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Protecting Earth From Comet/Asteroid Impacts Through International Cooperation: Issues & Current Status

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PROTECTING EARTH FROM COMET/ASTEROID IMPACTS THROUGH INTERNATIONAL COOPERATION: ISSUES & CURRENT STATUS

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Abstract

Compelling evidence of a catastrophic asteroid impact on Earth 65 million years ago [1] has given rise to international discussions about the probability, consequences, and prevention of future impacts. 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 threat posed by Near-Earth Objects (NEOs) and discusses associated technical and geopolitical issues and the current status of some related international activities.

Introduction

There has been much discussion in recent years of the threat posed by comet and asteroid impacts on Earth, along with the consequences of such events on modern-day society and possible techniques for threat mitigation. Such discussions have arisen essentially because of our increased awareness and understanding of these near-Earth objects. We know they have played a fundamental role in the formation and evolution of life on Earth, underscored by the contention by Alvarez et al [2] that the dinosaurs went extinct because of a massive asteroid impact. We gaze in awe upon other solid bodies in our solar system, including our moon, and observe the impressive impact cratering records NEOs have left behind.

Most recently, our attention has been sharply focused by several detected NEO near-misses of Earth [3,4] and by the upcoming predicted impacts of comet Shoemaker-Levy fragments on Jupiter [5]. Whether this issue will be of passing interest or the beginning of a major new area of scientific and public inquiry remains to be seen. In any event, credible debate and research have ensued and awareness has increased in the public and government sectors. The open flow of information, both scientific and perspective, to the public and their representatives is a critical and necessary ingredient in allowing decisions to be made regarding actions to be taken on this issue, if any.

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Our ability to explore, discover, understand, and rationalize about the world around us has rapidly progressed due to the many advancements made in science and technology. Gradualism and the long time scale evolution of life on Earth are giving way in a number of areas to various environmental catastrophism constructs which can occur on relatively short time scales by geologic standards [1,6,7]. Examples include: global warming, ozone depletion, resource depletion, incurable diseases, and, of course, the possibility of massive local or regional damage and even mass extinctions of life from NEO impacts. Action responses in each of these areas are being driven by well-informed representatives of many nations, not only by individual scientists and government representatives, but by the public as well.

This paper deals specifically with the presumption that someday we will detect a NEO of significant dimensions to be on a collision course with Earth. While the probability of such an impact is small, the consequences of inaction are not. The time for debate and discussion will end by default and certain organizations, peoples, and/or nations will resort to action to protect Earth from the approaching threat. The more that is known *a priori* about the threat and ways to deflect or fragment it and the more warning time that is available, the greater will be our probability of successfully defending against it. Background information is provided herein on the NEO threat along with perspectives on technical and geopolitical issues requiring attention before we can expect to have a reasonable hope of mounting an effective defense against such a threat.

Consequences and Probabilities of Comet/ Asteroid Impacts

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 [8,9,10]. Long-term effects (minutes to years) can include dust and debris, fires, tsunamis, global cooling, atmospheric and oceanographic chemistry changes, and even global warming [11]. 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 magnitude of a NEO impact on Earth is dramatically illuminated by the 30 m diameter stony asteroid atmospheric impact above Tunguska, Siberia in 1908 [9] which released 10-20 Mtons of TNT equivalent energy and caused massive localized damage. What is most significant about this event is that it happened during modern times with vivid eyewitness accounts of the impact event, and the resultant damage has been carefully quantified and studied. In that event, 2,000 km^2 of forest was felled, hundreds of reindeer were killed, and human injuries occurred [12].

The scientific evidence is undeniable that Earth has been (see Fig. 2) and will continue to be impacted by comets and asteroids [13]. Space-based optical sensors looking downward toward Earth have detected a steady flux of smaller meteoroids impacting our atmosphere [14]. Figure 3 shows the locations of "flashes" detected since 1975 by these sensors which most likely were caused by meteoroid impacts into the atmosphere. The current estimate of impact frequency on Earth is shown in Fig. 4.

Based on current observational data from optical telescopes, it is believed that the NEO impact flux is greater than shown in Fig. 4 for the smaller bodies, less than about 50 m in diameter, by perhaps as much as an order of magnitude [15]. It should be noted that absent in the impact frequency curve in Fig. 4 are error (or uncertainty) bars on the probabilities. This flux estimate dates back to 1983 [16]. The impact flux probability for the smaller objects (and possibly even for larger objects) may be higher because of a sparse existing data set and very limited observations being made. Obviously more observational data are required.

A NASA study - called the Spaceguard Survey - conducted in 1991 [13], at the behest of the U.S. Congress [17], concluded that a worldwide network of six new 2.5 meter telescopes would provide over 90% discovery completeness of NEOs larger than 1 km over a time frame of 25 years. The other major NEO observational mechanism is ground-based radar, which primarily provides very accurate astrometric data on detected NEOs [18], i.e., range and range-rate data from which highly accurate orbits can be determined.

Warning of an Approaching NEO

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 [3,4]. Some detections are made only hours to days before closest approach, others only detect the object after closest approach. Of course, trajectories of already discovered and catalogued objects can be (and are) routinely projected forward to predict possible future close-approaches with Earth.

