PREPARING FOR PLANETARY DEFENSE:
Detection and Interception of Asteroids on Collision Course with Earth

Subject and Problem Statement

As the Earth revolves around the Sun, it orbits through planetary debris left from the formation of the solar system. Many of the debris objects are asteroids and comets in orbits bringing them close to the Earth and are referred to as Near-Earth-Objects (or NEOs). Of the total NEO population, some portion are in orbits actually intersecting or crossing the orbit of the Earth. The asteroids of this class are known as Earth-Crossing-Asteroids (ECAs). Occasionally, the motion and relative position of the Earth and an ECA in their respective orbits cause them to collide.

The geologic record amply demonstrates that many collisions have occurred in the Earth's past, with over 100 large impact craters still visible around the world. Work over the last decade by the astronomical community validates that impacts will inevitably occur again in its future. In view of these predestined impacts, this paper's purpose is simply stated: Investigate development of a capability to protect our planet from planetary debris (comets, asteroids and large meteoroids) detected in trajectories which will strike the Earth. Such strikes would result in wide-spread devastation or even catastrophic alteration of the global ecosystem.

This paper first investigates the magnitude and frequency of the threat by reviewing the extensive research by the scientific community on this subject over the last several years. Then it looks at some of the technologies and methods for detecting, cataloguing, and tracking planetary debris objects that may be on a collision course with Earth. The focus then shifts to issues associated with mitigation efforts and technology for interception and deflection or destruction of these objects. Finally, it examines the potential cost and benefits of a Department of Defense (DoD) role in an international planetary defense effort. Because of benefits which may be derived, not only to DoD but the world community as a whole, specific recommendations are made on how the DoD might best become actively involved.

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During the last fifteen years, research on objects crossing Earth's orbit has increased dramatically. Spurred by the now widely accepted theory that a large asteroid impact caused the extinction of the dinosaurs, the astronomic and geophysics communities have focused more effort in this area. Astronomers, looking skyward with more capable equipment, have been discovering new, potentially Earth-threatening asteroids at an average rate of 10-20 per year. Physicists, enlightened by recent research on the devastating effects even a limited nuclear war would cause to the Earth's ecosystem, have preliminarily investigated the effects on the Earth from an asteroid strike. They estimate that impact by even a relatively small asteroid will release energies equivalent to tens of megatons of TNT. The combined results of these efforts has been a realization that there is a potentially devastating but still largely uncharacterized natural threat to Earth's inhabitants. Thus, the time has come to investigate development of appropriate technologies and strategies for planetary defense.

In fact, recognizing the potential seriousness of such events, the Congress in 1990 mandated that the National Aeronautics and Space Administration (NASA) conduct two workshops to study the issue of NEOs. The first of these workshops, the International NEO Detection Workshop or "Spaceguard Survey" held in several sessions during 1991, defined a program for detecting kilometer-sized or larger NEOs. The second workshop, the NEO Interception Workshop held in January 1992, studied issues in intercepting and deflecting or destroying those NEOs determined to be on a collision course.

Through the end of 1992, 163 NEOs had been detected and catalogued with over 120 of them greater than half a kilometer in rough diameter. But astronomers estimate that ninety-five percent of potentially Earth-threatening objects have not yet been discovered. There are potentially 2,000 to 5,000 asteroids orbiting the sun near the Earth large enough to have devastating consequences on the ecosystem should they collide, and upwards of 10,000 additional objects large enough to inflict considerable damage.

Earth-impacting objects can vary in size from a few centimeters to more than 10 kilometers across. When the object is small, less than 50 meters, the collision is usually mitigated by the Earth's atmosphere, where it burns up or explodes into tiny pieces before it can physically impact the surface. Larger objects strike much less often but of course do much more damage. Sixty-five million years ago, for example, evidence suggests the age of dinosaurs was brought to an abrupt end by the impact of an asteroid that is thought to have been 10 kilometers across. It struck with the force of 100 million megatons of TNT, leaving an impact crater 185 kilometers across in the Gulf of Mexico off of the Yucatan Peninsula. And in 1908, a 50 meter asteroid is thought to have caused the devastation of a forested area covering over a thousand square kilometers (greater than the size of the Washington, D.C. area) when it exploded in the air above the Tunguska River in Siberia. Had it entered the Earth's atmosphere only three hours later, the Earth's rotation would have effected a 10-15 megaton air burst over Moscow, a force 1000 times greater than the nuclear weapons dropped on Japan in 1945.

Impacts such as the Tunguska incident are thought to occur about once in one hundred years based on the density of impact craters on the Moon. But because of the modest detection research to date, it is not known whether there are any large NEOs having orbits that will definitely intersect the Earth's in the next few decades. Astronomers have been unable to thoroughly catalogue the total population because of limited equipment dedicated to the effort. With an observation network proposed by the Detection Workshop (consisting of six dedicated astronomical telescopes located around the world and data linked to a central survey clearing-house and coordination center), a comprehensive census might still take 20-25 years. Development of this system will benefit from the experience gained by the US Space Command in its space surveillance mission for man-made Earth orbiting satellites, which in turn will benefit from technology developed for detection and tracking of asteroids. After such a system is in operation and has completed the initial catalogue, most large objects headed toward Earth could be detected years or even decades in advance, which is ample time to take action to prevent a collision.

Now that it is recognized that collisions with objects larger than a few hundred meters in diameter not only can threaten humanity on a global scale but have a finite probability of occurring, means for mitigating them seem clearly worth investigation. It should also be recognized that the technology required for a system to mitigate the most likely of impact scenarios is, with a little concerted effort, within humanity's grasp. Such a system could use the latest nuclear explosives, space propulsion, guidance, sensing and targeting technologies coupled with spacecraft technology. These technologies are already related to defense capabilities, but how they are developed for use in space (and what effects they have) will be invaluable experience for defense efforts. Furthermore, a handful of the thousands of nuclear weapons being deactivated under the Strategic Arms Reduction Talks (START) agreement might offer the most expeditious solution to this problem. Hence, there is much which might be gained from DoD involvement in this effort.

At the same time, the US should not go it alone. The hazards are global, detection efforts will require observation sites throughout the world, and other countries possess heavy lift and other space-related capabilities which could be used. Therefore, any response should involve the international community. This is particularly prudent as mitigation efforts could relate to nuclear capabilities and these intentions will affect arms control treaties. Such an effort is best conducted under the auspices of the United Nations.

The cost for such a system, which might be analogous to buying life insurance, also rightly belongs in the international arena. Gregory H. Canavan, Senior Scientific Advisor for Defense Research at Los Alamos National Laboratory and Johndale Solem, Coordinator for Advanced Concepts at Los Alamos National Laboratory, suggest a possible graduated funding approach. A few million dollars per year could support requisite observation surveys and theoretical study on mitigation efforts. A few tens of millions per year could provide research on interception technologies and procure the dedicated equipment needed to search for large Earth-threatening NEOs. And a hundred million dollars could develop a spacecraft to intercept NEOs for the necessary characterization and composition analyses of NEOs of all sizes.

The conclusion of this paper is that existing US efforts need to be more closely consolidated, coordinated and expanded under national leadership. While there is no reason to live in daily fear, there is a significant danger to our planet from an asteroid impact. Other species are now extinct because they could not take preventive action. Humanity must avoid delusions of invulnerability and acknowledge that as a species we may not have existed long enough to consciously experience such a catastrophic event. But we currently have the technological means for detecting and mitigating the threat and would be remiss if we did not use it.

The Capability and Its Relevance

Most of humanity is oblivious to the prospect of cosmic collisions, but this hazard from space is a subject of deadly concern to the entire population of the planet. Work by several nationally recognized scientists who have been investigating this issue for a number of years, some for decades, has brought an awareness that, to the average citizen of the US, the risk of death may be just as great from an asteroid strike as from an aircraft accident.[1] Those unfamiliar with these studies may find this incredulous when, in fact, there have been no recorded deaths due to asteroid strikes, albeit there have been close calls from small meteorites striking cars and houses.[2] However, the probability is finite, and when it occurs, the resulting disaster is expected to be devastatingly catastrophic. But because we are dealing with events, time scales, and forces well beyond the human experience, the threat is not universally recognized.

The Earth's atmosphere protects us from many dangers in the harshness of planetary space. These dangers range from intense solar radiation to the most common variety of planetary debris, called meteoroids, with diameters measuring only tens of meters or less. As the small meteoroids enter the atmosphere, the heat from friction created by the force of their entry (at 10 to 30 kilometers per second), causes them to completely burn up or explode before they reach the ground. If they burn up, they are then referred to as meteors; if they explode, they are called bolides.

Sometimes, however, even the atmosphere cannot offer total protection. Some meteoroids are of sufficient size and substance that they do not completely burn up before impacting the surface. These remnants are referred to as meteorites and are frequently of an iron-metallic composition. Meteorites are not uncommon and frequently impact in many locations around the world.

