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DANGERS FROM ASTEROIDS AND COMETS: RELEVANCE OF INTERNATIONAL LAW AND THE SPACE TREATIES

by

Eugene Brooks
Plainview, New York, USA

ABSTRACT

This paper sets out the scientific basis of the danger to Earth from impacts with asteroids and comets, and whether the hazard requires international action. It then summarizes cooperative searches underway to detect these bodies, and proposed interception techniques.

International laws and the space treaties are examined to determine whether obligations have been created requiring States to detect celestial threats, to notify other States and population of danger and to consult with each other to mitigate any danger.

The paper recommends a stepped up coordinated international network to detect rogue asteroids and comets but suggests caution in developing measures to deflect them.

Treaties banning nuclear explosions in space may have to be reconsidered. Ultimately, international structures may be needed to decide whether, when; and how to test deflection methods, to intercept asteroids if required, and to prevent potential misuse or miscarriage of such activities.

Finally, the desirability of combining asteroid and comet surveys to avoid impacts with the appraisal and use of their resources, is recommended.

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SCIENTIFIC BACKGROUND

Barring an unexpected apparition of a large asteroid or comet on collision course with Earth, one about 1 kilometer or more in diameter, the chance of a total catastrophe is one third of a million years away[1] It is estimated that based on the geological record of platinum group layers, especially iridium, and the record of marine extinction (plankton) there have been about 24 peaks - 5 major and 19 minor - extinctions of over 25% -90% of extant genera in the last 540 million years[2]

The best known extinction is the one that took place about 65 million years ago at the boundary between the Cretaceous and Tertiary (KT) periods. The dominant theory is that the impact of a 10 kilometer asteroid or comet traveling at least 30 km per second on the Yucatan Peninsula in Mexico created an immense shock wave, an expanding fireball of vaporized rock, and a further ejecta of rock which heated the region of the air and surface. A blanket of dust settled down through the atmosphere, blocking sunlight, chilling the earth and killing most life. Months of cold persisted, then water vapor and carbon dioxide released from calcium layers of rock, led to a greenhouse effect heating earth, while large quantities of acid rain poisoned air, water, and soil. This extinction is thought to have killed the dinosaurs and 60% of other animals and plants, leaving earth to those smaller mammals that survived[3]

An impact of Yucatan magnitude is thought to occur once every 23 million years. A long interval surely but, smaller objects crash down at greater frequencies - once every century a 50 meter (104 foot) body capable of destroying a city if it landed there, is believed to fall to earth, or explode above it.[4] One asteroid of this size exploded several km over the Tunguska Valley in Russia in 1908, leveling 2000 square kilometers of forest (about 50 kilometers across). There are an estimated .5 million to 1.5 million asteroids larger than 50 meters whose orbits cross the orbit of earth.[5] It is the statistical scope of damage, offset by the infrequency of its occurrence, that presents the problem: how much effort shall be given to the detection and mitigation of damage from celestial bodies?

ORIGIN OF ASTEROIDS AND COMETS

The standard theory of cosmology states that the universe came into being with a sudden explosion of energy from a central point - the Big Bang singularity. The universe, including space and time, rapidly inflated, and cooled. Various forces (gravity, the strong, the weak, and electromagnetic) separated, until atoms were formed. Immense gas clouds, mostly hydrogen and helium, contracted under the force of gravity to become galaxies and stars. The larger stars burned their hydrogen into helium, and then into heavier elements quickly, then exploded, seeding space with gas, dust and heavier elements.[6]

In our part of the universe, a large cloud of gas, dust, and heavier elements condensed, and ignited to become the sun, rotating by virtue of the rotation of the galaxy, the pull of other stars, and turbulence of the original gas cloud. The centrifugal force of this rotation prevented all the matter from becoming part of the sun. Some of the matter formed a disk of small particles, mostly ice and rock, which accumulated over a period of one hundred million years to form the planets. As the earth took shape it was bombarded with extremely large objects, and heated, but over time as the random objects were used up, the collisions became less frequent, and this allowed the earth to cool and, ultimately, life to begin.

Not all the matter gathered into planets, but remains as asteroids and comets, orbiting the sun at varying distances in the large expanse of the solar system[7]

ASTEROIDS

An asteroid is a small planetary body in orbit about the sun. The vast majority, several million, ranging in size from micrometers to several hundred kilometers in diameter circle the sun between the orbits of Mars and Jupiter,[8] a distance between 2 and 4 Astronomical Units (AUs) or between 196 and 392 million miles from the sun.[9] These, the main belt asteroids, are rocks that were kept from forming a planet by the gravity of Jupiter.

In addition to the main belt, swarms of other asteroids orbit the sun closer to earth than the orbit of Mars. These are called Near Earth Asteroids (NEA's); there are about 100,000 over 50 meters across in size, but approximately 1000 to 2000 whose diameters are 1 kilometer or larger[10] and about ten, which are 10 kilometers wide or larger.

A subset of NEA's are Earth Crossing Asteroids (ECA's) whose orbits cross the orbit of earth at some point. As of 1995 those discovered numbered 250,[11] but estimates put the number of asteroids that have the potential to be Earthcrossers as follows: 1500 larger than 1 km[12]; 4-8 thousand larger than 500 meters and .05 to 1.5 million larger than 50 meters.[13]

The source of NEA's and ECA's is probably asteroids in the main belt. Collisions with each other and gravitational forces replenish the numbers of NEA's and ECA's. Thus the population is in steady state, older asteroids have either crashed on a planet or have been ejected from the solar system[14] and have been replaced by newer ones.

Asteroids vary in composition as well as in size - a significant factor in determining the method of asteroid deflection, and of course, prospects for mining of asteroid resources. Generally NEA's appear similar in composition to main belt asteroids, as inferred from radar and spectroscopy, as well as by the actual composition of recovered meteorites. Uncertainties prevail. No spacecraft has landed on an asteroid, but Gaspra, Eros and Mathilde have been photographed. Near Earth asteroids are diverse in composition, ranging from low density carbonaceous, (C type), containing volatile elements (oxygen, carbon, hydrogen, nitrogen, sulfur and chlorine) with a metallic alloy of iron, nickel, cobalt, platinum,[15] to stony and stony iron objects (S-Class), metallic bodies containing nickel-iron alloys, and other rocky bodies.[16] Some asteroids preserve evidence of the early sun history and the original composition of primitive planetesimals[17] Many contain extinct comet cores containing ice useful as propellant for space missions[18] The size, composition and velocity of an asteroid determines whether it will break up and explode in the atmosphere or penetrate it to hit Earth, and these factors bear on the magnitude of damage, selection of asteroids for on-site inspection; selection of methods to deflect them, and use of resources.