Another important issue is the rapid dissemination of warning information, especially for smaller objects and newly discovered long-period comets and larger asteroids. Currently there are a number of existing formal (e.g., International Astronomical Union Central Bureau for Astronomical Telegrams) and informal (e.g., e-mail) networks for reporting and learning of NEO discoveries. 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 [19], and the Russians are devoting some of their assets to similar missions [20].

Beginnings of International Cooperation

Because the warning time of an approaching NEO can be so short and the consequences of impact so great, cooperative international attention and action to detect and mitigate such an eventuality seems warranted. In fact, nations of the world have already begun their first tentative steps individually, and in some cases jointly, to study the threat and discuss ways to ameliorate it. Collectively, nations of the Earth already have most, if not all, of the requisite component technologies, and certainly a broad framework for international cooperation is already in place to mitigate the threat. What remains is for people and governments to become more aware, get involved and act to develop at least a workable process for a NEO detection and mitigation system.

In addition to the Spaceguard Survey, NASA has also conducted a study on mitigation of the NEO threat [21]. In both these studies, there were varying levels of international participation, as mandated by the U.S. Congress [17]. The Russians have also been particularly active in soliciting international cooperation. The Institute for Theoretical Astronomy in St. Petersburg, Russia, hosted an international conference on the asteroid hazard in October 1991 [13]. The new international science and technology center being created in Russia is actively seeking and considering many proposals for international centers of research in Russia to study detection and mitigation of the NEO threat.

It is quite evident in the scientific and technical literature that there is significant and broadening interest and research activity in this issue by individuals. On organizational, national, and international scales there appears to be limited activity on an inverse scale to the order given. Some individuals are in the early stages of organizing an international conference on comets and asteroids, to include the issue of NEO threat detection and mitigation. The main objective would be to effectively inform the public and governments on mainly the benefits to mankind which could be derived from the discovery and exploration of comets and asteroids.

It is proposed here for discussion purposes the following two-part plan to incite and focus worldwide cooperative actions: 1) track-two diplomacy [22] between scientists of the world to research the issue from a bottom-up approach and 2) the creation of a special international body or committee dedicated to understanding and addressing the NEO threat from a top-down approach.

Track-two diplomacy in this instance is based on the thesis that non-governmental individual-to-individual interactions on an international scale can affect change through the open sharing, peer reviewing, debate, and independent reproduction of scientific information and results. These types of interactions are accomplished by scientists and technologists interacting informally in various conferences, meetings, and one-on-one collaborations. Example issues of where track-two diplomacy between scientific researchers has cascaded into international consensus and action are: 1) ozone depletion - many nations accepted the presented link between the use of Chloroflourocarbons (CFCs) and ozone depletion in the atmosphere and agreed to stop their production [23], 2) global warming - many nations, again, accepted the presented link between greenhouse gas emissions and future global warming and agreed to limit their emissions [24], and 3) orbital debris - spacefaring nations accept that man-made debris is currently growing seemingly without bound and have agreed to take positive actions to limit their own on-orbit debris generation. Action was brought about by the transition of peer-reviewed scientific information from the laboratory to open public and government policy-level debate.

The creation of an international committee, either formal or ad hoc, is proposed which would be composed of an international cadre of scientists, technologists, and policy-makers. They would be charged with these actions: 1) study and advocate NEO threat detection and mitigation by member nations, 2) inform governments and the public about the NEO threat, and 3) in times of emergency, assess the level of detected threat and initiate mitigation actions. It might make sense for the committee to report to the UN to ensure that the world's representatives and people would become aware of NEO threat issues and of a detected threat and be able to agree upon a timely course of mitigation action.

Of course, it is entirely possible that the mitigation task could be accomplished by a nation or particular nations with the wherewithal to do so. Such would be permissible under Arts. 51 & 52 of the UN charter [25]. The important point here is that an international organization or committee should be convened to cooperatively address the NEO detection/mitigation issue and determine the merit of developing at least a protocol to mitigate a NEO threat in the event one materializes which might require a short time frame of action.

Technical Issues

Response to the NEO impact threat can be broken into two primary areas - detection and mitigation. Detection involves locating, describing, cataloging, and providing timely warning on all NEOs; while mitigation deals with the delivery and use of some type of device or scheme to deflect or disrupt the approaching body. The following sections describe technical issues requiring attention before an effective worldwide NEO protection system can be planned or developed.

Threat Detection

Detection research would determine the ideal mix of observational capabilities to find, track, describe, and warn of menacing NEOs on Earth-crossing orbits. Reference [13] provides an excellent summary of detection related issues and existing observational capabilities. It also describes a cooperative international plan to comprehensively survey near-Earth space to find and catalog the majority of the larger Earth-crossing NEOs. As mentioned earlier, it may even be possible to team with various military observational facilities, and even existing astronomical facilities, on a non-interference basis to provide an even quicker accounting of NEOs. A compilation of some worldwide NEO detection activities is given in Table 1.