What is less commonly known is the force with which these objects can enter the atmosphere and explode or impact the Earth 's surface (figure 1). When a stony meteoroid of 10 meters in diameter hits resistance from the atmosphere greater than its own internal structural integrity, it will explode with a force of about 20 kilotons of TNT.[3] The exact yield of course will depend on the speed of entry and specific composition, but this is greater than the force of the device which destroyed Hiroshima.

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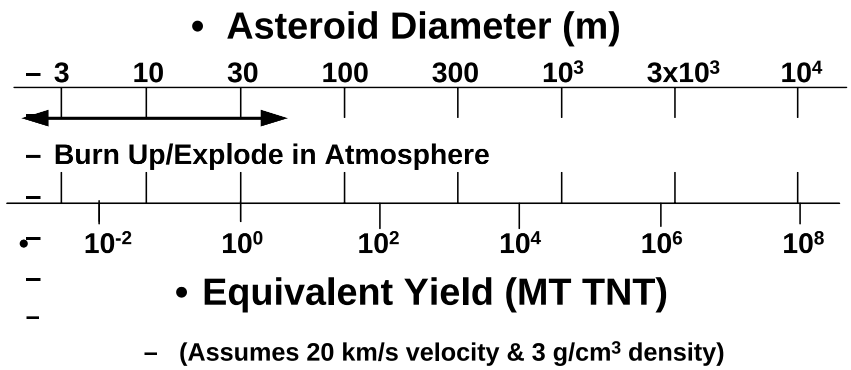

Figure 1: FORCE OF IMPACT
(From Chapman and Morrison)

Many times air-bursts of this magnitude are not witnessed by humans or even detected by earth-based sensing equipment. However, according to data recently released by the Air Force, they are regularly detected by Defense Support Program (DSP) satellites. At least 136 airbursts with a force greater than 1 kiloton of TNT have occurred around the world since 1975,[4] with the latest being detected just this February (with a force equal to 100 tons TNT).[5] But as impressive as this is, keep in mind that these are just the ones that weren't big enough to make it to the ground.

Scientists calculate that it would take a stony object of greater that 50 meters in diameter to survive penetration of the atmosphere.[6] (Planetary debris of this size and larger, up to several hundred kilometers, are generally referred to as asteroids.) Based on calculations derived from surveys of the age and density of impact craters on the Moon, a 50 meter asteroid impact probably occurs at least once a century, and would impact with a force of 10 megatons (Mtons) of TNT[7] (figure 2).

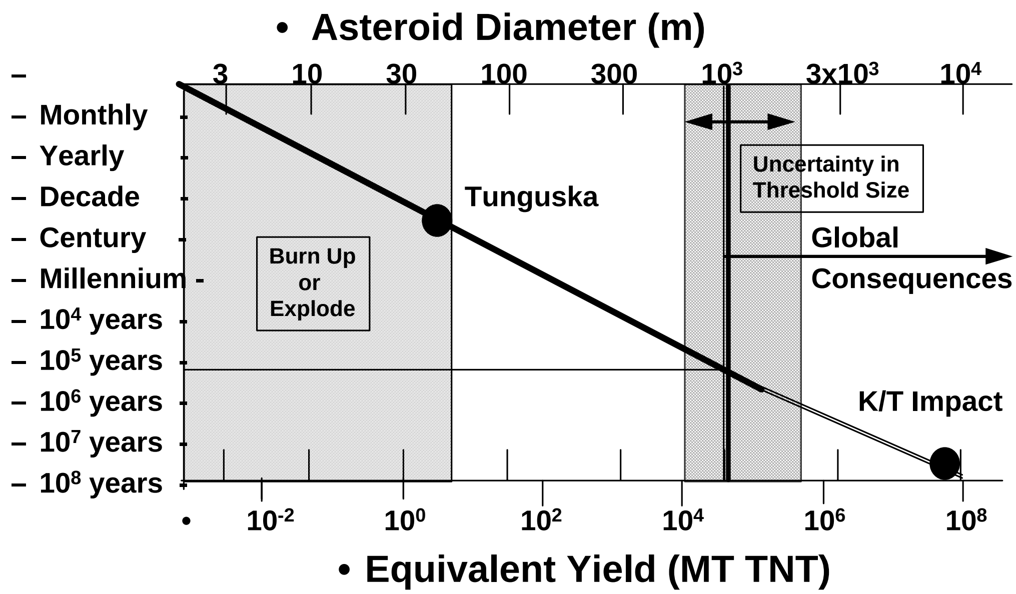

Figure 2: Average Impact Interval versus Size

(From Chapman and Morrison)

An event of this magnitude last occurred on 30 June 1908, in Tunguska, Central Siberia. Although this object did not impact the surface, it is calculated to have exploded with a force of approximately 12 Mtons of TNT at an altitude of 5 to 10 kilometers. It devastated forests over a 1,000 square kilometer area and ignited large fires over thousands of acres near ground zero[8] (figure 3). Had the event occurred just three hours later, a mere microsecond of geologic time, it would have been catastrophic for the citizens of Moscow. There is also evidence that a similar event occurred over New Zealand's South Island about 800 years ago.[9] As populated areas continue to spread across the Earth's surface, the probability of a strike in a population center increases accordingly.

But a 50 meter asteroid impact would only produce relatively localized effects. Meteor Crater near Winslow, Arizona, is an evident example of such a comparatively small impact. Larger impacts have caused more damage, as is evident from the Moon, although it has taken satellite imagery, such as from LANDSAT, to help realize the extent here on Earth. Using satellite photos, geologists have begun detecting more and more features on the Earth's surface that are actually remnants of impact sites. Some are quite large, such as the Manicouagan Crater in Canada at over 65 kilometers in diameter. Almost all have been partially obscured due to centuries of exposure to the effects of weathering, making them difficult to detect while on the ground.

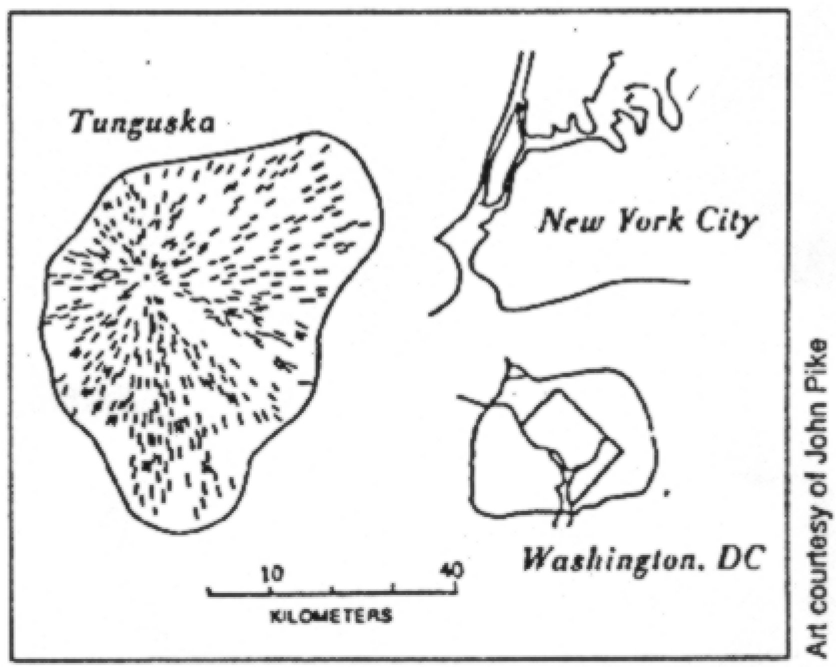

Figure 3. A perspective of the area of devastation caused by the Tunguska event compared to current urban areas. If such an event were to occur over an urban area, hundreds of thousands would be killed, and damage would be measured in hundreds of billions of dollars.[10]

There is also mounting evidence that an impact by a large asteroid (or asteroids) brought an end to the dinosaurs. A theory first advanced by the father-son physicist-geologist team of Luis and Walter Alvarez in 1980, it is now widely accepted, by geologists and paleontologists alike, that an impact by one or more relatively large asteroids occurred approximately 65 million years ago. This cataclysmic event is believed to have wiped out the dinosaurs and many other species on the Earth as well from the immediate and more long term effects of the impact(s).[11] Scientists now believe the most likely site of at least one large impact from that time is in the Gulf of Mexico, off the northern coast of the Yucatan Peninsula. Readily visible evidence of the impact has long since been obscured by the Earth's dynamic surface changes but the subsurface rock still bears wounds from this catastrophic event.[12]