Eventually over a period between 10 million to 100 million years, near-earth asteroids will collide with a planet, another asteroid, or will spin out of the solar system by gravitation, particularly Jupiter's. Earth-crossers have a life span according to differing estimates of from 93 to 244 million years.[19] This means that the hazard will continue to the indefinite future with a supply of asteroids furnished by the main belt.

The destructive effect of an asteroid depends upon its size, composition, velocity, and place of impact. A Tunguska like object (about 50 meters in diameter), between 10-20 megatons of energy would destroy a city. Correspondingly, a 350 meter object might destroy a small State; a .7 km object lay waste to a large State like Virginia. It has been estimated that the threshold for a global catastrophe (agricultural collapse and mass starvation, but not human extinction) would be reached by the impact of an asteroid over 1.7 kilometers in diameter striking earth at a speed of 20 km per second. This event might kill about one-quarter of the world's population.[20] An oceanic impact would cause large Tsunamis and correspondingly immense damage to coastal areas.

The frequency of such impacts is said to be from one to several times every million years. Obviously the risk of this happening in the near future is negligible. A Tunguska-like event may occur about once a century. The likelihood of its exploding over a populated area of Earth is once every 3000 years. Every thousand years a celestial object may detonate on Earth with an energy release equivalent to fifty megatons. The possibility of a global or regional catastrophe has led NASA, and others to assert the dominant view, that an asteroid search program should focus on the detection of the estimated 1500 asteroids over one kilometer in diameter, and later to extend the search to diverse smaller bodies.[21] The minority view was that the detection effort be expanded to search out smaller objects (50 to 100) meters as well.[22]

COMETS

Comets are bodies orbiting the sun in highly elliptical orbits. Unlike the asteroids, they were formed in the outer reaches of the solar system. An estimated 100 billion to one trillion comets populate the proposed Oort "cloud" reaching out to one fifth the distance to the nearest star and another theoretical swarm, the Kuiper belt, beyond Neptune's orbit. Their nuclei are composed of organic materials - carbon, ice, dust and other materials, in various degrees of compactness.

Occasionally, a comet is thrown out of its distant orbit by the gravitational force of a passing star, or massive interstellar clouds, or in case of the Kuiper belt, by Neptune, and veers into the solar system. As it approaches the sun, the volatile elements on the outer surface of the comet evaporate to form a tail or tails, visible to the naked eye or telescopes. At length the sun burns away the volatiles, and the comet becomes dead - a virtual asteroid.[23]

Comets may be classified as short period comets if their orbital periods are less than twenty years, intermediate period comets if their periods are between twenty and 200 years and long period comets if their periods are over 200 years.[24] Halley's comet, about nine km wide, returns every 76 years[25] Another large comet, Swift-Tuttle, parent of the annual Perseid meteor showers, is twenty-five km in diameter and has a period of 130 years. Though both comets cross earth's orbit, neither is likely to hit Earth in the next millennium.[26]

There appear to be about twenty-five known short and intermediate earth crossing comets, (ECC's) and an estimated 100 intermediate period comets larger than 1 km in size in earth crossing orbits, constituting about 5% of the 1 kilometer impactor (asteroid and comet) flux to earth[27]

While gravitational effects of the planets on asteroids introduce orbital uncertainties over time spans greater than two centuries, cometary outgassing results in perturbations which result in much greater uncertainties for those bodies.[28] They fit Yeats' description of "disheveled wandering stars."[29] Giant comets are believed to have brought volatiles, including water, to Earth after the early bombardment sterilized it.[30] Recently NASA announced that its Polar spacecraft discovered thousands of "dirty snowballs," diminutive comets the size of houses exploding in the upper atmosphere every day, sending down rain for billions of years.[31]

Though the comet threat appears to be less than that posed by asteroids, their larger velocities make their impacts more catastrophic.

PRESENT SEARCH EFFORTS

The 1908 Tunguska, incident stirred no extraordinary research effort.. The remoteness of the site and political turmoil in

Russia delayed an expedition until 1927.[32] Meteor Crater in northern Arizona, 1200 meter wide, 170 meters deep, was not conclusively recognized as a meteor impact site until 1936.[33] Thereafter, a confluence of factors stimulated interest in the reality of celestial impacts. The late Dr. Eugene M. Shoemaker, a geologist of the United States Geological Survey, among others had studied Meteor Crater. He and his colleagues in the 1960s systematically analyzed lunar cratering rates from Apollo data with a view to estimating the cratering rates on earth. In the 1980s the father-son team of Luis W. Alvarez and Walter Alvarez hypothesized from the disappearance of microfossils, the appearance of iridium at the K/T boundary sediment layers, and the mapping of other impact craters, that the cause of these phenomena was an impact of a large comet or asteroid with earth. Further research pinpointed the site of the now eroded crater on the Yucatan peninsula. The US Geological Survey confirmed that the Chicxulub melt rocks were of K/T age.[34]

The first Earth crossing asteroid was discovered in 1932. Further searches were interrupted by World War II, then resumed. In 1972, Dr. Shoemaker along with Dr. Eleanor Helin initiated the Planet Crossing Asteroid Survey (PCAS) using a Schmidt telescope and photographic exposures; later in 1982 Dr. Shoemaker expanded this into the Palomar Asteroid Crossing Survey (PACS). In 1981 under the auspices of NASA a workshop at Snowmass, Colorado considered the impact flux on Earth.[35]

In 1981 Tom Gehrels of the University of Arizona started a “Spacewatch” team at Kitt Peak using a 0.9 meter Schmidt telescope; a 1.8 meter telescope will soon be added, to be used by Dr.Gehrels and astronomer Dr.Robert McMillan. A new process of light detection uses electronic detectors called charge coupling detectors (CCD’s). This process, reading 80% more photons than photographic film was adapted by Dr. Gehrels for Spacewatch[36] and with the help of computers discovers 2000 new mainbelt asteroids and 3 NEO’s a month; but only the latter are pursued for further observation.[37] However, Spacewatch can cover less than 20% of the sky per month[38]

