

Near-Earth Object (NEO) Hazard Background²

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Introduction

The fundamental problem regarding NEO hazards is that the Earth and other planets, as well as their moons, share the solar system with a vast number of small planetary bodies and orbiting debris. Objects of substantial size are typically classified as either comets or asteroids. Although the solar system is quite expansive, the planets and moons (as well as the Sun) are occasionally impacted by these objects. We live in a cosmic shooting gallery where collisions with Earth occur on a regular basis. Because the number of smaller comets and asteroids is believed to be much greater than larger objects, the frequency of impacts is significantly higher. Fortunately, the smaller objects, which are much more numerous, are usually neutralized by the Earth's protective atmosphere. It is estimated that between 1000 and 10 000 tons of debris fall to Earth each year, most of it in the form of dust particles and extremely small meteorites (ref. 1). With no atmosphere, the Moon's surface is continuously impacted with dust and small debris. On November 17 and 18, 1999, during the annual Leonid meteor shower, several lunar surface impacts were observed by amateur astronomers in North America (ref. 2). The Leonids result from the Earth's passage each year through the debris ejected from Comet Tempel-Tuttle. These annual showers provide a periodic reminder of the possibility of a much more consequential cosmic collision, and the heavily cratered lunar surface acts a constant testimony to the impact threat. The impact problem and those planetary bodies that are a threat have been discussed in great depth in a wide range of publications and books, such as "The Spaceguard Survey" (ref. 3), *Hazards Due to Comets and Asteroids* (ref. 4), and *Cosmic Catastrophes* (ref. 5). The following sections give a brief overview on the background of this problem and address some limitations of ground-based surveys for detection of small and/or faint near-Earth objects.

Range of Threat

Threatening near-Earth objects (NEOs) are typically divided among three classifications based on their orbital characteristics and telescopic appearances: near-Earth asteroids (NEAs), short-period comets (SPCs), and long-period comets (LPCs). Many publications also use the terms Earth-crossing asteroids (ECAs) and Earth-crossing comets (ECCs) to specifically identify objects whose orbits can intersect the Earth. Although the primordial population of NEAs has long been cleaned out from the solar system by collisions and gravitational ejections, it is important to recognize that the population of NEOs is constantly being replenished through a variety of mechanisms. A description of each classification and its source is provided subsequently. A great many publications have been written, such as *Asteroids II* (ref. 6), that deal with these planetary bodies in great depth and address the composition and characteristics of the objects. The following sections are designed to provide a brief overview of each object type and describe the differing characteristics that directly relate to the Comet/Asteroid Protection System (CAPS) study effort.

Although comets and asteroids have become the typical classifications applied to NEOs, there are asteroids that exhibit some amount of comet-like behavior, and some extinct comet nuclei may be classified currently as asteroids. The impact threat can also be further classified as short-period objects and

²Chapter nomenclature available in chapter notes, p. 217.

long-period objects, which more aptly distinguishes between the difficulties in protecting against these impactors. Precise orbit knowledge is the paramount factor for determining an impactor. More rapidly determining an impacting object's orbit allows more warning time and opportunity to divert the object or mitigate against impact effects. The following four categories define the impact threat from a warning time standpoint assuming current detection methods:

1. Well-defined Orbits
Detected ECAs
Warning time = Decades
2. Uncertain Orbits
Newly discovered ECAs and SPCs
Warning time = Years
3. Immediate Threat
LPCs; small ECAs
Warning time = Months
4. No Warning
LPCs; unknown ECAs
Warning time = Days to seconds

Near-Earth Asteroids

NEAs are organized into three groups based on their orbits in relation to the Earth's orbit—Atens, Apollos, and Amors. Atens and Apollos are asteroids whose orbits cross that of the Earth. Atens have orbital periods of less than 1 year and aphelial distances greater than 0.983 astronomical units (au), while Apollos have orbital periods greater than 1 year and perihelial distances less than 1.017 au. Amors have orbits that lie completely outside Earth's orbit (perihelial distance between 1.017 and 1.3 au) but have the potential to be perturbed into Earth-crossing trajectories. There is another group of NEAs that is likely to exist, but it has not been observed to date. These are asteroids with orbits that lie completely within the Earth's orbit (aphelial distances less than 0.983 au), and like the Amors could be perturbed into becoming Earth crossers. These objects have been referred to as interior-Earth asteroids (IEAs) and await an official designation after their existence has been confirmed.