Estimated to be greater than 10 kilometers in diameter, the suspected asteroid would have struck with a force of about 100,000,000 Mtons of TNT, or 10,000 times the total of all the world's current nuclear arsenal.[13] Not only did this impact create a large crater, but it would also have thrown trillions of tons of material into the Earth's atmosphere and started a global firestorm which would have added more smoke and soot to the layers of dust already in the stratosphere. Then a global winter resulting from blockage of the Sun's heat reaching the surface might have lasted for more than a decade, accounting for the extinction of at least half of the different species of life on the Earth at that time.[14] The settling of this dust to the surface created what geologists refer to as the "Cretaceous/Tertiary (K/T) Boundary," which is a physical demarcation in Earth's geologic record (i.e., rock layers) between these two ages and led to the Alvarez theory. Furthermore, paleontologists have discovered several other points of mass extinction (figure 4) in the geologic record with the speculation being they may have been caused by the same type of event.[15]

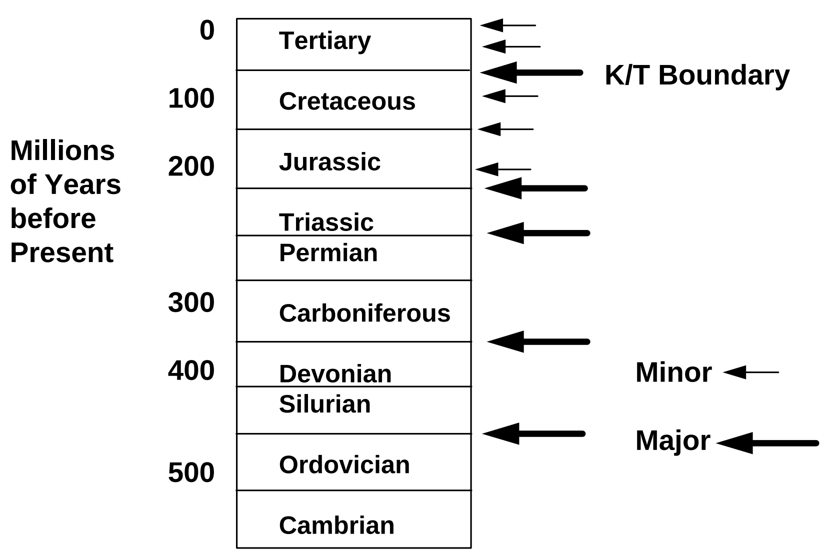

Figure 4: Mass Extinctions in Geologic Record
(From Chapman and Morrison)

But it doesn't take a "planet buster" of 10 kilometers diameter to wreak global havoc. Scientists estimate that the effect from an impact by an asteroid even as small as 0.5 km could cause climate changes sufficient to dramatically reduce crop yields for one or more years due to killing frosts in the mid-latitudes in the middle of summer. Impacts by objects 1 to 2 km in size could therefore cause a significant increase in the death toll due to mass starvation by a significant portion of the world's population as few countries store as much as even one year's required amount of food. The death toll from direct impact effects, blast and firestorm, as well as the climatic effects could approach 25 percent of the world's human population (figure 5).[16] Even though it may be a rare event, happening only every few hundred thousand years, the average annual fatalities from such an event could still exceed most natural disaster more familiar to us (figure 6).

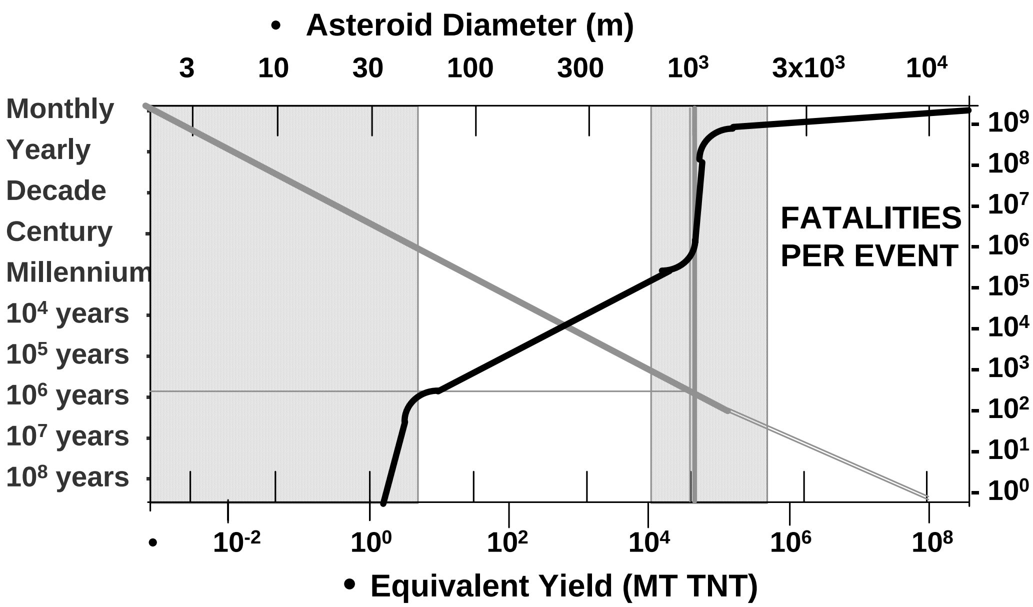

Figure 5: Fatalities per Impact Event

(From Chapman and Morrison)

This would be a natural disaster totally outside the human realm of comprehension and leads many people to be skeptical that anything like this could ever happen despite the results of many recent studies by the scientists. It is similar to an individual's egotism that a fatal accident will never happen to them, only on a much grander, entire species-level scale. Like the danger of a large earthquake in southern California, people do not comprehend the risks involved as having any relation to their daily lives. But the threat discussed here gives new definition to "The Big One."

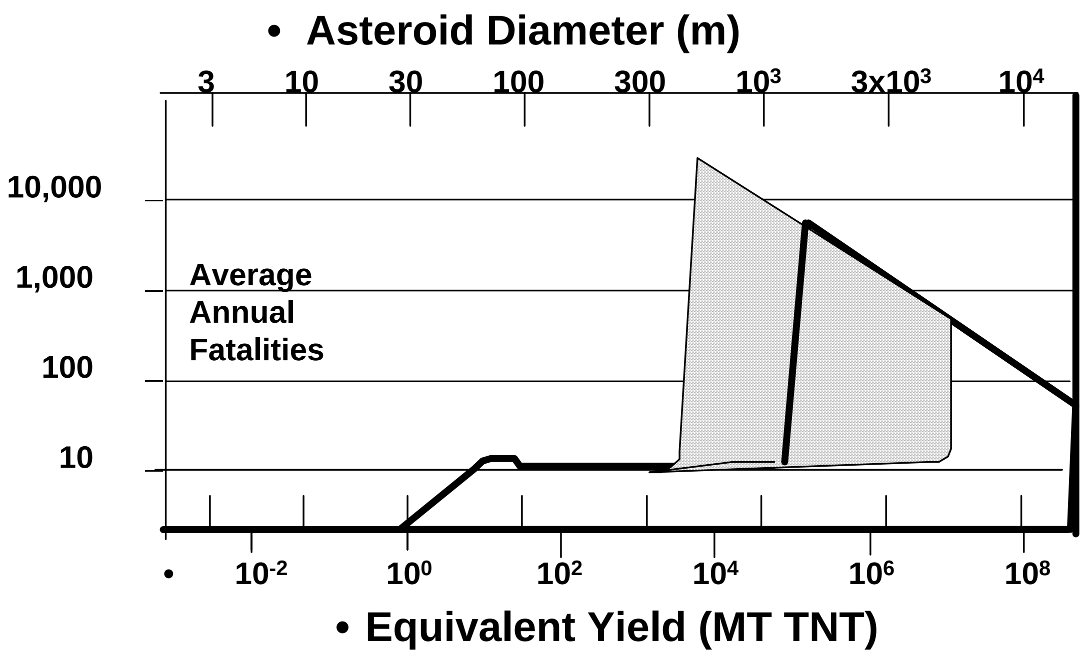

Figure 6: Average Annual Fatalities vs Impact Event
(From Chapman and Morrison)

As devils advocates," some might argue that all asteroids of this size have already been swept clear by the planets over the millennium. However, in the last two decades, astronomers have catalogued over 120 asteroids of 0.5 km or larger in orbits around the Sun that also cross the Earth's orbital path.[17] (See tables on ECAs in Attachment 1.) The work to detect the NEOs has been going on for a couple of decades and new techniques and technology have increased the rate in which they are being discovered. On average, two or three NEOs of a few tens of meters or more in size are currently being found every month.

As timely proof that cosmic impact events do still occur, a comet named Shoemaker-Levy 9 is predicted to impact the planet Jupiter in late July of this year.[18] (figure 7). This is certainly not an every day occurrence and this is the first time astronomers have known about such a spectacular event in advance, providing a chance to observe it happen. This will be an event of unprecedented interest to all space scientists and astronomers, as it should be for all planetary inhabitants, as a demonstration of what cataclysms can occur in the natural environment.