Threat Definition

Once an approaching NEO is detected and before an effective defense could be mounted, it would be necessary to know specifics about its physical characteristics, e.g., geometry, mass, 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 (see Fig. 5) composition and geometry (see Figs. 6 and 7), but not the internal composition and structure of the body. The NEO's internal structure will be a driving factor of its response to a particular mitigation scheme. Detailed material properties of interest are given in [26].

The threat detection issue 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, 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 only considering probing the surface with a kinetic energy impactor to help assay its surface composition. What is really required are missions to rendezvous and soft-land on a NEO. The canceled Comet Rendezvous and Asteroid Flyby (CRAF) mission would have been a great start - it was canceled, but the upcoming Rosetta and Near-Earth Asteroid Rendezvous missions may provide additional information.

<u>Mitigation Analysis and Experimentation</u>

An effective NEO protection scheme, or schemes (if there are significantly different types of NEOs, e.g., ice, rock, and iron), for use against an approaching object would require extensive study and research *a priori* to determine the best way to 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 a particular mitigation scheme. 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 [21,27,28]. Figure 8 shows a compilation of different possible coupling schemes into NEOs.

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 incremental velocity changes or body fragmentation. Mass, momentum, and/or energy deposition, or - for discussion purposes - just 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 radiational/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 shock.

Knowing how energy couples into various target materials is the basis for selecting one defensive scheme over another. This can be done only through carefully controlled laboratory 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 [26,29,30]. One potential source of data worth exploring might be the military labs which may possibly have conducted energy coupling (or weapon effects) tests on similar or related materials.

<u>Defensive Measures</u>

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 asteroids and long-period comets, it seems 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. Once the Spaceguard Survey is initiated and more NEO observations are made, we may someday be surprised to discover: 1) the magnitude of the problem was greater than we thought and 2) we detected a consequential object heading our way. In this light it seems prudent that some level of mitigation planning be considered, just in case.

Geopolitical Issues

The following non-technical issues also require attention and resolution before an effective protection scheme(s) could ever be planned or possibly deployed against a detected impact threat:

Mechanisms for International Cooperation

It was stated earlier that there are two ideally suited existing structures by which the NEO threat issue can be discussed and addressed: track-two diplomacy and oversight and advocacy by an international committee or organization, perhaps even one associated with the UN. Partially as a result of track-two diplomacy, scientists from spacefaring nations have successfully exchanged data, hardware, and research personnel for years in cooperatively addressing diverse areas such as orbital debris, space exploration, and satellite communications. It would seem logical for the UN to be the body responsible for addressing the NEO threat from a top-down approach.

The UN already has an existing framework for formal and informal interactions between nations to maintain international security, take collective measures to mitigate threats, and achieve cooperation in solving international problems [25]. General examples are: various arms control agreements, actions to bring Iraq back in line with other nations of the world, and the humanitarian mission to feed starving people in Somalia. More specifically, the scientific and technical sub-committee of the UN Committee On Peaceful Uses of Outer Space (COPUOS) and its attendant international scientific bodies, like the Committee on Space Research (COSPAR) and the International Astronautical Federation (IAF), have been very effective at successfully coordinating and advocating action on issues of concern to the space-faring nations. This could serve as a model or possibly as the approach for nations of the world to study and address the NEO threat issue.

Goals and Forums for International Dialogue

The primary goal of such activities ultimately should be the achievement of technical and political consensus of all nations, through their well-informed representatives, in the NEO impact threat from comets and asteroids and ways to effectively protect ourselves against that threat. Suitable forums include national and international technical and policy-level meetings, gatherings, colloquia, personnel exchange programs, and even one-on-one interactions.

Information Exchange and Openness

This is a critical aspect, which typically is accomplished through various conferences, meetings, and individual interactions. A new consideration here is the apparent lifting of the veils of military secrecy by both the Russians and Americans [19,20]. Collective safety and security can only occur long term through openness rather than through secrecy, or antagonism. It is apparent in the literature and at some of the NEO meetings that there exist different individual and organizational polarizations which may be hindering the flow of information. Scientists must first strive to harmoniously understand and be understood before we can expect the public and government sectors to accept and act upon our results.

As a confidence- and team-building measure, we should resolve to be open to and participate in new research and policy-level collaborations 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 benefits as a result.

Public Education

Only through the unbiased, open, understandable, and widespread dissemination to the public of information on the NEO threat and potential mitigation schemes can informed judgments be made by the peoples and governments of the Earth regarding action(s), if any, to be taken in response to the NEO threat. This is only fair since it is the public who would have to support such activities with their hard-earned tax allocations, and the public who generally suffers the consequences of such risks whenever they become reality. Thomas Jefferson once said of risk communication that "diffusion of knowledge among the people" is the only sure strategy "for the preservation of freedom and happiness" [31].

On the other hand, we must be careful not to trick the public by manipulating impact risk statistics or scaring them by making dire predictions of impending doom. Certainly we want to put the NEO hazard issue in as humanly understandable terms as possible, but we must exercise caution in dealing with the media in making sure they understand the technical information we provided. They sometimes have a tendency to subjectively sensationalize information. A good example of the media running off was on how they reported news of the upcoming near-miss between comet Swift-Tuttle and Earth in 2126 [32]. The newsprint media made it sound like a catastrophic collision was a given. The U.S. Newsweek magazine had a depiction on the cover of the November 23, 1992, issue of a comet heading directly towards Earth with the accompanying caption, "Doomsday Science / New Theories About Comets, Asteroids and How the World Might End." Not reporting our work in a responsible way risks our future credibility on this issue.

