MITIGATION OF HAZARDOUS COMETS AND ASTEROIDS

It is known that large asteroids and comets can collide with the Earth with severe consequences. Although the chances of a collision in a person's lifetime are small, collisions are a random process and could occur at any time. This book collects the latest thoughts and ideas of scientists concerned with mitigating the threat of hazardous asteroids and comets. It reviews current knowledge of the population of potential colliders, including their numbers, locations, orbits, and how warning times might be improved. The structural properties and composition of their interiors and surfaces are reviewed, and their orbital response to the application of pulses of energy is discussed. Difficulties of operating in space near, or on the surface of, very low mass objects are examined. The book concludes with a discussion of the problems faced in communicating the nature of the impact hazard to the public.

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Preface

The chapters in this book are based on a series of invited lectures given at the "Workshop on Scientific Requirements for Mitigation of Hazardous Comets and Asteroids," which was held in Arlington, Virginia, on September 3–6, 2002. The focus of the workshop was to determine what needs to be done to ensure that an adequate base of scientific knowledge can be created that will allow efficient development of a reliable, but as yet undefined, collision mitigation system when it is needed in the future.

To achieve this goal essentially all aspects of near-Earth objects were discussed at the workshop, including the completeness of our knowledge about the population of potential impactors, their physical and compositional characteristics, the properties of surveys that need to be done to find hazardous objects smaller than 1 km in size, our theoretical understanding of impact phenomena, new laboratory results on the impact process, the need for space missions of specific types, education of the public, public responsibility for dealing with the threat, and the possible roles in the United States of the National Aeronautics and Space Administration (NASA), the military, and other government agencies in mitigating the threat.

Most of these topics are, we believe, well covered by the material contained within this volume and so it should serve both as a snapshot of the state of the collision hazard issue in the United States in late 2002 and also a useful sourcebook for reference into the associated technical literature. In addition, other opinions and insights into these and other topics discussed at the workshop can be found in a companion volume of extended abstracts that is available on the World Wide Web at http://www.noao.edu/meetings/mitigation/eav.html.

During the workshop it became clear that the prime impediment to further advances in this field is the lack of any assigned responsibility to any national or international governmental organization to prepare for a disruptive collision and the absence of any authority to act in preparation for some future collision mitigation attempt. In addition, some 18 major conclusions were formulated that provided the basis for five recommendations. The full report of the workshop can be downloaded from http://www.beltonspace.com but, in brief, the essence of the recommendations is:

- That, in the United States, NASA be assigned the responsibility to advance this field.
- That a new and adequately funded program be instituted at NASA to create, through space missions and allied research, the specialized knowledge base needed to respond to a future threat of a collision from an asteroid or comet nucleus.
- That the United States sponsored Spaceguard Survey be extended to find the hazardous part of the population of possible impactors down to 200 m in size.
- That the military more rapidly communicate surveillance data on natural airbursts.
- That governmental policy-makers formulate a chain of responsibility for action in the event a threat to the Earth becomes known.

It is our earnest hope that through the publication of this volume interested scientists, engineers, politicians, and governmental managers will find an adequate source of reliable and quantitative information to underwrite the work that needs to be done to achieve the sense of the above recommendations.

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We would like to thank E. J. Weiler and C. Hartman at the Office of Space Science of the National Aeronautics and Space Administration for providing the primary support for the "Workshop on Scientific Requirements for Mitigation of Hazardous Comets and Asteroids" and underwriting the publication of this book. Other essential support was also received from Science Applications International Corporation, Ball Aerospace and Technologies Corporation, Lockheed Martin Space Systems Company, the National Optical Astronomy Observatory, and the University of Maryland. Thanks are also due to our colleagues R. Greeley, S. Mitton, J. Garget, and E. Yossarian at Cambridge University Press for helping us with the production of this book and to M. A'Hearn and L. Diamond and their colleagues at the University of Maryland who provided logistical support during the workshop. We also thank D. Isbell at the National Optical Astronomy Observatory for organizing press and public outreach activities surrounding the workshop. M. Newhouse, D. Bell, and D. Gasson helped maintain the website and the online abstract submission procedure for the workshop. M. Hanna, P. Marenfeld, and A. Heinrichs helped us with the graphics. S. Ostro and R. Binzel kindly provided the figures for the front and back covers.

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Glossary

a *See* semimajor axis.

ablation Removal of molten material from a meteor due to heat generated by friction as it travels through the atmosphere.

absolute magnitude Magnitude (a logarithmic measure of brightness typically in the V spectral band) corrected to a heliocentric and geocentric distance of 1 AU and to a solar phase angle of zero degrees. Note: this definition is different to the common usage of “absolute magnitude” by non-planetary astronomers. *See also magnitude*.

achondrites A class of stony meteorites without chondrules. They may have non-solar composition.

albedo Ratio of reflected light to the amount incident. Shiny white objects have high albedos whereas rough black surfaces have low albedos.

aphelion Furthest point in a heliocentric orbit from the Sun.

aphelion distance Distance from the Sun to the aphelion, generally denoted by Q.