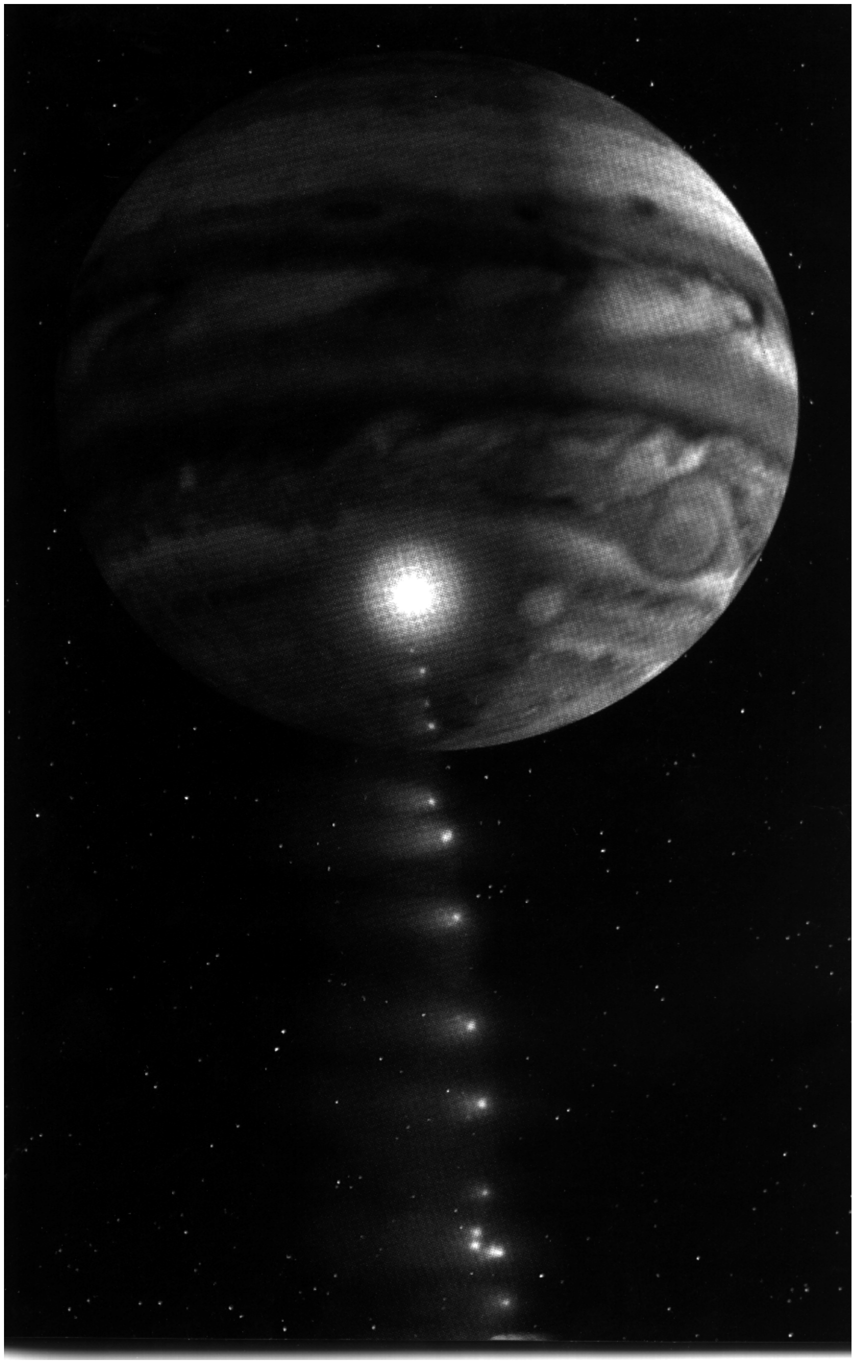

Figure 7. Depiction of the first components of Shoemaker-Levy 9 striking the surface of Jupiter. The comet was broken up by an earlier close encounter with the gas giant in July 1992 and there are 22 pieces, at last count, strung out over almost a million kilometers. The components, the smallest visible from Earth estimated to be at least 1 kilometer in diameter, are predicted to impact approximately every six hours between 16 and 22 July 1994. Visible remnants of these impacts might be features similar to Jupiter's current Giant Red Spot, shown to the right of the first impact in this illustration.[19]

Astronomers believe they may have found only about 5 percent of the total number of asteroids greater than 0.5 km in size. Based on estimated asteroid population densities, astronomers believe there are well over 2,000 such asteroids in Earth crossing orbits. However, at the current rate of progress, it will take over 100 years to ensure they have catalogued at least 90 percent of them.[20] A proposed global detection system might reduce this to 25 years, but even so, new members of this ominous population are continuously being created by the interaction of the planetary gravitation fields on the main asteroid belt between Mars and Jupiter and the comets entering the inner solar system from deep space.[21]

So how does all this boil down to the rather significant risk of death by asteroid mentioned earlier? In round numbers, scientists estimate there will be an impact on the Earth of an asteroid large enough to have global consequences every 500,000 years. So the probability of a strike in any one year is 1 in 500,000 assuming they are completely at random. Since 25 percent of the world's population could die as a consequence, the risk of death for any one individual, if such a strike occurred, will be one in four as a worldwide average. Therefore, the risk of death in any one year for an individual is 1 in 2,000,000. Over a seventy-five year lifetime the risk will then be about 1 in 25,000. This is within the ball park of the before mentioned risk of death to a US citizen in an aircraft accident or any number of other yearly accidents or natural disasters such as hurricanes, earthquakes and floods (table 1), all for which this nation spends tens of millions of dollars each year to both warn people of their approach or to mitigate their effects.[22]

The authors wish to make clear they are not crying, "The Sky is Falling!" and are not advocating a crash program costing billions of dollars to build an asteroid deflector. No specific asteroid projected to impact the Earth has yet been identified and many years may pass (hopefully) before one is. However, the probability is finite. Indeed, one day it will be exactly equal to one. Even if one does find the risks of death due to an asteroid outlined above difficult to accept, it is known that the Earth has been impacted by large objects in the past and that someday the planet will be faced with the prospect of another such catastrophe. Currently, astronomers have no idea when that day will come, hence a modest but prudent ECA detection program is warranted. A few million dollars judiciously spent may buy mankind substantial peace of mind. However, it may also alert us to the prospect that our day of reckoning is closer at hand than currently realized.

Table 1: Relative Probability of Death by Asteroid Impact (From Chapman and Morrison)

Chances of Dying from Selected Causes in the USA

Motor Vehicle Accident	1 in 100
Murder	1 in 300
Fire	1 in 800
Firearms Accident	1 in 2,500
Electrocution	1 in 5,000
Passenger Aircraft Accident	1 in 20,000
ASTEROID IMPACT	**1 in 25,000**
Flood	1 in 30,000
Tornado	1 in 60,000
Venomous Bite or Sting	1 in 100,000
Fireworks Accident	1 in 1 million
Food poisoning	1 in 3 million
Drinking Water with EPA limit of TCE	1 in 10 million

Therefore, it is also prudent that some effort, mainly mental, be spent to examine what capabilities we currently have versus what capabilities we may need to counter such a threat. Once these are identified, contingency plans can then be formulated to have on the shelf, if the need arises. Also, a coherent path could be developed to get capabilities to a more viable state by encouraging the development of applicable technologies which will not only help to deal with this problem, but would also offer many benefits in the exploitation of space and spin-offs for commercial applications.

This brings the discussion to why the DoD should take an active interest in this issue. Of course should such a disaster actually occur, at least four compelling reasons come immediately to mind.

1. <u>The resulting need for humanitarian relief</u>. The DoD will certainly be involved in any humanitarian relief effort after such a disaster. Humanitarian relief efforts have become a significant mission for our forces, with many examples during the last few years, not only in the US with relief efforts for victims of Hurricane Andrew in 1992 and the Midwest Floods in 1993, but also wherever it might be needed in the world.

But these examples will be relatively minor efforts compared to what might be needed in response to even a relatively small impactor if it occurred in a populated area. This might require a concerted effort from many nations and place a severe strain on the resources of the international community even if everyone was cooperative.

2. The possible destabilization of the international community. A natural disaster of this magnitude could put tremendous pressure on the nations involved, both friend and foe, destabilizing not only their economic but social fabric. Indeed, such a calamity will affect the entire world community. Governments have lost stability to lesser disasters when they found their resources lacking to adequately respond to the needs of its victims. Many times it has only been the infusion of external aid that has prevented more severe outcomes. What will be the result when a significant portion, such as 25 percent, of the world's population is in need of aid, particularly when it is not known how long the effects may last?

3. The possible threat to national security. Given such an event, the effects could very well threaten the national security of the US, even if it were not physically impacted. How will the international community deal with scenarios in which a significant portion the world has almost literally been turned upside down? The devastating effects to governmental and societal structure are equivalent to those thought of when talking about a post-global-nuclear war holocaust, lacking only (maybe) the lethal radiation effects.