Until January 1997 the Southern hemisphere sky was scrutinized by the Anglo American Earth Asteroid Survey (AANEAS) headed by Dr. Duncan Steel at Siding Spring, Australia.[39]

In 1995 the US Air Force, at Congress’ urging, upgraded its Ground Based Optical Deep Space Surveillance System (GEODSS) and a one meter telescope at Mt. Haleakali in Hawaii with CCD’s. This effort is now in effect under the banner of the Near Earth Asteroid Tracking System (NEAT), a joint effort of the Air Force, NASA and the Jet propulsion Laboratory (JPL) under the leadership of Dr. Eleanor Helin formerly of PCAS. (Both PACS and PCAS have been discontinued as has, as previous indicated, the Australian effort.) [40] Earth crossing asteroids larger than one km in diameter are being discovered at a rate of twenty per year. One new addition is the Lowell Observatory Near Earth Object Survey (LONEOS) at Flagstaff, Arizona led by Dr. Edward Bowell. Another is Lincoln Laboratory, New Mexico, the Lincoln Near Earth Asteroid Research (LINEAR) which uses a telescope similar to NEAT's.

When Spacewatch, NEAT and LONEOS become fully operational, it is anticipated that 90% of Earth-crossers larger than one km could be discovered and catalogued in about twenty to thirty years with current financial support. Dr. Shoemaker recommended a 40 % higher appropriation, reducing the period for 90% one km earth crossing asteroid discovery to ten years.[41]

Outside the United States an NEO search started up in 1995 at Xing Long, China; and France too looked skyward in 1996 at Cote D'Azur.[42]

The above surveys constitute dedicated search programs to which may be added the findings of observatories around the world and amateur astronomer efforts.

THE INTERNATIONAL "CLEARING HOUSE"

International ad hoc non governmental institutions now serve as a clearing house or houses for the reception and coordination of astronomical information gathered by the world wide efforts described above. Newton's laws of gravitation and his laws of motion are so well understood that, within limits, the orbits of asteroids and comets can be predicted and plotted with almost unerring accuracy.

The International Astronomical Union (IAU) has by agreement arranged with the Institute of Theoretical Astronomy located at St. Petersburg, Russia to maintain and publish the ephemeredes (celestial positions) of all numbered minor planets. The worldwide center for receiving observations of newly discovered and established asteroids and comets is the Minor Planet Center, located at the Smithsonian Astrophysical Observatory at Cambridge, Massachusetts under the leadership of Dr. Brian Marsden. The center collates incoming observations, assigns designations, calculates orbits and publishes results on a monthly basis through Minor Planet Circulars.[43] Appropriate institutional networks are already in place. The question arises as to whether they should be expanded and coordinated or consolidated with other institutions.

DEFLECTION OF ASTEROIDS AND COMETS

The developments that led to increased surveillance of asteroids - the Alvarez hypothesis, moon crater scrutiny implicating large meteors, and computer predictions of nuclear winter in case of all out war - stimulated discussion of impact damage. At the same time, Spacewatch discoveries indicated that the number of earth crossing asteroids known and undiscovered, was larger than previously thought.

In 1990 the US House of Representatives commissioned NASA to set up a workshop to define systems to destroy Earth-bound asteroids and comets - in tandem with the detection workshop. NASA and the Department of Energy's Los Alamos National Laboratory collaborated in fashioning a report which was presented to the House of Representatives in 1992. Hearings were held by the subcommittee on Space (now named the Subcommittee on Space and Aeronautics) in March, 1993. The subcommittee's then chairman, Rep. Ralph M. Hall of Texas, was impressed by the information that on March 23, 1989, an asteroid over 100 feet in diameter and traveling 8 miles per second, missed earth by six hours.[44] This study and other studies have explored the subject exhaustively and in depth.

There is at present no national or international project in place to deflect asteroids and comets. Whether or not any classified deflection plan exists is, of course, unknown.

It is beyond the scope of this paper to describe in detail each proposed technical measure to intercept, destroy and /or change the orbits of asteroids and comets. The following conclusions may be drawn from current publications:

- Present technology exists or can be adapted to deflect or destroy an offending body. This includes rockets, launch vehicles, tracking and homing, and finally the energy delivery to the offending body.

- A precondition of successful interception and deflection is early detection and observation. The approaching asteroid's orbit must be known as early as possible.

- The ability to deflect depends on: the size, distance, velocity, and composition of the target body. Obviously, a large body, over 1 km in diameter, would require a large force to deflect it. For the same reason, the velocity of a body would determine the ability of a force to change the body's orbit. The distance from earth of an approaching mass would dictate the ease of interception, and the way a counteracting force would be applied. The optimum case would be one in which the orbits can be predicted years, or decades in advance, particularly if the object was large (greater than one kilometer in diameter). A long lead time would permit a precursor mission to the object to determine more precisely the size, rotation and composition.

- The cost of a deflection system depends on the programmatic effort adapted from: a few million dollars per year for laboratory and theoretical studies; $10 million a year for telescopes and intensified studies; $100 million per year for robotic spacecraft missions, and additional funds for preparation of an implementation program which would include launch infrastructure vehicles, explosive devices, etc.[45] One estimate ascended to the range of ten million to 100 million dollars per year worldwide as a "balanced response" to the NEO problem - an amount that is a sizable fraction of funding for air safety and control.[46]

- Workshop opinion was divided as to whether planning for testing of methods to alter asteroid orbits on "representative objects" go forward or whether to defer the testing until an actual impact was threatened.[47] In any case, international consultations and participation would be required.

Among deflection methods proposed were the following:

◊ Nuclear explosives: buried, surface, or stand off.
◊ Kinetic energy, deflection or pulverization.
◊ Attaching a thruster to the asteroid .
◊ Mass drivers (steam rockets, conveyor belts, electromagnetic guns) to thrust up from the asteroid masses of material, the thrust reaction of which would move the asteroid.
◊ Solar sails - huge arrays to "tow away" the asteroid.
◊ Crack - outgassing: drilling holes in the body to induce outgassing to propel the asteroid to a new orbit.
◊ Laser deflection - earth or moon based to "blow off" a portion of the object's surface.