Apollo asteroids Asteroids with semimajor axis $\geq$ 1.0 AU and perihelion distance $\leq$1.0167 AU.

argument of perihelion Angle along the orbit of an object measured from the ascending node to perihelion.

Amor asteroids Asteroids with perihelion distance, q, given by 1.0167 AU $< q \leq$ 1.3 AU.

ascending node One of the two points of intersection between an orbit and the ecliptic plane. Of these two, the ascending node corresponds to the point where the object moves north of the ecliptic.

Astronomical Unit (AU) Mean distance between the Earth and the Sun (149.6 million km).

Aten asteroids Asteroids with semimajor axis < 1.0 AU and aphelion distance >0.9833 AU.

asteroids Small rocky objects that generally have orbits between Mars and Jupiter. They are the primary source of meteorites. The largest asteroids are few hundred kilometers in size, but most are much smaller.

binary asteroids Two asteroids gravitationally bound to each other that orbit around the common center of gravity.

bolides Bright meteors. Typically brighter than the brightest stars, they can be as bright as the full moon.

C-class asteroids A taxonomic class of asteroids common in the outer part of the main belt. They are often presumed to have a similar surface composition to carbonaceous chondrites.

carbonaceous chondrites Chondritic meteorites with abundant carbon. They appear to be the most primitive type of meteorite.

charge-coupled device (CCD) Detector used to capture images in visible light. A CCD is a solid state electronic device made out of a thin wafer of silicon. Its active area is organized into an array of pixels (picture elements).

Chicxulub crater A large crater situated near Mexico's Yucatan peninsula. Widely thought to be the impact crater associated with the K/T boundary mass extinction.

chondrites A class of stony meteorites containing condrules. With the exception of volatile elements their composition is similar to that of the Sun.

chondrules Roughly spherical objects found in the interior of chondritic meteorites. Chondrules are thought to have originated as molten droplets floating freely in the solar nebula.

comet A solar system object that is distinguished by a diffuse appearance and often a tail of dust and gas. As a comet comes close to the Sun, increased sublimation of volatiles from the nucleus forms a gravitationally unbound atmosphere (coma) rapidly increasing its brightness.

comet nucleus The solid part of a comet. A leftover icy planetesimal from the early solar system. The size of a typical nucleus is few kilometers across.

comet Shoemaker-Levy 9 A comet whose nucleus was broken into several pieces due to tides raised by Jupiter's gravitational field. It crashed into the atmosphere of Jupiter in July 1994 generating long-lasting disturbances in the cloud and stratospheric layers.

co-orbital Objects sharing the same or similar orbits.

Cretaceous/Tertiary boundary (K/T boundary) The abrupt change in Earth's fossil history in rocks laid down some 65 million years ago. It separates the Cretaceous (K) from the Tertiary (T) geologic periods, and is associated with a great mass extinction of many species including the dinosaurs.

debiased population Any population (such as the near-Earth objects) corrected for observational biases.

delay-Doppler image A two-dimensional image constructed using the time delay information in radar reflections from different parts of a solar system object.

Delta *v* Change of velocity needed for a specific alteration to the trajectory of a spacecraft.

descending node One of the two points of intersection between the orbit and the ecliptic plane. The descending node corresponds to the point were the object moves south of the ecliptic.

dielectric constant Property of a material that describes how it interacts with electromagnetic fields.

Doppler effect Changes in the wavelength as seen by an observer due to the radial motion of the observer or the source. A source moving away from the observer results in a redshift while a motion towards the observer causes a blueshift.

e *See* eccentricity.

Earth-crossing asteroid (ECA) An asteroid in an orbit that crosses the orbit of the Earth.

eccentricity Measure of the elongation of an ellipse. Eccentricity of a circle is 0 while that of a parabola is 1.

ecliptic comet population The class of comets with small orbital inclinations and Tisserand parameter larger than 2. These are thought to have originated in the Kuiper belt which exists beyond Neptune's orbit.

equation of state Relationship that describes the behavior between the physical properties (e.g., pressure, density, and temperature) of a substance.

ESA European Space Agency.

escape velocity Minimum velocity required to escape the gravitational field of an object. This is also the minimum impact velocity of an impactor on a direct approach from afar. Earth's escape velocity is about 11.2 $\mathrm{km\,s^{-1}}$.

fireball *See* bolides.

gravity regime The situation in which the formation of a crater is controlled by the gravity of the target rather than its material strength.

H *See* absolute magnitude.

Halley-type comets Comets in isotropic orbits with orbital periods less than about 200 years and Tisserand parameter less than 2. These are thought to have originated in the Oort cloud.