4. The anticipated nation-wide call for action. Were an impactor to be detected in advance, the nation and perhaps the entire planet will quite naturally look to the DoD for the fortitude, technical expertise and leadership, not to mention the required force in the form of nuclear devices, to counter such a threat to its citizen's lives and well being. Other organizations and agencies will certainly be involved, including the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), the Federal Emergency Management Agency (FEMA), and the Office of Foreign Disaster Assistance. There will also most likely be an international effort. However, few organizations other than the US DoD have the experience and wherewithal to even attempt such an effort. The Russian military and space infrastructure is probably the only other viable capability equal to the task, but such a project could indeed take a consolidated effort and probably rightfully should, given the common fate. Suffice it to say that the DoD will form the core around which the rest could organize.

All these potential effects from an asteroid impact are currently within the DoD charter of responsibilities, as contained in the National Military Strategy and Joint Doctrine for Contingency Operations (Joint Pub 3-00.1), for any number of more commonly occurring events. Just because it may only happen once in 300,000 years doesn't absolve the current defense team of at least a moral responsibility if it does occur on their watch, particularly if they had the capability to prevent or at least mitigate it. Perhaps for the first time in not only human history, but the battered history of the planet, the inhabitants of Earth are on the verge of having such capability.

There are no known techniques for preventing many natural disasters such as earthquakes, hurricanes and tornadoes. Some cannot even be detected in time to give adequate warning to the affected population. Such is not the case with asteroids. Mankind certainly has the technology that, with a relatively modest investment, will provide warning of an impending catastrophe maybe years and perhaps decades in advance. In most cases more than enough warning time could be given to allow evacuation of affected areas for the smaller objects once an adequate detection system is in operation. Humans also possess the technical understanding of the forces required (orbital mechanics and nuclear explosives) to prevent such disasters, at least up to a 10 km size asteroid, given enough warning time.

Potential Technologies to Counter the Threat

Work is needed in two broad areas: capabilities to detect and characterize the potential threat and capabilities to mitigate it once a specific threat is identified.

A threat is defined as a planetary debris object (asteroid or comet) of sufficient size and composition to do significant harm to Earth's inhabitants either by direct impact effects or damage to the ecosystem should it strike the planets surface or explode in its atmosphere. The analysis examined earlier showed this to be, at most, all objects greater than 50 meters in size because these are the ones with the potential of surviving their entry into Earth's atmosphere. However, one could argue that objects smaller than 500 meters should not be of concern since their effects would be relatively localized and most probably, at least for another century or so, would fall in unpopulated areas. This fortunately was the case for the Tunguska event (which was not even an impact), but had it occurred over a populated area the loss of life would have been consequential. As the human population spreads, the probability for great loss of life due to any sizable impact anywhere on land goes up.

Even ocean impacts of these smaller objects are of some concern because of the potential for tsunamis being created by even an object as small as 100 meters.[23] A fifty foot ocean wave could do significant damage to surrounding coastal areas, actually increasing the destructive potential above that from a same sized object's land impact. This is a hypothesized phenomena not yet well understood. Also, some might even consider the loss of flora and fauna in even unpopulated areas to be of significant enough concern to be worth some amount of effort. So drawing the line somewhere above the 50 meter size invites some debate.

However, the remainder of this paper concentrates on objects greater than 0.5 km and up to about 10 kms, with the understanding that anything larger is an exceedingly rare event, even by our standards. Capabilities against this chosen class, defined as smaller than (<) 10 km but larger than (>) 0.5 km, will also give significant capability against anything smaller, with the notable exception being distant detection of the object.

Surveillance - Detection, Tracking and Characterization

Scientists who have worked with this issue for a number of years have put much thought into the surveillance issue. Some prototyping of potential systems has already been done, a notable example being the Spacewatch System at Kitt Peak, Arizona, organized by Dr. Tom Gehrels of the University of Arizona who has worked on this issue for over three decades. There are already some specific ideas and programs which could be quickly initiated using dedicated ground based sensor networks based on current technology. Unfortunately, lack of any significant funding has kept even a modest program from being started. Until this year, the Spacewatch System was run on a shoestring through private donations.

In the report of the NASA study commissioned by the US Congress, resulting in three Near-Earth-Object Detection Workshop sessions held during 1991, the scientists propose an internationally supported detection system they call the "Spaceguard Survey Network," after a system conjectured by Arthur C. Clarke in his science fiction novel *Rendezvous with Rama*. This system will provide detection of objects as small as 1 km diameter within a suitably large volume of space using a network of six globally dispersed 2.5 meter aperture, f/2 prime focus reflecting telescopes, each with four 2048X2048 pixel charge-coupled device (CCD) detectors in the focal plane. Automated signal processing and detection computer systems will recognize asteroids and comets from their motion against the background of stars. All technology for this system has already been demonstrated in the prototype at Kitt Peak. Acquisition costs for such a system could be as low as $50M and the annual operations and maintenance costs will be in the $10M range. This system could be in operation in less than 5 years after funding is made available.[24]

This system sounds remarkably like the Ground-based Electro-Optical Deep Space Surveillance System, or GEODSSS, albeit with smaller one meter telescopes and CCDs, but built at four sites a decade ago and currently operated by the Air Force to track man-made geosynchronous satellites. However, this Space Command surveillance asset does not do wide area searches needed for asteroid detection, but rather searches for man-made objects based on their predicted position and rejects the detection of any object which moves as fast as an asteroid, providing it were close enough to be seen. In a way, GEODSSS does the converse of what Spaceguard sites will need to do. However, it could probably be upgraded to do asteroid detection if it weren't already heavily tasked with its current mission.

But, there are many parallel techniques between what the Spaceguard Network will be required to do and what is currently done by US Space Command's network for space surveillance of man-made objects. The Spaceguard Report also speaks to the need for a "survey clearinghouse and coordination center" to catalogue newly discovered objects, coordinate observations by other sites to verify existence of each object and collection of additional sightings to determine their orbits. This center will also project the orbit of each object, both for recovery (sighting of the object on the next orbital pass) and to determine if it poses a threat to Earth. All this is currently done for asteroids and comets by the International Astronomical Union's Central Bureau for Astronomical Telegrams and Minor Planet Center in Cambridge, Massachusetts, but at a rate far less than will be needed for the Spaceguard Network. NASA has plans to establish such a center at the Jet Propulsion Laboratory in Pasadena, California. This activity could benefit greatly from the experience and automation used for similar tasks done for man-made objects in Earth orbit by Space Command's Space Surveillance Center (SSC) at Cheyenne Mountain AFB, Colorado. This is not to say that this existing network could easily take on this additional task (it couldn't), but it is to say that Space Command has significant experience in a closely related area which could be applied to the problem.

However, Space Command's current space surveillance mission could also benefit from systems developed for asteroid surveillance. Optical systems developed to detect and track these relatively dim objects (down to 22nd magnitude) might also find application against the tracking problem presented by man-made orbital debris. Precise tracking of asteroids can also be greatly enhanced with augmentation by powerful deep space radar systems. Currently there are only two such system available (Arecibo, Puerto Rico, and Goldstone, California) and even their performance is limited in relation to this task. Research and development on more capable radar systems will probably be of benefit to the traditional space surveillance mission, not to mention other defense related areas. Work on sensors, both active and passive (microwave, multi-spectral and hyper-spectral) could also be of mutual benefit. In the software and modeling arena, both missions will benefit from development of more precise and comprehensive, as well as rapid, orbit prediction models. This might also lead into further use of parallel processing techniques for space surveillance that are just starting to be investigated. The bottom line is that great potential can be seen for cross flow of technology, equipment and techniques between these two space surveillance missions which in itself will warrant interest by the DoD.

So far, only ground based technologies have been addressed. It is always advantageous when dealing with dim celestial objects to get up above the atmosphere to eliminate its interference with the object's signature and the diurnal constraints imposed by the Earth's rotation. The asteroid detection and tracking mission by itself may not warrant space based capabilities, but coupled with other more traditional Air Force missions a mutual benefit will be gained. More distant, and therefore earlier, detection of both asteroids and comets will be possible from space based systems. It will also give greater capability against a class of asteroids, called the Atens, which are defined by their orbits about the Sun being inside of Earth's but reaching out far enough to cross the Earth's orbit (orbit diagrams, figures 8-11). Because ground based systems will almost always be looking toward the Sun to see objects in this class, they are difficult for ground based observatories to detect. Although less than 15 objects in this class have so far been discovered, it is speculated this class may be at least as common as the Apollo class, asteroids in orbits more similar to Earth's and the class to which the majority of known ECAs (over 100) belong. Astronomers point out that Mercury, the planet closest to the

Sun, has more craters than any other object in the solar system.[25] Therefore a space based surveillance system, perhaps even Moon based or at a stable Earth-Sun Lagrangian point (L2 or L5), would have distinct advantages in covering certain classes of objects.

