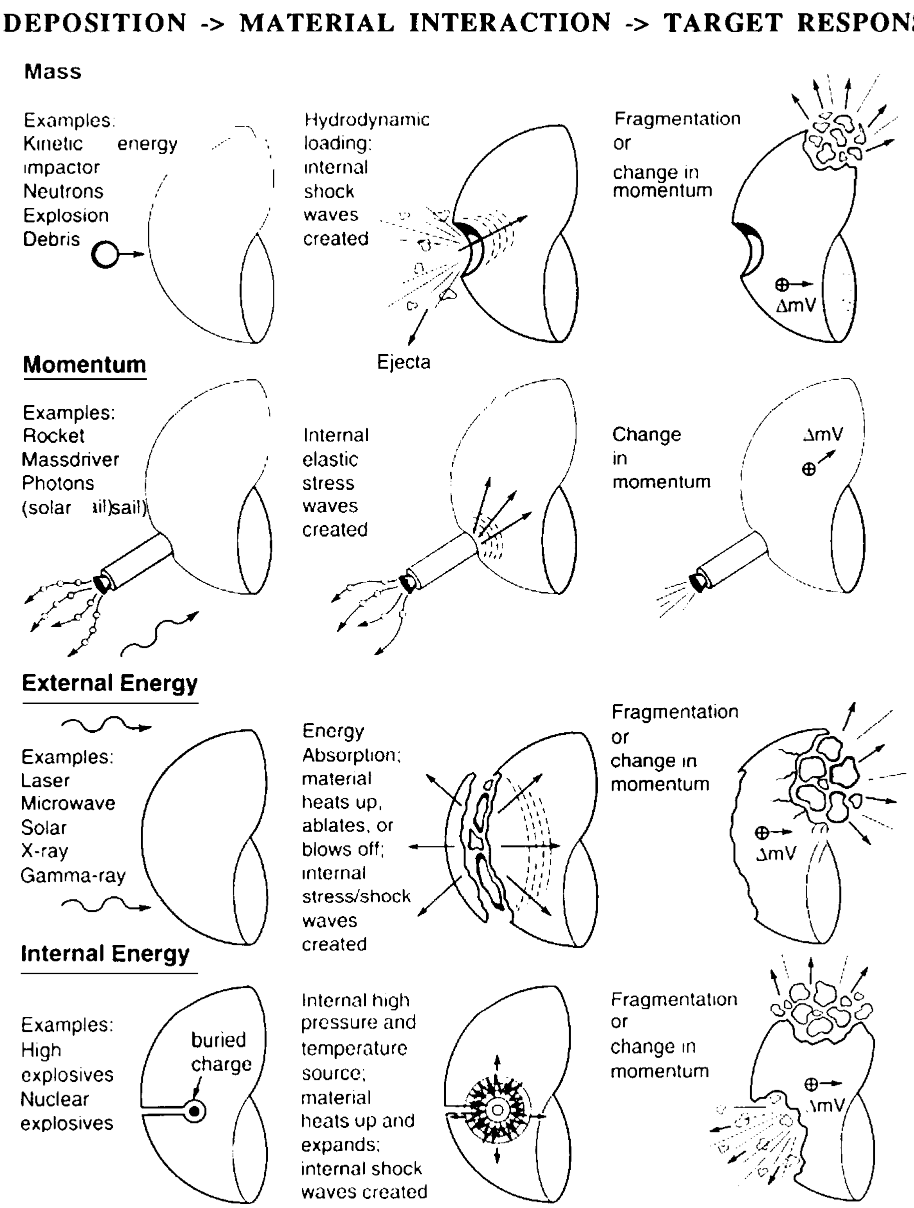

Figure 3. Mitigation schemes for deflecting or fragmenting NEO threats.