Hohmann transfer Most fuel efficient intermediate transfer orbit when moving from one orbit to another.

hopping Movement with a light jump or skip. A spacecraft maneuver proposed for low-gravity environments.

hovering The act of remaining or lingering above the surface. A spacecraft maneuver proposed for low-gravity environments.

hypersonic Equal to or larger than five times the speed of sound in air. Supersonic refers to speeds greater than that of sound in air.

IAU International Astronomical Union.

i *See* inclination.

inclination Angle between the orbital plane and the ecliptic plane.

interior-to-the-Earth objects (IEOs) Objects with aphelion distances less than 0.983 AU.

interplanetary dust particles (IDPs) Dust particles in interplanetary space. The origins of IDPs include collisions among asteroids and Kuiper belt objects (KBOs), cometary activity, and dust grains from the interstellar medium.

Jupiter-family comets (JFC) A subset of ecliptic comet population influenced by the gravity of Jupiter. Tisserand parameter is between 2 and 3. Thought to be of Kuiper belt origin.

K/T boundary *See* Cretaceous/Tertiary boundary.

Kuiper belt A large reservoir of cometary nuclei beyond the orbit of Neptune. The first Kuiper belt object (KBO) was discovered in 1992.

longitude of the ascending node Angle from the first point of Aries (an astronomical reference point) to the ascending node of an orbit.

LINEAR The Lincoln Near-Earth Asteroid Research program of the Lincoln Laboratory at the Massachusetts Institute of Technology.

lossy medium Medium in which electromagnetic or elastic wave attenuation occurs.

magnitude Number expressed on a logarithmic scale to indicate the brightness of a celestial object. A magnitude difference of 5 equals a brightness difference of 100. Brighter objects have lower numerical values for the magnitude. Often magnitude measurements are made with a spectral filter (e.g., U, B, V, R, I) that corresponds to a particular wavelength band of light. *See also* absolute magnitude.

main belt asteroids Asteroids whose orbits lie between the orbits of Mars and Jupiter.

mass driver A machine proposed to alter the orbit of asteroids. Reaction forces due to ejection of surface material by the mass driver cause the orbit to change.

meteor A glowing object in the atmosphere caused as a meteoroid enters the atmosphere and is strongly heated by friction.

meteor shower An event in which many meteors appear to radiate from the same point in the sky. They occur when the Earth passes through a cometary dust trail.

meteorite An object of extraterrestrial origin which survives atmospheric entry and reaches the surface of the Earth largely intact.

meteoroid A small solid extraterrestrial body that becomes a meteor as it enters the Earth's atmosphere.

microgravity conditions An environment in which the net gravitational force is very small (e.g., on the surfaces of NEOs). Microgravity conditions can be simulated when free-falling.

minimum orbital intersection distance (MOID) Closest possible approach distance between the osculating orbits of two objects. However, the objects themselves need not be at the closest orbital locations at the same instance.

mitigation The act of alleviating, e.g., alleviating hazards posed by asteroids and comets that may be on a collision course with Earth.

monolithic asteroid An asteroid whose structure is that of a single rigid body.

Monte Carlo simulations Numerical technique that uses random samples and statistical methods to solve physical or mathematical problems.

NASA National Aeronautics and Space Administration.

near-Earth objects (NEOs) Those asteroids or comets whose orbits cause them to pass close to Earth or to cross the Earth's orbit. Near-Earth asteroid (NEA) refers specifically to an asteroid with such an orbit.

NEA *See* near-Earth objects.

nearly isotropic comet population A sub-population of comets with orbits that are randomly inclined to the ecliptic plane. Tisserand parameter is less than 2. They are thought to be of Oort cloud origin.

NEAT Near-Earth Asteroid Tracking program at the Jet Propulsion Laboratory in Pasadena, California.

non-gravitational forces Forces that are not of gravitational origin which act on asteroids and comets and that can sometimes significantly alter their orbits. Examples include reaction forces due to outgassing of volatile materials and the Yarkovsky and Poynting–Robertson forces.

Oort cloud A large reservoir of cometary nuclei extending from few thousand AU to nearly 100 000 AU from the Sun. The outer part of the Oort cloud is approximately spherical. The Oort cloud has never been observed but its existence is inferred from the orbits of comets with long orbital periods or with nearly parabolic trajectories.

outgassing The phenomenon of the loss of volatile materials from a solar system body, e.g., the sublimation of water and other gases from cometary nuclei.