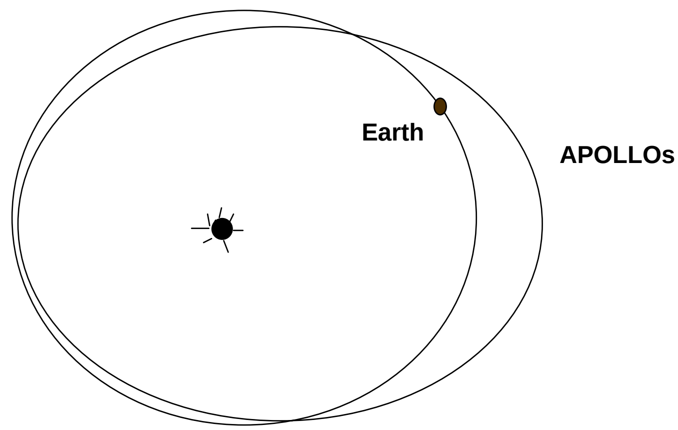

Figure 8: Orbits of Apollo Asteroids

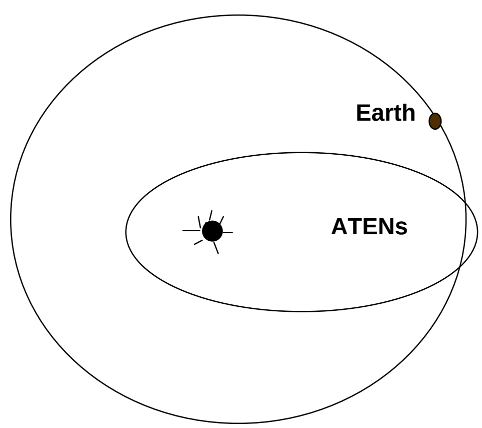

Figure 9: Orbits of Aten Asteroids

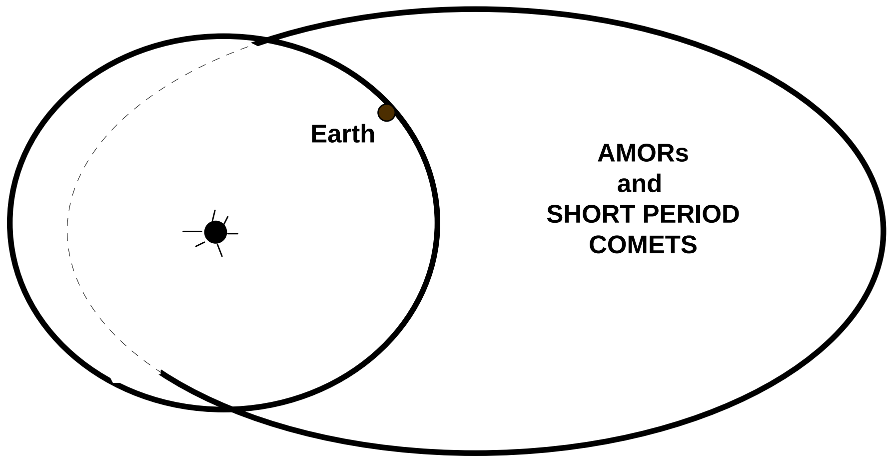

Figure 10: Orbits of Amor Asteroids and Short Period Comets

Note: The dotted portion of the orbital path represents motion of the asteroid or comet below the plane of the Earth's orbit. This is due to the high inclination of the object's orbit which is common for these types of objects.

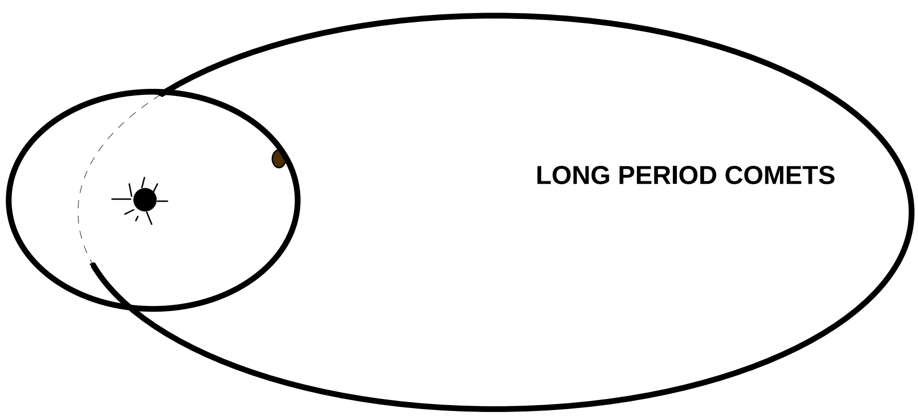

Figure 11: Orbits of Long Period Comets

Finally, discussion of the surveillance mission, ends with characterization of the asteroids and comets. Although their existence has been known for almost two hundred years, still little is known about their composition, or even if it is common for them to be the typical solid, large rock-like body usually envisioned. There is some speculation that many of them may actually be more like orbiting rubble piles. Little more is known about comets although they are typically thought of as dirty snowballs.

Many things can certainly be learned from a concerted remote sensing program. But before we can have full confidence about what effects certain mitigation techniques might have, a closer-in survey will need to be done, especially given enough warning about a specifically identified threat to impact. Hence, asteroid and comet rendezvous missions are of great importance to the surveillance of this potential threat to ensure as much as possible is learned about these possible threats. Because of the space community's interest, close approaches to main-belt asteroids were added to the Galileo Jupiter mission. It passed within 1600 km of the asteroid Gaspra in October 1991, and to within 3200 km of the asteroid Ida in August of 1992, discovering it has as smaller asteroid moon orbiting it. NASA Space Sciences Office is also planning a Near Earth Asteroid Rendezvous (NEAR) spacecraft to co-orbit for at least one year with an Apollo asteroid later this decade. These are examples of the kind of missions that can be done with current technology. The currently ongoing Ballistic Missile Defense Office NASA sponsored Clementine mission to the Moon, with a planned close approach to the asteroid Geographos to test SDI developed sensors, is an example of the kind of mission with mutual benefits which can be conducted.[26] The recent attitude control malfunction with Clementine will probably lead to the cancellation of this phase of the mission (as of this writing, 25 May 94). However, the mission as planned still stands as an example of the kinds of projects which can be done. History may well look back on the Clementine mission as the DoDs first foray into this new mission area.

Threat Mitigation

Mitigation of Earth-threatening asteroids and comets, to include both deflection and fragmentation options, has received substantial attention over the last three years. In particular, the NASA-sponsored Near-Earth-Object Interception Workshop investigated the subject in-depth and made this conclusion: "... chemical or nuclear rockets with nuclear explosives are the only present or near-term technology options available that have significant probability of success without significant research and development activities."[27] More succinctly, the Chairman of the workshop indicated to Congress that "... technologies currently exist that could be integrated into systems capable of protecting the earth from most any NEO impacts."[28] In short, technology options exist, if pursued, which can mitigate the asteroid and comet threat.

As both background and support for the conclusions above, this section addresses mitigation strategy and intercept scenarios, reviews the NEO threat in light of these intercept scenarios, and then presents a selection of mitigation options. Finally, this section addresses the sensitive implications of using nuclear explosives in an earth-defending role.[29]

Mitigation Strategy

The fatality curve introduced in a previous section (figure 5) serves as a guide to both optimize and prioritize mitigation systems. This curve rises sharply and peaks with asteroids one-to-two kilometers in diameter--the threshold size for global effect as previously discussed--and then decreases inversely with asteroid size. Or, from a different perspective, as asteroid size increases, the effects of impact shift from being regional to global in nature. At the same time the probability of impact goes down. The combination of these two characteristics shape the curve and create the peak. The point is this: asteroids and comets correlating to the peak in average annual fatalities should be the first focus of any mitigation development efforts; in short, threshold-sized objects. Those beyond threshold size are second in priority while those smaller are, of course, third. Intuitively, options which dispatch large asteroids should also accommodate the small ones, but this may lead to a situation analogue to trying to kill a fly with a hammer. There may be less-complex, less-costly, and thus more appropriate options for handling small NEOs, and these should be considered as well. Now, before considering potential options, it is helpful to consider intercept scenarios and re-consider the threat.