What would be involved is the delivery of a quantity of mass, momentum, and/or energy to the approaching target body, or in proximity to it, which would then be "coupled" into the body to accomplish the intended objective. The key element here is the efficient coupling or deposition into the target of the incoming mitigation fluence and the resultant physical processes by which useful actions occur to the target body, like velocity changes or body fragmentation. Mass, momentum, and/or energy deposition is the initial step in the process of altering the target body's state. The delivered energy fluence interacts with the target body thereby causing a change in thermodynamic state - usually by some form of heat transfer and/or hydrodynamic loading process, i.e., from impact shock heating and compression, solar heating, or radiation/electromagnetic heating - which can result in either material blow-off with a resultant impulse to the body, or body fragmentation because the target material could not structurally sustain the induced loading conditions.

Knowing how energy couples into various target materials serves as the basis for selecting one defensive scheme over another. This can be done only through carefully controlled experimentation and modeling, whereby various target materials are probed and characterized experimentally and analytically by a number of viable energy fluences. The target material response is observed, measured, and quantified (i.e., scaled up) in terms of it's effectiveness at imparting momentum to or physically fragmenting a larger body composed of this material. While some experimental data are available, much more material property data and energy coupling experimentation are required (Remo, 1994; Shafer et al., 1994; and Tedeschi et al., 1994). Laboratory experimentation and modeling provides very cost effective mitigation option choices and should therefore be pursued.

Arms Control

The current international arms control environment is summarized best by the phrase, "reduce the danger of weapons of mass destruction." A number of bilateral and multilateral international protocols have either been signed or are being negotiated to limit the spread, impact, and reduce the numbers of weapons of mass destruction worldwide; e.g., 1970 Nuclear NonProliferation Treaty, 1995 Nuclear NonProliferation Treaty, Strategic Arms Limitations Talks, Strategic Arms Reduction Talks - 1 and - 2, Biological Weapons Convention, Chemical Weapons Convention, Threshold Test Ban Treaty, Peaceful Uses for Nuclear Explosives Treaty, Intermediate Nuclear Forces, and Comprehensive Test Ban Treaty. The planetary defense community must be congruent in their activities vis-à-vis these constraints and the current geopolitical environment.

Safety

Mitigation schemes which might contain massive amounts of stored energy would have to be very carefully safeguarded against accident or unintended use. In no way can the cure be potentially worse than the malady. The main issue here must be to ensure that powerful mitigation technologies accountably include reliable safeguards against accidents and misuse. The potential impact to people and our environment must be minimized and balanced against the risk. In the current case of high consequence activities, such as the high explosives business, extreme care in every phase of the process is taken to protect the public safety and that of our environment against accidents and unintended misuse. Formal accountability back to the people and governments through mandatory process control protocols are the checks and balances necessary to help maximize the probability of a safe outcome.

Safeguards

Concern has been raised over the possibility of misuse of mitigation technologies [Harris et al., 1994 and Sagan and Ostro, 1994]. In perspective, though, during the 40-year Cold War with 10's of thousands of nuclear warheads in existence [Brown et al., 1994], there has not been a single case of an accidental or unintended nuclear detonation anywhere. This has been the case because of exceedingly careful attention having been given to meeting exacting requirements of security and use control throughout the lifetime of a weapon system. Misuse is a valid concern, but one which can be addressed to minimize the risk through suitable design hardware and procedures, as well as through the continuation and strengthening of appropriate international control protocols, e.g., IAEA and NPT, and other confidence-building cooperative activities. It has been proposed for consideration that a high-level international agency be charged with rationally coordinating the worldwide response, including that of safeguards, to the NEO impact threat (Tedeschi and Teller, 1994).

Perhaps of graver concern is the proliferation of certain information on powerful mitigation technologies (both systems and component materials). Extreme care must be taken to safeguard such information and hardware against unintentional dissemination. In the case of nuclear explosives and their effects on NEO materials, it may be highly prudent to limit dissemination of this information to countries already possessing such capabilities. Just as in the case of safety, formal accountability back to the people and governments through mandatory process control protocols are the checks and balances necessary to help maximize the probability of a secure and predictable outcome.