There are believed to be two main sources of NEAs. The first is the main asteroid belt, which is believed to replenish the NEAs through collisions and chaotic orbital dynamics. The main asteroid belt is a vast toroidal region between the orbits of Mars and Jupiter (approximately between 2 and 4 au from the Sun) containing most of the asteroids that orbit the Sun. The main asteroid belt is estimated to contain millions of asteroids ranging from the size of a pebble to approximately 1000 km and is believed to be the origin of most NEAs. The observed composition of NEAs is very similar to main-belt asteroids, and it is believed that collisions and orbital resonances with Jupiter can result in changes in their orbits that can put them into Earth-crossing orbits. The recent Sloan Digital Sky Survey provides an estimate of 700000 asteroids in the main belt that are 1 km in diameter or greater, a number significantly lower than previous estimates of approximately 2 million (ref. 7). This lower number, together with the millions of smaller asteroids, still provides an ample supply of debris that could eventually find itself on a collision course with Earth. The second source of asteroids is believed to be extinct comet nuclei. Several asteroids have orbits very similar to short-period comets, and at least one cataloged asteroid is associated with a significant meteor shower on Earth. Meteor showers typically result when the Earth passes through the debris trail of a comet. The Geminid meteor shower is associated with asteroid 3200 Phaethon (ref. 8). Additionally, nongravitational forces appear to alter the orbits of some asteroids, indicating that some cometary activity is present in these bodies (ref. 3).

NEAs are classified into three major categories based on their reflectance spectra (primarily in the visible through infrared wavelengths) and their geometric albedos (visible). Although there is significant heterogeneity in the major categories, and a number of additional classes, the main asteroid classifications are identified as S, C, and M types. S-type asteroids are reddish in appearance (similar to stony-iron meteorites) and have moderate albedos (0.07 to 0.23). C-type asteroids are dark with some having extremely low albedos (0.02 to 0.07) and are similar in appearance to carbonaceous chondrites. M-type asteroids are believed to be mainly metallic in composition (primarily nickel-iron), have moderate albedos (0.10 to 0.22), and exhibit high radar reflectivity (refs. 9 and 10). Approximately 55 NEAs have been spectrally characterized to some extent and the results published. Unpublished data exist on approximately 40 other NEAs. From this limited population of imperfectly characterized NEAs, approximately 50 percent are S-type, 24 percent are C-type, and 6 percent are M-type. Several other classes exist (each containing a single object or a few objects) and provide the remainder of the classified NEA population. Because the photometric and spectroscopic techniques required to classify NEAs favor the relatively bright objects, the actual proportion of very dark C-type NEAs is likely to be closer to 50 percent (ref. 11).

The density of asteroids is assumed to correspond to the range of meteorites that have been collected. The density of these meteorites can vary widely due to differences in composition as well as porosity of the material. The densities of stony meteorites range from approximately 2300 to 4000 kg/m³, while iron rich meteorites can possess a maximum density of approximately 7900 kg/m³ (ref. 10).

Estimates of the NEA population differ somewhat and are constantly being refined. Recent data gathered by NASA's Near-Earth Asteroid Tracking (NEAT) system indicate that the population of large NEAs (diameter > 1 km) may be only half the previously estimated range of 1000 to 2000. The population estimated from the NEAT data estimates 700 ± 230 NEAs with an absolute magnitude (H) < 18, and assuming an albedo of 0.10 (ref. 12). As additional data are acquired these estimates will be refined further; however, it is certain that the number of smaller NEAs is much greater than the larger objects, as the curve demonstrates in figure 1 (adapted in ref. 13 and originally from ref. 14). This plot, with the error band in gray, shows the much larger population of asteroids less than 1 km in diameter that is believed to exist, and the area under this curve highlights the vast number of potentially threatening ECAs.