The consensus was reached that kinetic and other non-nuclear measures might be appropriate for small objects only, but were too costly for larger objects. The preferred method suggested was the "stand off" nuclear explosion.[48] The literature on deflection stressed the danger of fracturing an asteroid so that the sum of the pieces falling on earth would do more damage than the original object.

LEGAL AND POLICY IMPLICATIONS

GENERAL OBERVATIONS

The survival of all or a considerable portion of the world's population touches the supreme interest of every nation. One would therefore expect positive action by the international community to mitigate catastrophic dangers.

The subject has attracted extensive media speculation, including television documentaries which emphasize the perils rather than the science, to say nothing of elaborate science fiction motion pictures.[49] One might therefore make an effort to de-sensationalize the topic.

One might also observe that there are many pressing and more immediate international and national problems. Among these are: problems of the global economy, the breakdown of nations, famines, nuclear proliferation, malnutrition and disease. Serious ecological hazards include over-population, global warming and possible climate change.[50] The eventuality of global warming and climate change is estimated to occur within the next century or two, a much more imminent world wide danger than asteroid impact.

The overall asteroid-comet impact has a low rate of probability. Still, the possibility of global or regional impact catastrophe still remains and scientists concede its eventual inevitability. Prudence demands some action. The real question is how much.[51] As indicated earlier, specific action has been taken on a national level (NASA-Air Force) and on an international non-governmental level (Spacewatch and the Minor Planet Center). But what further obligations are imposed on States?

DETECTION, DISCLOSURE AND MITIGATION OF DANGERS

CUSTOMARY LAW

There appears to be no overarching positive rule of international law that binds States to protect the world or any region of the world from a natural disaster including dangers from asteroids and comets.

However, one may say that a fundamental obligation of a State is to protect the lives of its subjects. Whether the Universal Declaration of Human Rights, which asserts that everyone has the right to life, liberty and security of person[52] states customary law too broadly in view of repressive acts of some governments throughout history, it is clear that each State feels obligated to protect its own nationals as distinct from those of other nations, from peril. The preamble of the United States Constitution is expressive of this obvious rule. This would certainly include the obligation to notify its citizens of any possible threat to life. States have, however, cooperated on an ad hoc basis to deal with natural and man made disasters. Absent binding agreements, this assistance is granted or withheld as policy dictates.

INTERNATIONAL AGREEMENTS - GENERALLY

The answer to whether States have a duty to notify and protect other States and the world from catastrophe is somewhat different when international agreements and the activities of the United Nations are considered. These agreements and activities may be taken to be declaratory of an emerging practice of States to detect, share information about, and take measures to avoid natural (and some man made) disasters.

The Antarctic Treaty [53] and the Protocol to the Antarctic Treaty[54] both provide exchange of research information. The Protocol mandates sharing of information on potential environmental risk

(Art.6) and provides for Environmental Impact Assessments (EIA's) (Article 8 and Annex I) with notification to the public and the parties of activities anticipated to have more than minor transitory impacts. The United Nations Convention on the Law of the Sea[55] requires States to preserve the marine environment and to notify other States and competent international organizations of potential or actual damage by pollution.[56] The amended convention has now been ratified by the United States and other major maritime States and, the notification provision will soon be, if it is not now, declaratory of inter-national law.

The United Nations' various programmes and specialized agencies have each in their spheres marked out both preventive and remedial measures for natural and man made catastrophes.

Among the specialized agencies, the Food and Agricultural Organization (FAO) exists to ensure "freedom from hunger;" the World Health Organization's (WHO) mission is, among other things, to prevent the spread of disease; the World Meteorological Organization (WMO) facilitates cooperation of national networks for the rapid exchange of meteorological information. Recently the WHO, UNEP and WMO collaborated on a 1996 report that climate instability poses serious and widespread risks to human health.

One may point, in particular, to treaties to provide for preventive action with respect to environmental perils as being analogous to the asteroid hazard: i.e., the Ozone Convention[57] and the Montreal Protocol on Substances that Deplete the Ozone Layer.[58] The Ozone Convention requires cooperation in research, adoption of agreed measures to control human activities injuring the ozone layer (Art.2), provision for systematic observations of the ozone layer, collection and transmission of research (Art.3). It provides for a conference of parties to meet at regular intervals to review scientific information, and promote harmonization of policies. The Montreal protocol sets targets for phasing out production and consumption of ozone depleting substances.

In 1988, the UN General Assembly declared that global climate change was a common concern of mankind. It urged the United Nations Environmental Programme (UNEP) cooperate with W.M.O. and the International Council of Scientific Unions. An Intergovernmental panel set up by the WMO and UNEP provides coordinated assessments of the magnitude and impact of climate change.

The Framework Convention on Climate Change in force in 1994 created a Conference of Parties to make "decisions necessary to promote the effective implementation of the convention." One subsidiary body of scientific and technological advice would make assessments of climate related knowledge;

while another subsidiary body consisting of government representatives who were experts in climate related knowledge, would help the conference implement recommendations.[59] All major nations are signatories. The commitments of the treaty appear not to bind the parties as yet to specific numerical emission targets. Controversy among rich and poor countries and among special interests, has marked negotiations. A critical meeting in Tokyo in December, 1997 may lead to specific reductions and timetables.[60] The Conference of Parties and its subsidiary organs suggests an institutional structure that may be applicable, in a less elaborate form, to deal with the asteroid problem.

The foregoing review suggests that on the basis of the treaties cited above, a consensus may be emerging that all States are required to take measures to notify all others of natural perils, and to take action to prevent them.

OBLIGATIONS OF THE SPACE TREATIES

The various space treaties contain provisions directly in point on the matter of State obligation to deal with the asteroid/comet problem.

As to space dangers the Outer Space Treaty[61] requires States to immediately notify other States of phenomena constituting danger to the life and health of astronauts (Art.V). This falls short of notification of dangers to the population of the world at large. States are further required to notify the Secretary General of "activities conducted in outer space" (Art.XI). This provision does not directly cover the case of mere surveillance of the sky from earth to detect asteroids but would apply to any activity in space directed toward an asteroid.

The 1979 Moon Treaty governing the activities of States on the moon and other celestial bodies[62] goes much further than the Space Treaty in several respects. First, it makes clear that the treaty applies to all celestial bodies in the solar system except where "other specific norms" apply (Art.1). If this were not obvious before, asteroids and comets are swept up into the treaty. In addition the interest of "future generations" is taken into account.