Treaties

It may be necessary 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 conceptualized, developed, built, and used in space. 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. Table 2 lists existing international agreements and resolutions which might someday limit or possibly even preempt our ability to mitigate a detected threat. At a minimum it seems that some discussion is warranted on how a mitigation process might unfold from a legal perspective.

Technology Availability

With the rapid global geopolitical changes and mounting economic pressures worldwide forcing reductions in spending, especially in relevant areas of science and technology R&D, e.g., in the space and military sectors, our ability to successfully respond in the future to a detected NEO threat may be adversely affected, especially if the warning time is too short.

We are in the midst of a rapid worldwide drawdown of weapon stockpiles, delivery systems, and the people and infrastructure to research, produce, and field mitigation technologies. It might be prudent to consider the long-term storage and safeguarding of certain unique mitigation technologies, like certain heavy-lift boosters and high-energy density explosives, rather than allowing these unique items to be totally dismantled or destroyed. Having to re-start production for even just a few of these items would be exorbitant, not to mention probably too late for some short-warning NEO threats.

An example of a lost capability was the heavy-lift U.S. Saturn 5 rocket used during the Apollo moon exploration missions in the 60's and 70's. It is not in production anymore, there are no more workable boosters left, and the manufacturing plans to make more are gone. Reconstituting such a capability would take years and at great cost. The very capable Russian Energyia booster is available, but for how long with the ongoing transition in that country? Part of the discussion should focus on identifying specific mitigation technologies which could be employed. Futuristic mitigation technologies (as given in [21]) appear very capable on paper, but who will pay for them and how long will we have to wait for them to become available?

Mitigation Planing

At a minimum, it seems that at some level, mitigation planning now is warranted to allow a timely response in the future when the need to do so may indeed arise. At the current time, actual deployment of a defensive mitigation system seems wildly premature. However, eventual deployment of a mitigation system cannot be ruled out. It ultimately depends on the success of the detection side of the house to find and catalog the larger NEOs and to provide at least many months of warning for approaching comets and other significant undetected and/or chaotic objects and events. A current example of chaos in our solar system is the disrupted comet Shoemaker-Levy fragments heading for a predicted collision with Jupiter in July 1994 [5]. What will happen if some of the fragments miss Jupiter? Will Jupiter's gravitational force send the fragments into new inner solar system orbits? Perhaps on Earth-crossing orbits? Other examples of chaotic randomly deterministic events include comet swarms and asteroid collisions/fragmentations.

Safety, Security, and Use Control

Mitigation schemes which might contain massive amounts of stored energy would have to be very carefully safeguarded against accidental or unintended use. In no way can the cure be potentially worse than the malady. 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.

Concern has been raised over the possibility of misuse of mitigation technologies [33,34]. In perspective, though, during the 40-year Cold War with 10's of thousands of nuclear warheads in existence [35], 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 given to meeting exacting requirements of safety and use control throughout the lifetime of a weapon system. Misuse is a valid concern, but one which can be addressed through certain design hardware and procedures.

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.

Current Status of International Efforts

A number of organizational, national, and international activities are ramping up on the issue of NEO detection and mitigation, examples of which are now provided. Several technical conferences - documented in reports or books - on NEO impact effects, detection, and/or mitigation have been held to discuss the threat and possible ways by which it can be mitigated [1,6,11,13,21,36,37]. Some current examples of technical issue resolution are: 1) Russian/German cooperation to characterize asteroid Toutatis using ground-based radars during its close approach in 1992, 2) U.S./Russian collaboration to analyze data from optical satellite sensors to detect and characterize meteoroid atmospheric impact events, 3) various international technical experts agreeing to team up and co-author chapters in the Univ. of Arizona's Space Sciences Series Book titled, Hazards Due to Comets and Asteroids [11], 4) an upcoming international gathering of technical experts in Russia in September 1994 to discuss and exchange information on NEO detection and mitigation issues.

Some current examples of geopolitical issue resolution are: 1) the International Astronomical Union (IAU) resolution in 1991 to study and advocate increased NEO detection research, 2) the U.S. Senate commissioning the two NASA detection and mitigation studies, with mandated international participation, and holding public hearings on the studies results, and 3) the Erice Conference [37] in 1993 where experts gathered to exchange and debate information.

Future Vision and Final Considerations

Perhaps the future vision for this whole activity is that the NEO detection and mitigation communities can cooperatively team on this issue, and other related scientific endeavors, to explore and better understand our Earth and the solar system, and that someday in the event of a detected NEO impact emergency, be it with little or longtime warning, we will be able to successfully respond to protect the rich diversity of life and culture on Earth because we made a conscious decision to do so.