Intercept Scenarios

There are two intercept scenarios, distant and close-in (table 2).[30] Distant intercept, which implies distance in both space (interception at the Sun, i.e., NEO perihelion) and time (interception at two or more orbits prior to predicted final approach), is the scenario of choice. This is desired since relatively small deflections suffice and, accordingly, lends to using the full range of propulsion and deflection technology options available. Importantly, it allows for a "deflect-look-deflect" style of operation which is prudently conservative in nature. Finally, if when attempting deflection fragmentation occurs, the resulting debris will have time to disperse before reaching Earth. By way of calibration, deflection velocities for the distant intercept scenario are on the order of centimeters per second.[31],[32]

Table # 2: Intercept Scenarios [33]

1) Distant Intercept ... *the simpler case*

- Small deflections suffice
- Allows full range of options
- Opportunity for deflect-look-deflect

2) Close-In Intercept ... *the harder case*

- Large deflections
- Limited to high energy options
- One or two shots

The close-in scenario is the more challenging case and involves interception of an object on final orbital approach. This will likely occur a few tenths of an AU from Earth (AU, Astronomical Unit = 150 million kilometers) and require deflections on the order of a thousand times larger than the distant intercept case.[34] The need for larger deflections will limit propulsion and deflection technologies to those providing high energy and, accordingly, have increased potential for inadvertent fragmentation. Finally, time may only allow for one or two attempts at deflection. It is now helpful to review the threat in light of these two intercept scenarios.

Threat Categories

Following the lead of the Interception Workshop, there are four threat categories as identified in Table 3. The first two categories are clear candidates for distant intercept while the second two will likely require close-in deflection. In each category, warning time is the obvious key figure of merit.

The first category includes objects whose orbits can be well-determined, specifically the ECAs. Once discovered and catalogued, subsequent optical measurements of these objects in combination with radar tracking can yield orbital predictions with tight position errors (i.e., on the order of one Earth's radius). These predictions can be made well into the future, giving decades of warning time.

Table # 3: NEO Threat Categories[35]

1) Well Defined Orbits
   - Earth-Crossing Asteroids (ECAs)
   - Warning Time: Decades

2) Uncertain Orbits
   - Newly Discovered ECAs; Short-Period Comets
   - Warning Time: Years

3) Immediate Threat
   - Long-Period Comets; Small ECAs
   - Warning Time: 1-12 Months

4) No Warning
   - Long-Period Comets; Unknown ECAs
   - Warning Time: 0-30 Days

The second category also includes ECAs, but newly discovered ones for which the orbits have not been well-determined due to limited tracking opportunities. Some asteroids may also display chaotic variations in orbital eccentricity which further confound prediction (figure 12).[36] In the words of Chapman and Morrison: "an asteroid can orbit for hundreds of thousands of years in a perfectly regular, sensible way, and then quite suddenly its orbit can change chaotically into a comet like, elongated path that comes near the Earth."[37] This category also includes short-period comets (period < 20 years) which, due to outgassing while near the sun, have non-gravitational components to their orbits which make them hard to predict. This outgassing creates their characteristic tail, but also creates the coma surrounding, and thus obscuring, the comet's solid body. This, too, contributes error. Orbital uncertainties for both of these objects, ECAs and short-period comets, limit warning times to years.

The third category includes long-period comets (period > 20 years) and newly discovered ECAs. The comets can come from any inclination and can be a first time visitor, making their early detection difficult but critical. Earliest feasible discovery of a long-period comet on "final approach" will yield at best several months warning time. Newly discovered ECAs, perhaps succumbing to Chaos Theory, or ones simply missed during the survey, may also yield limited warning times.

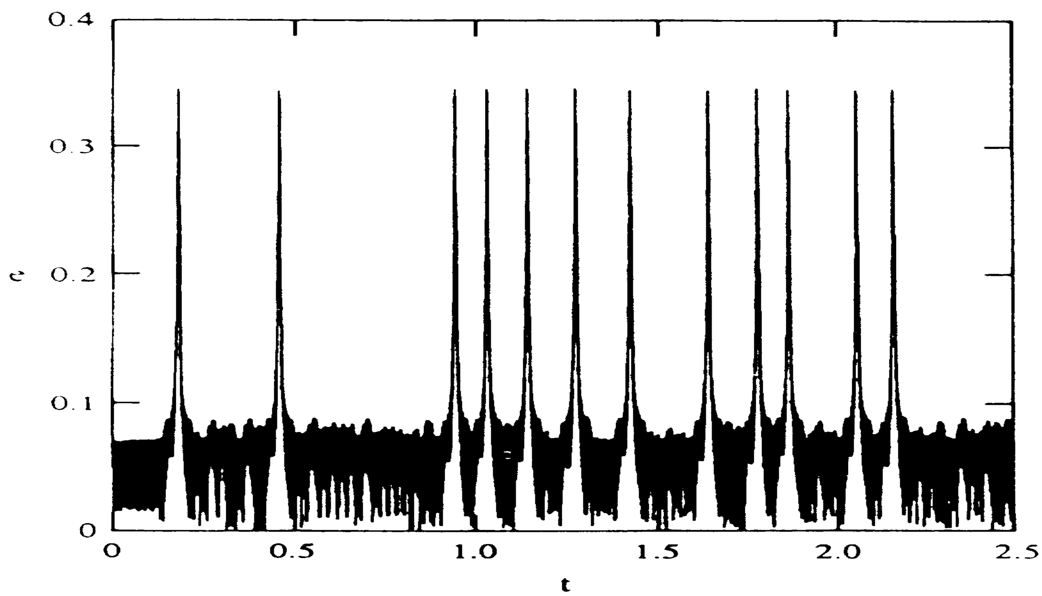

Figure 12: "Chaotic variations in the eccentricity of an asteroid orbit over 2.5 million years, as calculated by Jack Wisdom of MIT. Normally the orbit is quite circular, but at irregular intervals it becomes very elongated (eccentricity greater than 0.3)."[38]

The final category is the "horror scenario" and involves objects arriving with little or no warning. Ironically, because of the lack of detection capability, this scenario is the most likely case. As a result of this lack of warning, mankind will be limited to evacuating expected impact sites. There will not be time for defensive measures.[39] As survey efforts continue though, this category will decrease in scope while the others grow larger and we will have more time to employ appropriate defensive action. Having defined intercept scenarios and the threat, we now consider mitigation options.

Mitigation Options

To first order, current technologies can mitigate threatening asteroids and comets. There are basically two technology areas to consider: those related to propulsion and those related to deflection/fragmentation (table 4). Given the notional rigor of this paper, all the technologies discussed below are assumed applicable to both distant and close-in intercepts. System sizing and sensitivity analyses are beyond the scope of this effort.

Table #4: Propulsion and Deflection Technology Options [40]

1) Propulsion	
- Chemical	... Current Technology
- Nuclear, Mass Drivers	... Next Two Decades
- Hypervelocity, Antimatter	... Several Decades
2) Deflection/Fragmentation	
- Nuclear, Kinetic Energy	... Current Technology
- Lasers, Ultra-High Kinetic Energy	... Next Two Decades
- Antimatter, *in situ* Mass Drivers, Solar Sails, Asteroid Eaters	... Several Decades

For propulsion design, a system with high specific impulse is desired to maximize effectiveness. This property will give a rocket high enroute velocity and thus increase the chances for a distant intercept. It will also give high terminal velocities, and hence kinetic energy, which can broaden deflection/fragmentation options. And as a function of system design, high specific impulse could allow for relatively large payloads. Nuclear propulsion offers the best near-term advance in specific impulse over current technology, specifically by a factor of two or three over chemical propulsion designs.[41] Both the US and Russia have developed nuclear propulsion systems, but to the best of the authors' knowledge, none has yet been tested on-orbit. Recent efforts have been retarded or canceled given that no current or near term DoD lift requirements mandate nuclear capabilities.[42] Planetary defense could mandate such a design. Metastable fuels also hold the promise of increased specific impulse in the near future with metastable HE_4 offering a six times improvement over chemical designs.[43] Other propulsion options, clever but highly speculative and not likely to be available by 2020, include mass driver reaction engines located *in situ*, hypervelocity systems employing nuclear explosions to impart momentum, and antimatter devices.[44] But again, and in summary, it appears that chemical and nuclear propulsion systems now in development offer the best options for planetary defense.

Deflection/fragmentation options constitute the second technology area. Kinetic energy projectiles and nuclear devices offer current solutions. By way of calibration, a 200 kg projectile with 12 km/s closing speed (within the capability of chemical systems) could successfully deflect a 100 meter asteroid in a distant intercept scenario.[45] Similarly, a 100 Kton nuclear device could accommodate a 1 km asteroid while a 10 Mton device could accommodate a 10 km asteroid.[46] The best nuclear device for the purpose of NEO deflection will be an enhanced radiation design, one which provides a large flux of high energy neutrons. These are necessary to cause material blow-off from the object after irradiation by an explosion in a stand-off mode[47] (figure 13). Blast and overpressure, of course, provide no use in the vacuum of space.