Article 5 is on target with respect to a State's obligation to notify the world of space dangers. This article provides in part:

> "....3. In carrying out activities under this agreement, States Parties will notify the Secretary General as well as the public and the international scientific community of any phenomena they discover in outer space, including the moon, which would endanger life and health."

An asteroid on trajectory toward Earth would be such phenomenon to endanger life and health. The quoted article requires each State to notify all others of prospective danger. This obligation may seem obvious in real life, but it was wise to assert it clearly to avoid an unforeseeable future situation in which one country might decide, for whatever reason, not to disclose an impending danger to another region of the world.

LIMITATION AS TO MITIGATION ACTIVITIES

As indicated earlier, the mitigation of asteroid danger - barring some future method to manipulate gravity - requires the destruction of an asteroid, or altering its orbit. In the case of all but the smallest asteroids this requires one or more stand-off nuclear explosion, preferably years or decades in advance of probable impact.

Several treaties restrict proposed measures to deflect an asteroid or comet.

1. The Nuclear Test Ban Treaty[63]
2. The Space Treaty[64]
3. The Environmental Modification Treaty[65]
4. The Moon Treaty[66]

The Test Ban Treaty flatly bans any nuclear explosion in outer space. The Space Treaty prohibits the installation of "nuclear weapons or any other kinds of weapons of mass destruction" on celestial bodies, or stationing such weapons in outer space in any manner. The Environmental Modification Treaty bans changing "through the deliberate manipulation of natural processes," the dynamics, composition or structure of earth, or of outer space. The Moon Treaty precludes the placing of objects carrying nuclear weapons or other kinds of weapons of "mass destruction in orbit around or other trajectory to or around" any celestial body or placing them on a celestial body (Art.3.3) It also bars the testing of any type of "weapon" in space (Art 3.4).

With respect to all these treaties, a good argument may be made that the parties did not anticipate the danger to earth from asteroids, and that therefore the treaties have no application to the deflection of asteroids.

The Treaty on treaties declares as a general rule that a treaty shall be interpreted in accordance with the "ordinary meaning" to be given to the terms of the treaty in their context and in the light of its objects and purposes.[67] Among other things to be taken into account were "any subsequent agreement between the parties regarding the interpretation of the treaty or the application of its provisions."[68]

As to the Test Ban Treaty, certainly the "ordinary Meaning" of a "nuclear explosion" in "outer space" is quite clear. Yet it is apparent that in 1963, acute international concern was directed to the arms race on Earth, not to protect the Earth from a celestial marauder.

The Space Treaty prohibitions on the installation of nuclear weapons or weapons of mass destruction on celestial bodies or stationing such weapons in outer space left open several important questions relating to arms control. It is beyond the scope of this paper to revisit these contested questions: the interpretation of "peaceful" in relation to military uses or the definition of "weapons" and "mass destruction" or "stationing." These questions have been exhaustively discussed elsewhere.[69] The weight of authority appears to be that any nuclear or other object not only intended but capable of widespread damage, is objectionable. This interpretation would preclude sending or placing nuclear or any other devices that could cause mass destruction (kinetic deflection, lasers) in or to any part of space, including asteroids. It should be noted that an asteroid deflected toward Earth may itself be a weapon of mass destruction. Another interesting question was whether the Space Treaty ban on "weapons" includes trajectories to or from celestial bodies.[70] The trajectory question, as indicated earlier, is settled by Articles 1 and 3 of the Moon Treaty, by which reference to the moon applies to all solar system celestial bodies, including orbits around and trajectories to or around them.[71]

The combination of the Nuclear Test Ban Treaty and the Space Treaties would seem to prohibit any use of a nuclear explosion to alter an asteroid's orbit. The ban might also apply to any other device capable of causing mass destruction. In order to come to a different conclusion, one would be required to interpret the Test Ban Treaty to refer to outer space itself, not to celestial bodies, to interpret "weapons" in all treaties as referring to intended uses (asteroid deflection) rather than merely capable of use as a weapon, and/or to pronounce asteroid deflection outside the scope of any treaty, on the ground that asteroid deflection was not contemplated in the writing of the treaties.

Perhaps the time is ripe for the UN Space Committee to initiate discussions on whether an exception should not be made for nuclear or other drastic means to alter asteroid orbits. The Space Committee may also review whether nuclear explosions might not be used on celestial bodies for mineral extraction, with provisions for international consultations and agreed safeguards.

If the international community decides to clarify or modify the strict ban on nuclear explosions, the preferred path is one the Space Committee has already taken - forging new treaties, rather than amending or adding to existing treaties.

INTERNATIONAL ORGANIZATION TO DEAL WITH THE ASTEROID/COMET HAZARD

All the questions raised in the prior discussion should begin to be examined, first, on an institutional level (the space and military agencies, and the scientific organizations of the space nations and other interested countries); and then on a national and international level. The following questions should be highlighted:

- Shall States enter into new or more organized arrangements for asteroid detection. If so what arrangements?
- Shall States and the international community enter into preliminary discussions as to asteroid deflection? If so, in what manner - by informal national discussions, by articulation of a set or principles through the Space Committee and the United Nations, or by treaty?
- How shall matter of dissemination of information of detection activities and dissemination of particulars of an asteroid threat be accomplished?.
- How shall decision making as to asteroid deflection be made?
- Who will take action and under what conditions and safeguards?

PRESENT INTERNATIONAL PROGRAM FOR DETECTION

As noted previously, detection activities where and when done, are well done by non-governmental institutions with government financing and support, as in the United States, by its Congress and Air Force. These operations are incomplete because of the magnitude of the task and the cross section of the sky covered (the Southern hemisphere sky is not well represented). On the other hand, coordination of discoveries and prediction of asteroid and comet orbits are well advanced in the capable hands of the Institute For Theoretical Astronomy (ITA) and the Minor Planet Center at the Smithsonian Astrophysical Observatory at Cambridge, Massachusetts.