Final considerations are given as:
1) An international committee, such as the UN COPUOS in conjunction with COSPAR and IAF, should assume a leadership position in facilitating worldwide information exchange, advocating detection and mitigation research, and, as a first step, coordinating international perspectives.
2) Empowered individual scientists, technologists, and other representatives of the people should educate, advocate, and ask for support to continue and expand our understanding of NEO threat detection and mitigation.

Summary

This paper briefly described the impact threat posed to Earth by asteroids and comets, detection and mitigation issues, the associated technical and geopolitical issues requiring resolution, along with some examples of the fledgling international cooperation to date and a construct to protect ourselves against NEO threats in the future. Some national and international efforts have already taken place, but much more cooperative international research and analysis remains before we will have an adequate understanding of the threat and ways to negate it, along with the perceived need of the people and governments of the world to act against such a threat.

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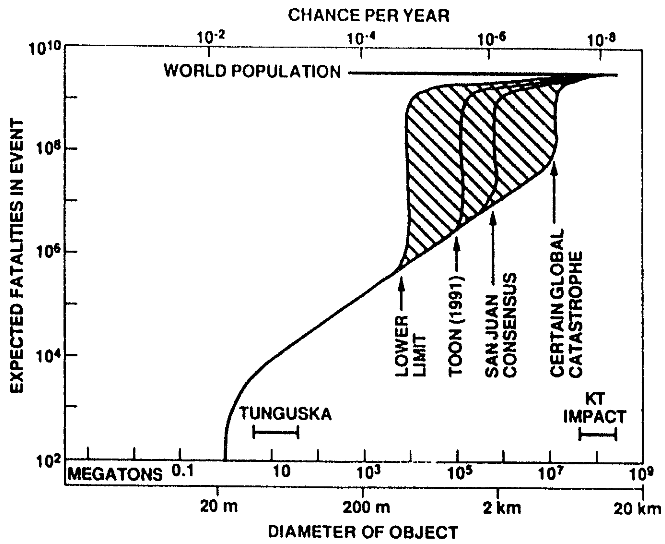

Figure 1. Estimate of expected human fatalities in an impact event versus impactor diameter, as taken from [13].

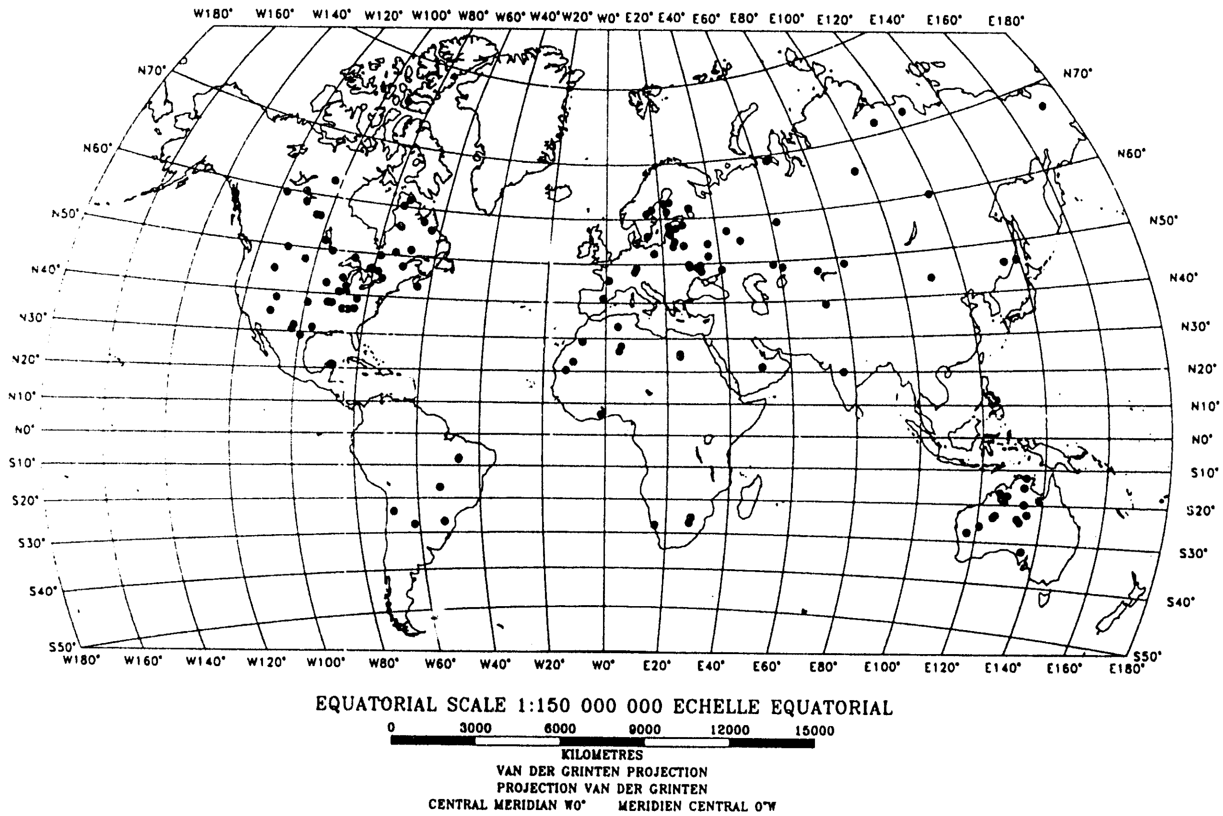

Figure 2. Known worldwide impact crater sites, as taken from [13].