Binary Asteroids

Asteroids are not necessarily lone wanderers moving through the solar system. A significant fraction of the asteroid population, including ECAs, have companions. Of approximately 28 known terrestrial impact craters larger than 20 km, at least 3 are confirmed to be double craters. Researchers estimate that approximately 16 percent of NEAs larger than 200 km in diameter are likely to be binary systems (ref. 15). In binary systems, the main asteroid is significantly larger than the smaller body, and rotates much faster than most solitary NEAs. Significantly more information can be obtained from observing binary asteroid pairs, particularly if radar measurements can be made. Whether a potential impactor consists of one or two bodies is important information when formulating a deflection or mitigation strategy.

Comets

While NEAs are a relatively recent discovery (the first NEA, Eros, was not discovered until 1898), comets have been observed by humans for thousands of years. Many comets can be easily observed by the naked eye as they approach the Sun, and the characteristic coma and bright tail are visible. Comets are made up of five main parts: the nucleus, the coma, the dust tail, the ion tail, and the hydrogen cloud

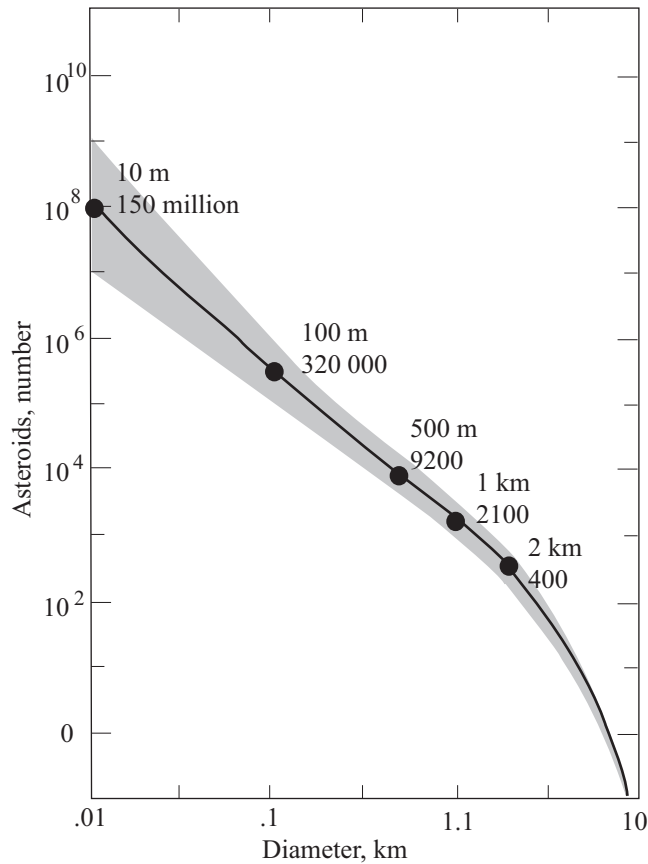


Figure 1. Estimated number of Earth-crossing asteroids.

(sometimes called the corona). Comet nuclei, typically described as a “dirty iceberg” or “dirty snowball,” are a mixture of dust and hydrocarbons and volatile ices (predominately water ice and carbon dioxide ice). There is a great deal of uncertainty in the densities of comet nuclei, but they are thought to range from 200 to 1000 kg/m³ (ref. 11). If some NEAs are actually extinct comet nuclei, the density of some nuclei could be higher. Comets can be extremely difficult to observe before becoming active because their nuclei can be extremely dark. A cometary nucleus was previously assumed to have a fairly high albedo due to its icy composition. However, spacecraft rendezvous missions in 1986 showed that the nucleus of Comet Halley is coated with dark hydrocarbons and has an albedo of only 0.03. This makes Comet Halley’s nucleus blacker than coal and one of the darkest objects in the solar system (ref. 16). As the comet nucleus approaches the Sun, the increasing temperature causes volatile ices to sublimate and then release gas and dust from the comet’s coma, which can be thousands of kilometers across. As the dust in the coma reflects more sunlight, the coma absorbs ultraviolet radiation and begins to fluoresce. A cloud of ionized hydrogen atoms, much larger than the coma, also develops as the comet approaches the Sun. This hydrogen cloud is visible in the extreme ultraviolet region of the spectrum and can only be observed from space. Two tails are formed when the comet becomes active. The Sun’s radiation pressure and solar wind accelerate the gas and dust away from the coma at different rates. The ion tail extends in a nearly straight line in the antisolar direction. The dust tail tends to bend toward the orbital path of the comet because the dust particles are more massive than the ionized gases.