What remains to be done in the detection area? The scope of the discovery program is presently limited. In 1995 NASA recommended a ten year census of asteroids and short period comets larger than 1 km in diameter at a cost of $24 million for the first five years, and about $17.5 million for the next five years. This program posited the discovery of 70% of such objects the initial five years, and 90% the next five years, expanding the search to smaller objects as well . Several dedicated telescopes along with detectors and software were deemed sufficient.[72] By contrast one author suggests a search program reaching the 200,000 two hundred meter and up objects with 85 computer driven telescopes, each costing $3 million at a total cost of $170 million, or better still 150 telescopes at a cost of $300 million. An additional cost of $600 - $900 million would be required for operations over 20 years to be 90% complete in that time.[73] That author compares the cost to the $1 billion bill for the Voyager outer planet flyby. Other mainstream astronomer collaborators see the need for a 20 year search using 12 telescopes in a worldwide network of three telescopes in each hemisphere. This search proposal envisages flushing out most larger ECA's in a 125 year search that would also identify most smaller Tunguska like asteroids. No cost estimate was given for this suggestion.[74]

The House of Representatives in April, 1997 recommended $3.4 million in 1998 and $3.4 million in 1999 for the Near Earth Object (NEO) survey, somewhat less than recommended by NASA in 1995; however, this does not take into account the Air Force contribution, nor the contribution of NASA's flyby and asteroid/comet probes projected now underway or contemplated.

In addition to Earth-based observations, space probes have already begun. Three perfunctory main belt asteroid flybys took place as part of the Galileo program - of Gaspra, dimensions 6x12 km in October 1991; of Ida 52 km long, in August, 1993; and of Mathilde 53 km in diameter in June, 1997.

Projected encounters include

- A Near Earth Asteroid Rendezvous (NEAR) with mainbelt asteroid Eros 14x40 km in January 1999 through February 2000.
- A flyby combining close-ups of mainbelt asteroid McAuliffe, in January, 1999 and Comet West-Kohoutek-Ikemura, in June 2000 under the Millennium Program.
- The "Muses C" joint cooperative mission between US and Japan which will touch down on Nereus (Earth crosser) in January, 2006, collect surface samples, and return them to Earth.
- A proposed comet tail sampling ("Stardust") mission to be launched in 1999 and to collect and return dust samples to Earth, in 2006.

The European Space Agency has proposed the Rosetta Mission, which includes a Mars flyby, two earth flybys, two asteroid flybys, and a comet rendezvous in 2011.[75]

Germany has in mind high resolution imaging of Near Earth Objects through four exploratory flybys. Different imaging systems, a magnetometer and infrared spectroscopic equipment, would be used, and the dust environment would be investigated.

Intensive radar imaging of a number of near earth asteroids has recently been commenced with the refurbished Aricebo dishes at Aricebo, Puerto Rico. The research includes accurate tracing of asteroid orbits.[76]

In regard to international cooperation, NASA suggested operational coordination among institutional telescope users, - scanning of complementary sky areas, with some stations concentrating on asteroid discovery, and others performing confirmation and follow up. At some point an international center might be required for data analysis and coordination.[77] NASA also recommended NEO computational and data centers.[78]

DEVELOPMENT AND ASSEMBLY OF DEFLECTION MEASURES

Deflection technology in the form of rockets and nuclear warheads is said to be theoretically effective against most asteroids up to a few kilometers across. The cost and effectiveness depends on the size, composition and speed of the asteroid, and the time between discovery and deflection. The longer the time available for mitigation the more chances for success and amortization of the cost.[79]

With these factors in mind, decision makers must consider the cost and effort of preparedness against the infrequency of possible need for action.[80]

Though the theoretical basis for deflection is well developed, there is no evidence that any government has made concrete plans for this activity. In 1996 China insisted on conducting underground nuclear tests to prepare for possible defense against doomsday rocks[81] among other possible uses.

Most writers would defer testing and development for several reasons. One reason is that more must be known of the physical characteristics of asteroids to determine the appropriate diversion method. Thus flight to representative asteroids by robot or geologists should precede hardware development. Another reason is that any present elaborate system of mitigation would be shortly out-dated.[82] Dr. Edward Teller believes that experiments involving stand-off nuclear explosions to obtain necessary data be not delayed except for strong reasons.[83] Carl Sagan was particularly wary of any precipitous project “to push asteroids around.” He recommended a combination of accurate orbit estimation, realistic threat assessment and effective public action. Yet in the end he favored robotic flybys and landings, sample returns, human landings, and finally cautious asteroid orbit deflections starting with smaller explosions, then nuclear fusion engines. Finally he somewhat contradictorily approved of “inserting small asteroids made of precious and industrial metals into Earth Orbit” - but in the 22nd century.[84]

The substantial cost of development of deflection technology must be added to the policy consideration mix; the low estimate runs to $100 million per year.[85]

THE DEFLECTION DILEMMA

The “deflection dilemma” (named by Gregory H. Canavan and Carl Sagan), based on statistical analysis, suggests that “the frequency of opportunities to misuse an interception system (by diverting an asteroid toward an enemy nation) is greater than the frequency with which you would anticipate needing to use the system to push an impactor away…" and that the defense system would be more dangerous to mankind than the asteroid itself.[86] More particularly since asteroid near misses are more than one hundred times more frequent than predicted impacts, the occasion or temptation to cause an impact arises one hundred times more frequently as the necessity to avert an impact.[87]

The "dilemma" aspect arises from the fact that if no deflection capability is developed in advance, the Earth is vulnerable to that fraction of NEO bodies or short period comets that may then present an immediate danger, while a complete system built in advance may present opportunity for misuse. This misuse may come from a rogue leader or nation or from an irrational group of people privy to the system,[88] and the opportunity for misuse would be as frequent as the number of new asteroids and the rate of discovery and would increase with the effectiveness of the system.[89] A dark view of mankind perhaps, but, strangely near unanimous.

It is clear therefore that an international consensus would have to be reached for modification of current treaties. David Morrison and Edward Teller recommend that any testing of target objects be taken by an appropriate international body.[90]

INTERNATIONAL ORGANIZATION FOR ASTEROID/COMET DANGER

In the UN Committee on the Peaceful Uses of Outer Space 1996 session some delegations urged that the Committee strengthen the scientific content of its work by promoting international cooperation in other space activities, "especially in the field of disaster warning and mitigation and global search and rescue activities."[91] No doubt disaster warning referred to remote sensing detection of terrestrial disasters, such as hurricanes, volcanoes, aircraft crashes, etc., but it could be expanded to include asteroid detection. The Committee might discuss amplification of asteroid/comet search efforts in its projected Third UN Conference on the Peaceful Uses of Outer Space to be convened in Vienna in 1999 but possibly 2000 AD.[92] One of the topics is likely to be environment and disaster warning, mitigation, and relief.[93]

WITH RESPECT TO DETECTION

What type organization, if any, shall there be for a world wide sky survey of asteroids?