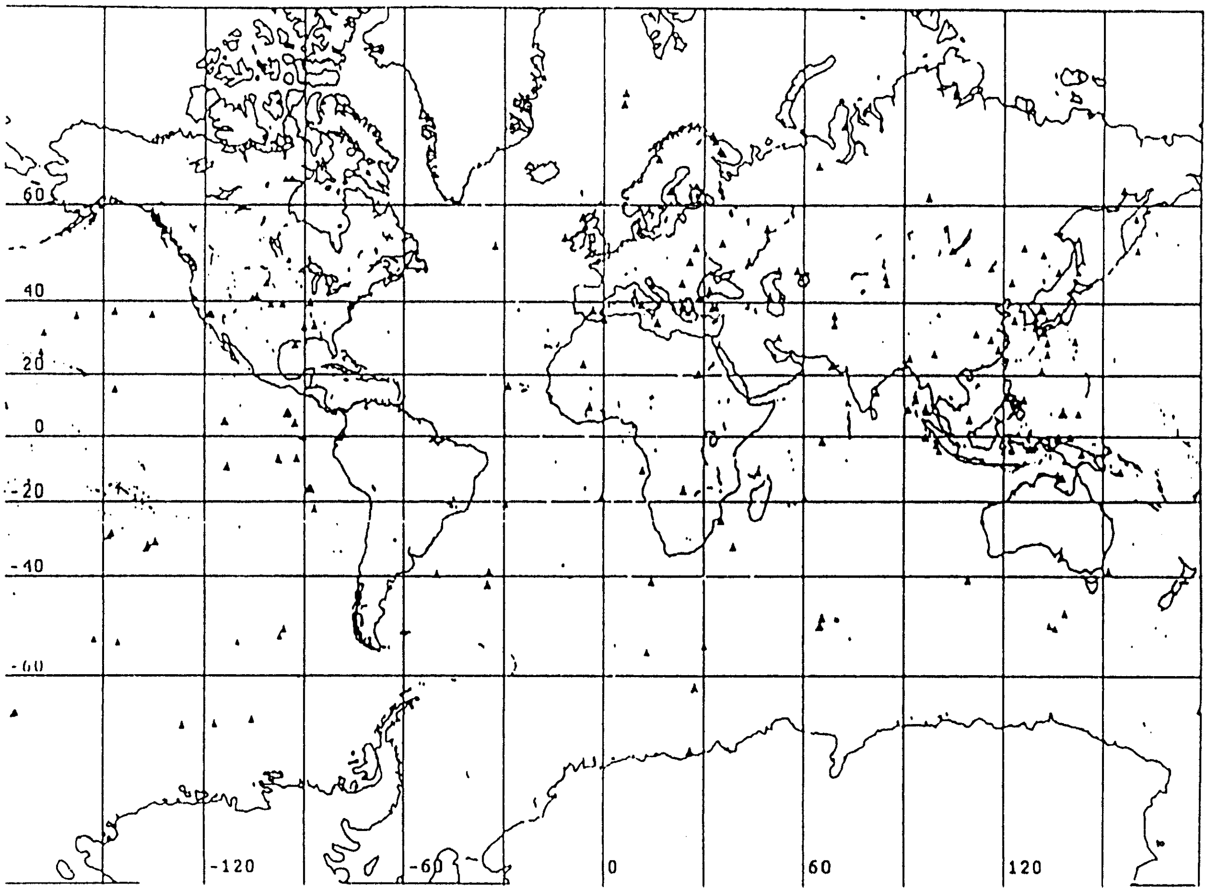

Figure 3. Locations of meteoroid atmospheric impact "flashes" detected by satellite-based sensors, as taken from [14].

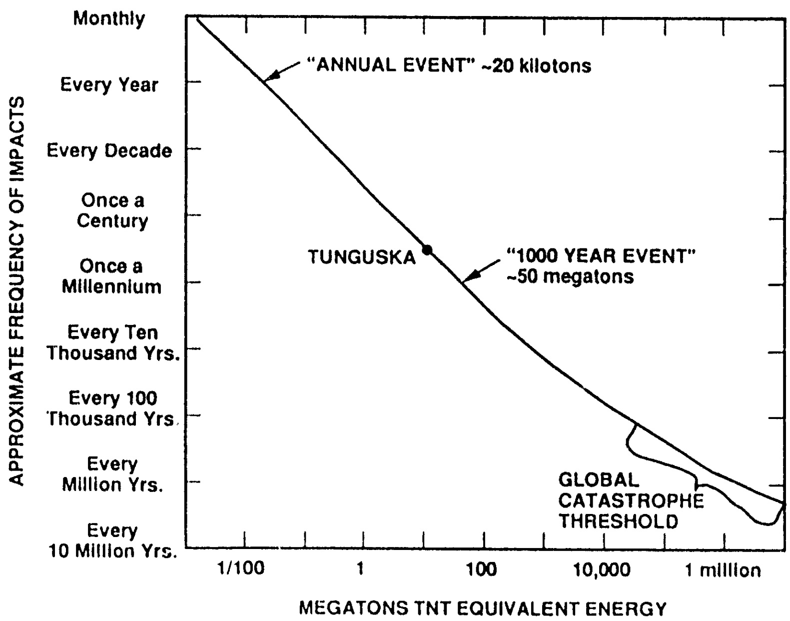

Figure 4. Estimated comet/asteroid Earth impact frequency, as taken from [13].