Palermo Scale (also called the Palermo Technical Impact Hazard Scale) A scale developed to enable NEO scientists to categorize and prioritize potential impact risks. It is a logarithmic scale which compares the likelihood of the detected potential impact with the average risk posed by objects of the same size or larger over the years until the date of the potential impact.

perihelion Closest point on a heliocentric orbit to the Sun.

perihelion distance Distance from the Sun to the perihelion. Generally denoted by q.

permittivity A parameter that measures how a material interacts with electromagnetic fields.

planetesimals Small rocky or icy bodies formed in the solar nebula and from which larger bodies such as the planets were formed. Some asteroids and cometary nuclei are planetesimals or fragments of planetesimals.

ponds A localized flat region on an asteroid devoid of craters and rocks (e.g., on asteroid Eros as revealed by the images from NEAR–Shoemaker mission).

porosity A measure of the empty space in a solid. A high porosity object is less dense.

potentially hazardous objects (PHOs) Near-Earth objects with minimum orbital intersection distance to Earth of 0.05 AU or less. PHAs refer to PHOs that are specifically asteroids.

Poynting–Robertson effect A deacceleration and spiraling inward of small dust particles orbiting the Sun due to their interaction with solar radiation.

radar Acronym for radio detection and ranging. A technique that uses the reflection of transmitted radio waves for detecting and characterizing a remote object.

radiation pressure Pressure (i.e., force per unit area) exerted by electromagnetic radiation.

regolith A layer of broken rocks and soil at the surface of an asteroid or a comet generated by collision with objects in space.

resonance Amplification of the response of a system to an external stimulus that has the same (or commensurable) frequency as the natural frequency of the system.

Roche limit The maximum distance from a planet where a strengthless satellite will be pulled apart by gravitational tides. If the density of the satellite is the same as the planet, the Roche limit is 2.4 times the radius of the planet.

rubble pile hypothesis Hypothesis that some asteroids are made up of a loosely held aggregate of collision fragments of different sizes. The aggregate is held together by gravity rather than by cohesive forces.

S-class asteroids A specific taxonomic class of asteroids. A common asteroid class found in the inner main belt.

scattered disk Component of the Kuiper disk containing objects with highly eccentric orbits.

seismology The science of studying sub-surface structures through the propagation of elastic waves.

semimajor axis Half the distance between perihelion and aphelion. The mean distance between the Sun and an object in a heliocentric orbit.

silicates Any rock or mineral containing silica (SiO_4).

solar concentrator A reflector to concentrate solar radiation on to an NEO and vaporize the surface material at the heated spot. The resultant thrust caused by outgassing causes the NEO orbit to change.

solar electric propulsion A technology that involves the acceleration of an ionized gas (e.g., xenon) to propel a spacecraft. It provides low thrust over extended periods and is sometimes preferred over conventional chemical propulsion in missions of high complexity. Also known as ion propulsion.

solar phase angle Angle subtended at an object by the directions to the Sun and the Earth. Sometimes called the phase angle.

solar sail A large ultralight sail that uses solar radiation pressure to provide an acceleration.

Spaceguard goal The goal of discovering 90% of NEOs larger than 1 k in diameter by 2008.

strength regime The situation in which the formation of a crater is dependent on the strength of the target rather than on its gravity.

synchronous orbit An orbit in which an orbiting body has an orbital period equal to the mean rotation period of the body being orbited (with the same direction as of rotation).

taxonomy Classification system based on observed properties; e.g., for asteroids their colors, spectral properties, and albedos are used.

thermal conductivity Measure of the ability of a material to conduct heat.

thermal inertia Measure of the ability of a material to conduct and store heat.

thermal-IR Region of the electromagnetic spectrum that corresponds to the range of dominant wavelengths of a room-temperature black body. The range of wavelengths cover approximately from 3 to 100 μm.

three-sigma error (or uncertainty) Statistical expression of error; e.g., for a Gaussian distribution, the probability of the value of a parameter being within its three-sigma error is 99.7%.

thrusters A propulsion device.

tides Surface deformations caused by the differential gravitational forces acting on a celestial body.

Tisserand parameter A conserved quantity in the restricted circular three-body problem. Tisserand parameter with respect to Jupiter is widely used to classify asteroids and comets from a dynamical perspective.

tomography A technique by which the interior structure is determined by the refection or transmission of elastic or electromagnetic waves.

Torino Scale A scale for categorizing the Earth impact hazard due to asteroids and comets. This is intended as a tool to communicate with the public in contrast to the more technical Palermo Scale.

TNT Unit of energy associated with atomic explosions. A 1 megaton TNT explosion is equivalent to 4.18×10^{15} J.

tsunami A huge sea wave caused by a sudden disturbance such as an earthquake, a landslide, or the collision of an asteroid into the ocean.

Tunguska event An explosion over Tunguska, Siberia, in 1908 that was caused by the collision and disruption of a small asteroid or a comet nucleus in the atmosphere.

volatiles Chemical species that evaporate at low temperatures.

Yarkovsky effect Acceleration due to recoil force caused by the thermal reradiation from an irregular object. This can cause substantial changes to asteroidal orbits and also affect their rotational states.