Present discovery efforts are eminently professional but admittedly incomplete.[94] The international mechanisms work very well at the present level of activity. Whether these activities should be more structured may depend on the degree of reliable funding by individual nations by formal agreement.[95]

The asteroid/comet search is primarily astronomical and electronic and there appear to be no precise functional models to turn to. Perhaps the World Meteorological Organization (WMO) which in addition to meteorology, encompasses aviation, shipping, geological and agricultural matters comes closest in terms of observational activity,[96] but because of its myriad activities, its organization is far too complicated to be a role model.

As suggested earlier, the most important precept to follow would be to avoid administrative overload. Therefore, no elaborate organization for asteroid detection and information dissemination is required. National networks can multiply on their own. A more formal coordinated search program which stresses follow up observations like the detection consortium proposed earlier may be desired. If so, it should not be part of any international space agency or under the aegis of any international regime set up by the Moon Treaty. The Minor Planet Center at the Smithsonian Astrophysical Observatory at Cambridge should probably be expanded with a "central nexus.... to coordinate the efforts of different teams...."[97]

An important adjunct to any institute created should be a public information division that would disseminate information frequently and in detail. The integrity of the information should be guaranteed by independent outside data review centers to verify information that might suggest close asteroid approaches.

WITH RESPECT TO TESTING AND HAZARD MITIGATION

As noted earlier, a totally different set of legal and policy problems arise in testing and deflection. The magnitude of the effort and the peril of the process indicates a totally different decision making structure is required.

Flyby missions to asteroids have already taken place and will continue bilaterally or unilaterally. Rendezvous and sampling missions are on the drawing board. Ultimately actual testing of deflection methods will occur. Close international cooperation and coordination are essential because of the cost and the necessity of agreeing on such matters as asteroid selection, technical aspects (orbital determination, propulsion, instrumentation) and financing.

Deflection of an asteroid on earth trajectory may not be needed for hundreds, if not thousands of years. A matter of such importance would imply a decision making organ requiring the highest degree of public confidence.

What would an international organ for activities leading to asteroid deflection, look like?

It should not take the shape of a cooperative enterprise like the Mir Orbiting Station where Russia, the owner and operator of the station, made vital emergency decisions in July, 1997, with the concurrence of the United States and France.[98] Recent Mir misadventures disqualify an overtaxed binational arrangement.

A tiered decision making structure would be necessary. One might suggest a three layered organization:

- The first layer, dealing with exploratory missions to asteroids, including flybys, rendezvous orbiters and sampling - whether robotic or manned - can be composed of a collegial body of scientists and astrodynamical experts, obtaining input from the detection community, and guided by a council composed of scientific advisers and Vice Presidents or other delegates of the space nations and delegates of non-space nations selected by pooling.
- The second layer would deal with the testing of deflection techniques. The present consensus is that any deflection testing should be done well away from Earth, to avoid dangerous errors. Carl Sagan suggested waiting several decades to change the orbits of small (100 meter wide bodies) while developing technology to deflect a large asteroid. Sagan would prefer to have us wait to the 22nd century to move small asteroids around the solar system, with nuclear fission engines.[99] Others think that large objects (1 km or more) should be testing targets because of their destructive capacity.[100] The second tier would require the counsel of senior scientists and political figures, in part drawn from the first tier, with consultations among the top leaders of nations (Presidents, Premiers, etc.). Input might also be encouraged from independent scientific and citizen bodies.
- The apex tier would be a body consisting of an executive council limited to 25 or so top world leaders and scientists chosen by the second tier and assisted by a larger advisory assembly, to make decisions on the deflection of asteroids on collision course with Earth. All decisions on testing of deflection and deflection itself would be carried out by "layers of safeguards."[101]

The maximum dissemination of information should be given to the public with respect to every activity.[102] All proposed activity reports should be accompanied by summaries of the possible effects on the space environment, similar to Environmental Impact Assessments for environmental matter. The United Nations Space Committee should soon begin to discuss the subject of detection and mitigation.

EXPLOITATION OF ASTEROID AND COMET RESOURCES

Most expert commentary on planetary resources focuses on the Moon and Mars. The reason for this is that those bodies may also serve as research bases and ultimately, manned colonies. Asteroids and comets have not, however, escaped attention as possible resource reservoirs.

RESOURCES

Since no asteroid and comet has yet been visited by man, the composition of these bodies has been deduced by other means. In the case of both, asteroids and comets telescopic observations are coupled with spectrographic interpretation to provide preliminary information. In the case of asteroids, the study of meteorites, made mostly of iron and stony irons, helps characterize some asteroids or their interiors. Meteorites, though, do not represent the full range of asteroid content.

Near Earth asteroids are compositionally diverse, and their resources are more varied than lunar materials. Current knowledge of asteroid resources is limited, however, and further research would be required merely to single out some asteroids for further scrutiny, leading to exploration and exploitation.[103]

About four-fifths of asteroids are metal rich, containing iron, magnesium, nickel, cobalt and platinum, while one-fifth contain volatile materials, such as hydrogen, carbon, sulfur and nitrogen compounds. The volatile products of carbonaceous asteroids would be particularly useful for extracting water used for life support, shielding against solar flares and cosmic rays, and for conversion to hydrogen and oxygen. Various mixtures of volatiles may also be used as rocket fuel; in fact, most asteroid material would initially be used in space for space related projects. One advantage of asteroid exploitation is an asteroid's low gravity, which allows the return trip to Earth or elsewhere to be made with less fuel or greater payload.[104]

Short period comets are extraordinarily rich in volatiles, particularly water, carbon monoxide and hydrocarbon dust grains. A typical cometary nucleus contains water ice, hydrocarbons, silicates and other volatile ices[105] A fraction of near Earth asteroids are extinct nuclei of short period comets and their interiors may also contain volatiles.