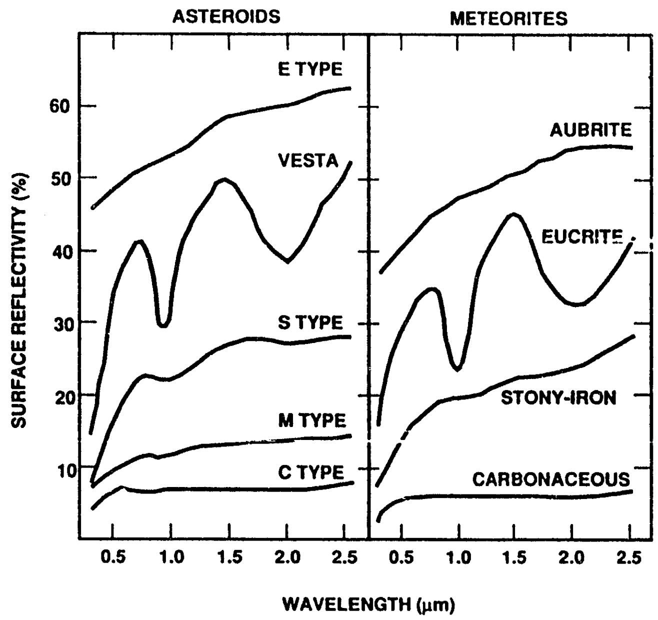

Figure 5. Optical and near-IR spectral reflectances of asteroids and meteorites, as taken from [13].

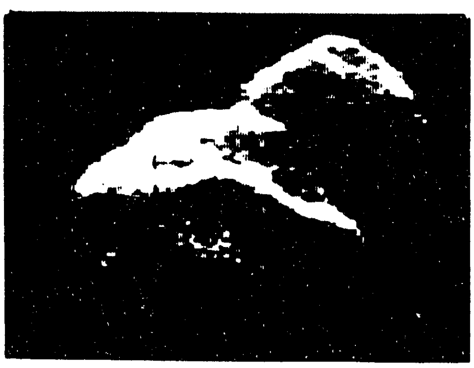

Figure 6. NASA Goldstone radar image of the apparent binary asteroid Toutatis during the Dec. 1992 close pass-by of Earth (courtesy NASA/JPL).

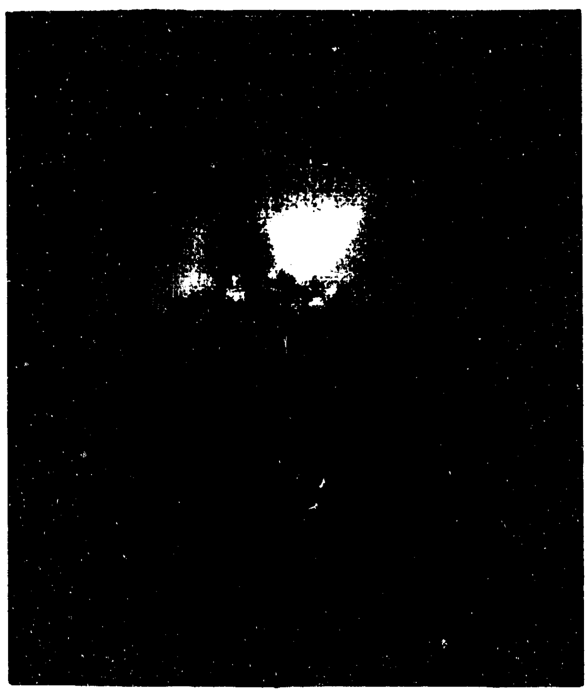

Figure 7. Photograph of comet Halley as viewed by the Giotto spacecraft (courtesy ESA).