Information exchange, public awareness, and accountability

This is a critical aspect of the whole issue because everyone is affected therefore everyone should know. Exchange can be accomplished by a multitude of techniques, e.g., conferences, meetings, public forums, TV, radio, newspapers, articles, and individual interactions. Only open, honest, factual, and widespread dissemination will allow careful decisions of support (or lack thereof) to be made. Biases and alarmist scare tactics must be avoided. Thomas Jefferson once said that "diffusion of knowledge among the people" is the only sure strategy "for the preservation of freedom and happiness [i.e., well-being]." It is reasonable to expect, however, that for obvious reasons some information on mitigation technologies and safeguards cannot be widely shared. There is also the issue of this community being accountable to the people for all our planetary efforts. They are our customers. They support our activities with their hard-earned financial resources. And, they (and all of us!!) are affected ultimately by the outcome(s) of our collective activities. Should some type of formal planetary defense protocol or deployment ever be required, it must be justifiable, reasonable, and affordable when balanced against the risks of not doing it. We must also be good stewards of the environment; not just here on Earth, but in near-Earth space as well. How many times have we belatedly learned about the "effect" part of cause-and-effect regarding the consequences of science & technology on a global scale, for example, ozone depletion, acid rain, orbital debris, DDT, and so forth. We each individually (and collectively) as researchers have a public trust to uphold as we carefully address this issue of global importance.

Peer review and consensus

This is necessary, as part of the accountability process, to ensure that all related planetary defense issues (and impact hazard issues, too) have been considered, addressed, reviewed, and accepted by all qualified and cognizant researchers, and by a majority of the general public as well. The consensus should consist at a minimum of a hierarchy of viable and accepted defense solutions which are dependent on the amount of warning time, physical characteristics of the approaching NEO, and timely availability of mitigation technologies. Periodic fora for discussing and forging consensus statements are an absolute must. The so-called "Swift-Tuttle" affair three years ago - that comet Swift-Tuttle could collide with Earth with some finite probability of occurrence during its next apparition in 2126 - was a good example of why this type of technical information should be thoroughly peer reviewed before release to the media/public.

International teaming and dialogue

Again, because the problem affects everyone, we should all have the opportunity to contribute to the solutions. The problem is very complex. As such, no one group has all the answers, nor should they. As a confidence- and team-building measure, we should resolve to be open to and participate in new research and policy-level opportunities between different individuals, organizations, and nations. While we have the astronomers to credit for starting the avalanche of interest in the NEO threat issue, it will now require the active interdisciplinary participation of many other scientific and technical experts. This is an international issue and it requires cooperative international participation and contribution between many different sectors, i.e., nation-to-nation, individual-to-individual, detectors-to-mitigators, university-to-military lab, private concerns-to-public/government concerns, and so on. Let us strive to work cooperatively together, everyone will benefit as a result. Suitable forums include national and international technical and policy-level meetings, gatherings, colloquia, personnel exchange programs, and even one-on-one interactions.

Precursor Mitigation Missions

Precursor mitigation missions may be warranted if our ability to mitigate someday in the future is significantly hampered without them. However, the burden of proof for such a need is on the planetary defense community. As such we could improve our understanding of: carrying deflection technologies long distances through the hostile environments of space, final approach and terminal homing with the target, the interaction of the mitigation technology with the NEO to deflect or fragment it, long range tracking and control, modeling and planning assumptions, and sub-scale energy coupling experiments on Earth, among others. Doing precursor missions allows smarter choices to be made in times of emergency. Others have either proposed NEO rendezvous missions (Nozette, 1995 and Tedeschi and Allahdadi, 1995) or are actively planning upcoming missions, i.e., NASA/NEAR and ESA/Rosetta.