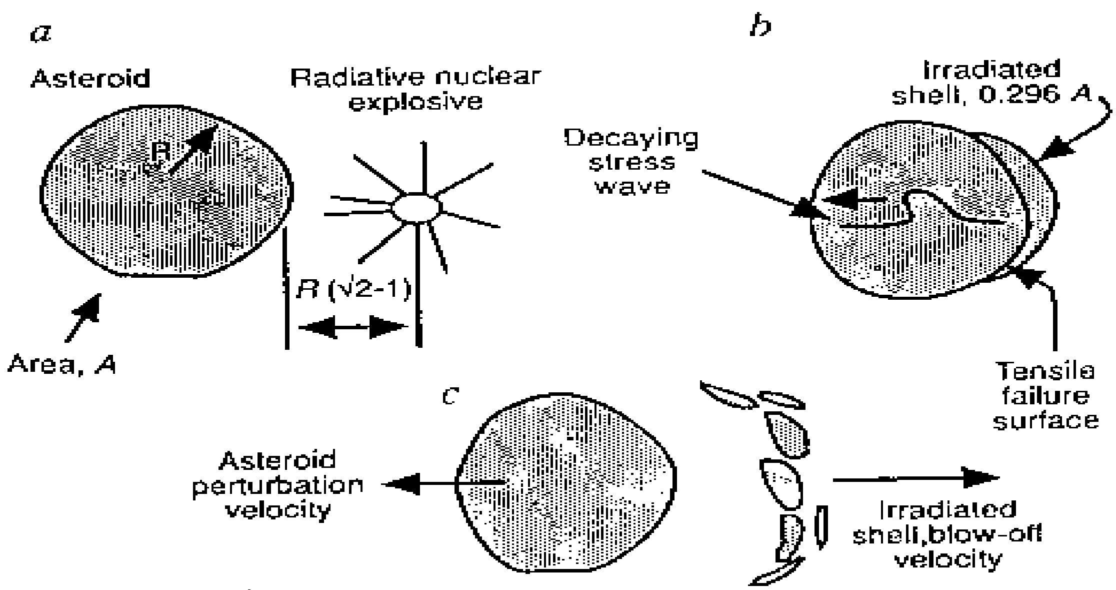

Figure 13: "How nuclear explosive radiation could be used to induce a velocity perturbation of ~ 1 cm s^{-1} in a near-Earth asteroid. *a:* Nuclear explosive designed to provide a substantial fraction, *e*, of its yield as energetic neutrons and γ-rays is detonated at an optimum height, (√2 -1)*R*, above an asteroid. At this elevation the asteroid subtends 0.27 of the area of a unit sphere around the explosive, which irradiates 0.296 of the asteroid surface area. *b:* Irradiated to a depth of ~ 20 cm, surface material subsequently expands and spalls away from the asteroid, inducing a stress wave of several kilobars amplitude in the asteroid. *c:*

Blow-off of the irradiated shell induces a velocity perturbation of ~ 1 cm s^{-1} in the asteroid." [48]

Employment of nuclear devices in a stand-off mode represents the gentle nudge of all the options available. Though technically much more difficult, nuclear devices exploded on or beneath the object's surface impart ten or more times the impulse of a stand-off explosion.[49] This approach will require detailed knowledge of the object's composition and propensity for fragmentation, however, and may also have larger payload requirements, thus offsetting any advantage. Relative to kinetic energy options, nuclear options appear to be favored for NEOs over about 100m diameter.[50]

Other near-term options relative to the year 2020 include the use of ground or space-based lasers to induce material blow-off, and ultra-high kinetic energy devices requiring nuclear propulsion.[51] Further in the future, options include the use of antimatter,[52] large solar sails,[53] and man-tended mass drivers or reaction engines located *in situ* (e.g., a man-tended rocket attached to an asteroid as described in Arthur C. Clarke's *The Hammer of God*).[54] Finally, there could come a time for "Asteroid Eaters." In this scheme one would infest the object with a few devices whose purpose is to replicate themselves using desk-top manufacturing technology and the asteroid itself as raw material. Over the period of several months or a few years, these devices, recreating themselves into an army of thousands, could completely mine the asteroid away, or at least reduce it to a size that is no longer a threat or is more easily maneuvered by propulsion technology. A variation on this is to have these devices also mine the asteroid for fuel that a propulsion system could use to move the object into a benign orbit. Technology advances are required in desk-top manufacturing, artificial intelligence, materials permutation (molecular breakdown and alteration), robotics and micro-machines or nano-technology. Advances in these areas could lead to many spin-offs in other defense or commercial applications.

Beyond deflecting or fragmenting an errant asteroid, there may be great advantage in capturing an ECA into Earth orbit. Besides just the experience in large space operations such an endeavor would give us, great benefits could be gained through mining of the asteroid's natural resources (including its orbital energy) or use of the asteroid as a space platform for large systems used in surveillance of the near-Earth environment. An asteroid parked in an orbit slightly higher than geosynchronous might be an ideal base of operations to maintain and salvage geosynchronous communication and surveillance satellites. Its orbit will naturally provide periodic revisit to all geosynchronous stations. A captured asteroid could also be used for large space based manufacturing or even as a space dock for buildup of interplanetary missions, eliminating the need to launch large structures from the bottom of Earth's gravity well. In summary, use of these asteroids could be stepping stones for man's future in space.

In short, there are many promising options for deflecting or fragmenting Earth-threatening asteroids and comets. The apparent best option today includes nuclear devices and perhaps nuclear propulsion. These, however, carry political ramifications we must address.

Nuclear Solution/Political Fallout

Though nuclear devices may well protect the Earth from threatening asteroids and comets, their employment carries heavy emotional baggage. Ironically, these devices "... could be notably straightforward to create and safe to maintain because they derive from vast research and development expenditures and experience accumulated during the forty-five years of the Cold War."[55] Technically, without an appropriate re-entry vehicle, these devices could not be used as ballistic weapons, though there is always the possibility of terrorism or misuse. In any event, effective international protocols and controls could be established through the United Nations to minimize downside potential. The debate will certainly continue, however, as evidenced by *The Deflection Dilemma:* "... the potential for misuse of a system built in advance of an explicit need may in the long run expose us to a greater risk than the added protection it offers." [56]

Near-Term Technologies and Operational Exploitation Opportunities

Near-term technologies support development of both detection and mitigation capabilities against Earth-crossing asteroids and comets. Specifically, ground-based telescopes employing CCDs with automated search techniques are viable for detection, while chemical or nuclear-propulsion rockets with kinetic energy or nuclear payloads are viable for mitigation. The challenge is not so much in technology development as in economical system design. But a further challenge, and perhaps the greatest, involves the nurturing of international coordination, cooperation, and support. The threat of NEO impact is a global problem and one which the entire world community should bear. So for the near-term, the authors' submit the following recommendation.

Recommendation

The longest journey begins with one small step. The current efforts by a few extremely dedicated individuals are commendable, but lack the national level focus and impetus to achieve the necessary results. A few farsighted predecessors led us into the true control and exploitation of the air. The authors believe the Air Force should now begin this inevitable journey into true control and exploitation of space. It should establish a project office to provide the leadership and advocacy necessary to achieve progress in this new but critical mission area.

Initially this project office will be responsible for examining and fostering capabilities to detect, track, characterize and mitigate planetary debris of sufficient size to cause significant destruction of human lives and property should it impact the Earth. To do this it will:

- Coordinate with existing efforts within DoD (if any), NASA, DOE, Academia, and others in the scientific community. It will coordinate resource support for these efforts where needed and consolidate efforts where warranted.

- Seek cooperation with and support for similar efforts in the international community and lead the efforts of the US team in the international arena.

- Advocate before Congress and international bodies the funding and fielding of an internationally supported surveillance system similar to that already proposed to Congress.

- Seek the set-aside of existing resources determined to be surplus which may aid in the surveillance and mitigation of the planetary debris threat. Specifically, this may include applicable spacelift-capable missiles and nuclear devices.

- Support the development and cross-feed of applicable technology efforts.

- Plan and program for potential future efforts to include:
    - Contingency planning for anticipated mitigation efforts.
    - Requirement definition for technology needs, emphasizing multi-use potential.
    - NEO rendezvous, characterization and deflection test missions.

For decades we have lived in fear of humanity's own destruction by the missile delivery systems and nuclear warheads designed to employ against ourselves. The authors find it somewhat ironic, but perhaps a sure indication of a divine sense of humor, that just as mankind rushes to rid ourselves of these devastating weapons, we find that we should now work together in learning to employ these same systems as the tools to deliver our planet from naturally occurring devastation.

The technology for a system to detect the threat is clearly in our grasp and only needs very modest funding to be built and put into operation. A rudimentary mitigation system could also be developed based on existing systems and maintained at modest cost compared to current defense systems. As the Clementine mission has shown, even asteroid rendezvous and characterization missions are only in the $100 million dollar range. Also, work on more sophisticated approaches will bring benefits in advanced technology in a number of defense related areas. All that mankind lacks is a greater awareness of the threat and the will to do something about it as opposed to accepting such a cataclysmic event as an act of God. This paper has attempted to increase the reader's awareness in the hope that a consensus of will might result. Mankind must now prepare for planetary defense.

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