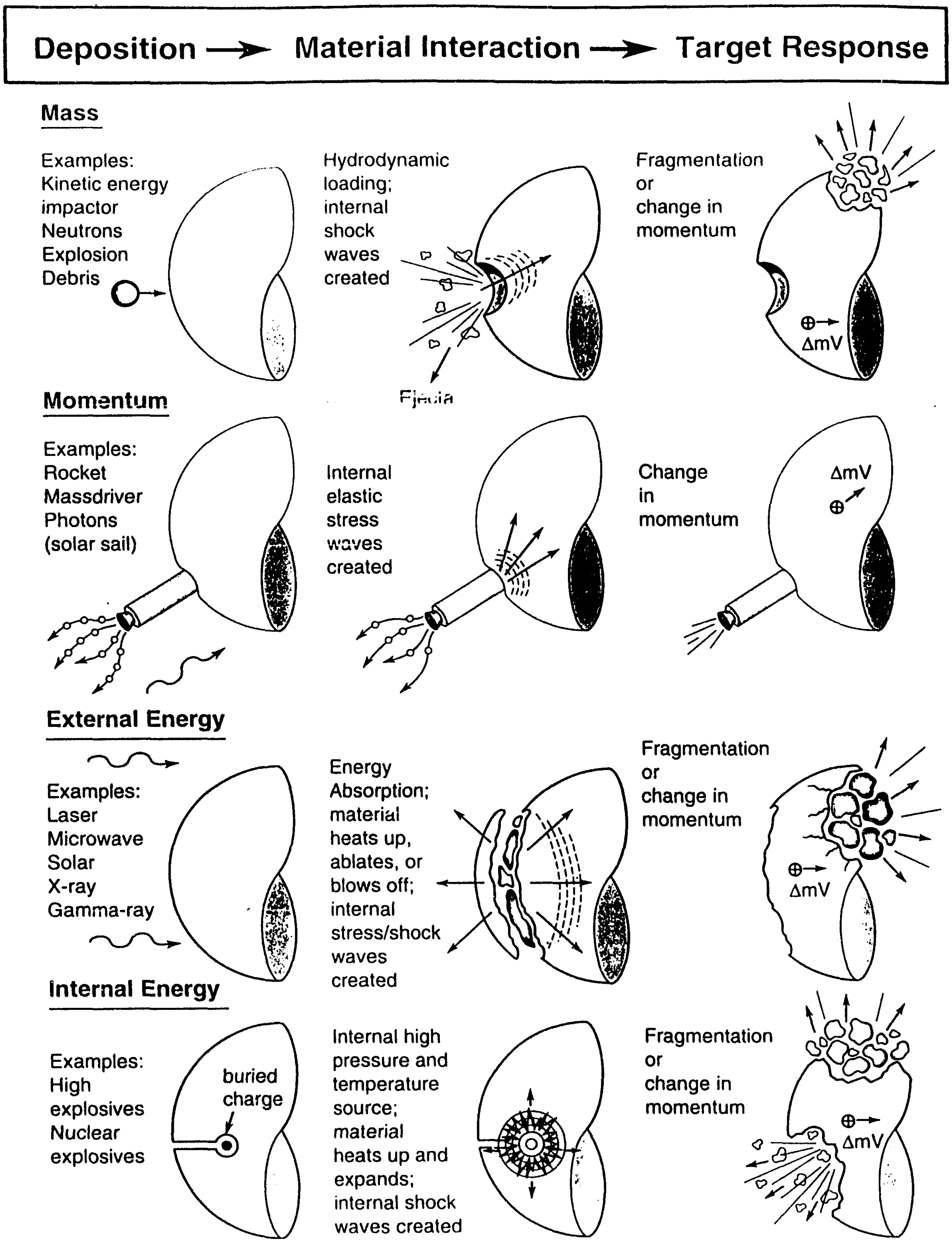

Figure 8. Mass, momentum, and energy coupling processes into NEOs.

Topic	Activity	Who	Status
Technical	Spacewatch CCD Survey - Telescopes	US	Ongoing
"	UK/Australian Asteroid Survey - Telescopes	UK, Australia	Ongoing
"	Palomar Asteroid/Comet Survey - Telescopes	US	Ongoing
"	Planet-Crossing Asteroid Survey - Telescope	US	Ongoing
"	Near Earth Object Search Program - Telescopes	China	Ongoing
"	NEO Search Program - Telescopes	Japan	Ongoing
"	NEO Search Program - Telescopes	India	Ongoing
"	European Near Earth Asteroid Search Observatories - Telescopes	France, Sweden, Germany, Italy	Ongoing
"	NEO Detection Using GEODSS telescopes	US	Under Study
"	Improved NEO Search Strategies/CCD Technologies	Worldwide	Ongoing
"	Lunar Impact Detection - Optical/IR sensors	US, Russia	Under Study
"	Space-Based Downward-Looking Optical Sensor - To Detect Atmospheric Entry Events	US	Demonstrated
"	Space-Based Sensor To Detect NEOs	US	Under Study
"	Other/Amateur Searches - Telescopes	Worldwide	Ongoing
"	NEO Passbys - Radar	US	Demonstrated
"	NEO Passbys - Radar	French	Demonstrated
"	Toutatis Passby Experiment - Radar	Russia, Germany	Demonstrated
"	NEO Passbys - Radar	Russia	Ongoing
"	International Science & Technology Center Research	Russia	Under Study
"	European Southern Observatory - Telescopes	Europeans	Coming On-line
Geopolitical	IAU Recognition/Advocacy For NEO Detection	Worldwide	Ongoing
"	Senate Directed Studies/Hearings on NEO Detection	US	Completed
"	International Science and Technology Center Studies	Russia	Under Study

Table 1. Technical and geopolitical threat detection worldwide activities.

Agreement	When	What
International Atomic Energy Agency (IAEA)	1957	Safeguards the storage and transportation of nuclear materials and information exchange.
Nuclear 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 celestial 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 indiscriminate 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.

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