Mitigating small vs. large NEOs

Should we mitigate smaller NEOs (like the Tunguska impactor), which have a higher impact probability, but which only cause local damage, or should we wait for the K-T class impactors? For the smaller impactors, it depends. If the impact is over water or remote land areas, which is likely to be the case - like Tunguska, we don't have to do anything, except perhaps evacuate the area for a short period of time. And provided, of course, that we have ample warning time, accurate tracking capability, and are confident in our trajectory and impact point calculations. If it's predicted to impact in a location where the resultant damage would be unacceptable to us, for example, at population or resource centers, then - yes, obviously - we will attempt to mitigate it. The time for debate will promptly end and someone or some group will make the decision to mitigate the threat as best we can. Whether we're successful or not will depend on how well prepared we were to mitigate it. And, of course, we must be prepared to defend against the K-T class impactors.

Deployment

Should we build and deploy a mitigation system for Earth? No, not right now. Premature deployment could be dangerous and expensive. Besides, what's the hurry? We don't even understand the problem yet. Therefore, how can we proclaim to have the mitigation solution in hand? Someday, however, if required, we may wish to deploy a mitigation capability to meet the shortest warning time threats and provided that the international geopolitical climate is hospitable for doing so. Another viable future option may be to store the mitigation system as separate parts, safely and securely under national and international safeguards, with proven contingency plans to rapidly generate a viable mitigation capability and respond to any NEO impact threat emergency. Deployment in one form or another can not be ruled out, but would necessarily first have to be preceded by many years and much effort defining the threat and the need for such action, and potential mitigation options.

Mitigation planning

Some level of mitigation planning seems prudent to help ensure a timely future response. Actual protection against NEO impacts could consist of passive and/or active measures. Passive measures could involve local evacuation from the impact zone, retreat to protective shelters, and other measures, like food and water storage, to safeguard people and their supporting infrastructure, if adequate warning time is provided. Some countries have similar plans in place now in the event of natural disasters, e.g., the U.S. Federal Emergency Management Agency (FEMA) and the international Red Cross agency. Active measures would involve the delivery and use of an existing mitigation scheme against a menacing object, or the existence of detailed plans to rapidly do so in the event of a detected threat.

One of the driving mitigation planning considerations is the amount of warning time provided before predicted impact. If the warning time is short, a more energetic mitigation device (or devices), a quicker delivery system, or an existing defense system may be required. In light of the current capability to provide little, if any, warning time against smaller objects and little time for newly discovered long-period comets and potentially some asteroids, it would seem prudent to at least consider different mitigation scenarios.

From the opposite perspective, that of having to conduct a mitigation mission, it should not be assumed that existing weapons and delivery systems can be quickly "reprogrammed" and used against an approaching NEO. This is so because existing weapon/delivery systems were built for very specific missions, with limited flexibility for other uses on short notice. Like planetary space exploration missions and to do things right, it takes years of effort to design, build, test, and qualify a complex weapon/delivery system, especially against an undefined threat like NEOs. The risk in not doing mitigation the right way is in fielding an ineffective system or fielding one with an unacceptably high probability for accidents - in which case the cure might be worse than the disease. Nor should it be assumed that appropriate mitigation technologies will even be available someday in the future when they might be needed.

Conducting a mitigation mission

Finally, mitigation would involve the delivery of an appropriate amount of mass, momentum and/or energy to an approaching NEO either to gently deflect the body or to disruptively deflect all or a significant amount of the body's mass away from an Earth impact. Related deep-space and defense missions have been conducted in the past. They are complex, and they take time, resources, and great effort. Activities involved include: threat detection, warning, and verification; tracking; authority to proceed; mission planning and end-game analysis; logistics and launch preparations; safety and security; delivery and survival in space of the mitigation technology; terminal homing and "intercepting" the target; assessing the results and trying again if necessary.

Summary

A number of systems-level issues were presented in regards to the study, research, development and deployment of a worldwide defense system for protection against catastrophic impacts by comets and asteroids. A number of guiding considerations will define in the coming years the extent to which humankind prepares for protecting ourselves against the impact hazard. Defensive preventive actions should be based on international cooperation, the level of which required has never before been witnessed in human history, but which could be the start of an exciting new chapter in the evolution of humankind on Earth. Through careful and appropriate preparation and timely action lives can be saved and the rich diversity of life on Earth preserved.

Acknowledgments

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