Asteroid and comet resource

development would be subject to financial and investment limitations, whether conducted by State agencies or private entities. The cost of an asteroid mine would run from one billion to five billion dollars with research, development, testing and delivery of components spread over fifteen years.[106] A long period of testing of processes for resources uses would be required, most effectively by computer simulation.

THE LEGAL REGIME RELEVANT TO ASTEROID AND COMET RESOURCE EXPLOITATION

Prior to the space treaties, States might obtain sovereignty over portions of celestial bodies as on Earth by effective occupation. Effective occupation to uninhabited and desolate regions is determined by some physical activity on the territory coupled with purposeful exercise of political rights purporting to cover the whole of a disputed terrain.[107] Under customary law, resources rather than the territory itself could be used exclusively with or without acclaim of ownership. Thus, prior to the Space Treaties, a State or an entity acting under its authority might take exclusive possession of a portion of an asteroid or an entire small asteroid and might use the iron, nickel or water as well.

The Space Treaty and the Moon Treaty appear to have introduced new concepts that broke away from traditional precepts of "res nullius" and "res communis," although echoes of both theories still vibrate in discussions of property rights on celestial bodies. Distinguished scholars have thoroughly surveyed the extent and limitations of property rights on celestial bodies, most recently in the Proceedings of the Thirty Ninth Colloquium on the Law of Outer Space.[108] These considerations apply to asteroids and comets.

In summary the Moon Treaty, which applies to all celestial bodies, extends the Space Treaty. It says that the exploration and use of celestial bodies shall be carried out for the benefit and in the interests of all countries (Art.4) that States have the right for scientific purposes to collect and remove "..... samples of its mineral and other substances" which shall remain at the disposal of the collecting States and may be used by them for scientific purposes and in support of their missions (Art.6-2). Article 11 (2) repeats the non-appropriation clause of the Space Treaty and continues:

> "Neither the surface nor the subsurface of the moon, nor any part thereof, or natural resources in place, shall become the property of any State, international, intergovernmental, or non-governmental organization, national organization or non governmental entity or any natural person"

Article 11(6) further obliges States "to undertake to establish an international regime ...... to govern the exploitation of the natural resources of the moon as such exploitation is about to become feasible" and with respect to the resources, sets out four purposes: orderly and safe development, the rational management of those resources, the expansion of opportunities, and equitable sharing of benefits, giving special consideration to the interests and needs of the developing countries, and the efforts of countries contributing to the exploration of the moon.

The Moon Treaty opened for signature in December, 1979, came into force in 1984 and as of 1996 has been ratified by nine States but the major space nations have not acceded to the treaty, despite the passage of eighteen years, so that the above provisions are not binding on them.

Intense controversy has swirled about portions of the Moon Treaty, particularly Article 11, generally pitting non-space nations against space nations. Disputes center on whether national or commercial ownership of natural resources has in fact been legally impaired, and to the extent that it is, whether these restrictions stifle incentive and thereby the development of resources, or whether these restrictions are necessary to prevent resource monopoly and profit running to solely private commercial entities. An ancillary legal question spotlights the prohibition of acquiring property to "natural resources in place" - is sanction given to property or ownership once the resources are extracted and removed?

Then, the whole matter of an "international regime" is supported or questioned. The Moon Treaty does not create an international regime, it merely asks States to promise to establish it once the exploitation of resources becomes feasible. Still, shall the international regime take the form of an enterprise or be merely a licensing authority? Shall it be the sole authority and/or eventually be one of the actors, as the Law of the Sea Treaty contemplates for its International Seabed Authority and its organ, the Enterprise, dealing with the seabed.[109]

The mineral resources of the Antarctic area presented the same institutional questions. They were addressed by the draft convention on Regulation of Antarctic Mineral Resources Activities.[110]

The solution there was to fold supervision of all Antarctic mineral resources into a Commission which would among other things entertain State sponsored applications for prospecting and ultimately exploration in designated areas under permits issued by Regulatory Committees for each area. No activities would be permitted outside the convention and exploration would proceed under a "Management Scheme." The Convention provided for commission membership and various decision modalities including a three quarters membership super majority on questions of substance. All activities were circumscribed by various financial, environmental and operational criteria.

Because of persistent environmental concerns, the draft convention has been sidelined for fifty years and may never go into force.

Different views of resource exploration can probably be reconciled. Apprehensions of suffocating incentive are probably overdrawn, particularly since even in the most free market economies, corporations are surrounded by desirable restrictions (wage hour laws, fraud statutes, securities regulations, anti discrimination statutes, price fixing and (some) monopoly barriers). With respect to an international regime, it is likely that the distance between Earth and the planets requires a firm hand, particularly in security and ecological matters which can be exercised by an organ in which the space nations dominate. There must certainly be financial incentives - wealth must be created before it can be distributed; and private enterprises may come to be major participants, dominating through investments and even operation. One the other hand,, one may also take notice of “socialized costs”, or collectivized loss, in which tax payers provide the funding while a small group reaps the profits. And developing nations are best served through the World Bank and other agencies directly, rather than by a functional enterprise.

Applying the above remarks to asteroids and comets, the number of worthwhile exploitation objects would be relatively few, the cost immense, and the likelihood of exploitation of resources far in the future. The Moon Treaty provisions against national appropriation and those restricting the creation of property interests should, for the time being, be strictly interpreted, and be implemented through the international regime, separate and distinct from any organ dealing with asteroid deflection testing and mitigation. Security concerns would be paramount as to asteroids and comets so as to prevent misuse discussed in the section on the “Deflection Dilemma.”

CONCLUSION

The number of worthwhile human activities is enormous, and scientific advances in all fields including space, have been superlative. Planetary exploration is a significant part of this progress. The asteroid/comet peril, and opportunity, occupies a small corner of worldwide attention or concern but in the long future, should not be wholly disregarded. It may ultimately become a test of human ingenuity.

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[107] East Greenland Case, PCIJ Ser. A/B No 53 (1933); see E. Brooks, Control and Use of Planetary Resources, Eleventh Colloquium on the Law of Outer Space (1968) P.339-350.

[108] Oct. 7-11, 1996, Beijing, China, Amer. Inst. Of Aeronautics and Astronautics, Reston, Virginia, P.1-60

[109] UNCLOS note 55, Section 4, especially articles 156, 157 and 170.

[110] Done at Wellington, New Zealand, June 2, 1988, 27 ILM 859 et. seq.