Short-Period Comets

SPCs have orbital periods of less than 200 years, although some researchers classify comets with orbital periods from 20 to 200 years as intermediate-period comets. SPCs are often referred to as periodic comets because their relatively short orbital periods allow observations during multiple perihelial passages. It is estimated that the population of SPCs on Earth-crossing orbits comprises 30 ± 10 larger than 1 km, 125 ± 30 larger than 0.5 km, and 3000 ± 1000 larger than 0.1 km (ref. 3). Many of these objects are thought to originate from the Kuiper belt, a vast population of small bodies orbiting the Sun in a thick ring beyond Neptune and extending 30 to 1000 au from the Sun. The Kuiper belt is estimated to contain 10^8 to 10^9 cometary bodies, with between 35000 to 70000 objects larger than 100 km residing in the region between 30 and 50 au (ref. 17). SPCs may also originate as LPCs with planetary interactions (primarily with Jupiter) perturbing them into short-period orbits.

Long-Period Comets

In 1950, Jan Oort noticed three main points when analyzing the trajectories of known LPCs with orbital periods greater than 200 years (up to 14 million years). First, no comet had been observed whose orbit conclusively indicated it originated from interstellar space. Second, in general the aphelial distance of LPCs was greater than 20000 au. Finally, the orbits of these comets had no preferential incoming direction (approximately 50 percent of currently known LPC orbits are retrograde). These observations led him to theorize that a massive cloud of comets surrounds the solar system. This vast reservoir of comets is known today as the Oort cloud (ref. 18). There is no direct evidence of the Oort cloud because no comet has ever been observed at this great distance. Although the number and mass estimates are not precisely known, the cloud may contain 10^{12} to 10^{13} comets with a total mass of approximately 30 Earth masses (ref. 17). It is believed that the inner Oort cloud begins approximately 1000 au from the Sun and may extend out to 100000 au (almost halfway to the Sun's nearest stellar neighbor). Figure 2 shows a three-dimensional depiction of the Oort cloud. At such large distances, these objects are only loosely bound to the Sun, and various perturbations can eject them into interstellar space or into the inner solar system where they can become impact hazards. The flux of LPCs in the inner solar system is difficult to accurately characterize. Based on the fact that approximately 700 LPCs have been observed during recorded history, it is currently believed that LPCs are only 5 to 10 percent of the ECA population. However, their much higher relative velocities, compared with NEAs, contribute disproportionately to impact threat. It is believed that LPCs could contribute about 25 percent of the total NEO hazards (ref. 3). Because LPCs are not likely to have been previously observed, they represent an impact threat with potentially very little warning time.

In general, LPCs do not become active until they are within approximately 5 au of the Sun, which is just inside the orbit of Jupiter (ref. 3). Before developing a coma and characteristic dust and ion tails, the nucleus may be quite dark with a geometric albedo approaching a limit of 0.02 (ref. 19). This value is approximately the same as the minimum albedo for C-type asteroids. Because the CAPS detection goal is to be able to confirm that an LPC is on impact trajectory when the object reaches a distance within approximately 5 au of the Earth (not just observing the object), it is likely that initial discovery and many follow-up observations would need to be made while the nucleus is inactive. As a worst case, an albedo of 0.02 was assumed for both LPCs and NEAs during this study.

The "Missing" Comet Problem

Our current understanding of the population and the evolution of cometary bodies is still far from complete. A deficiency exists in the number of observed LPCs and evolved SPCs when compared with

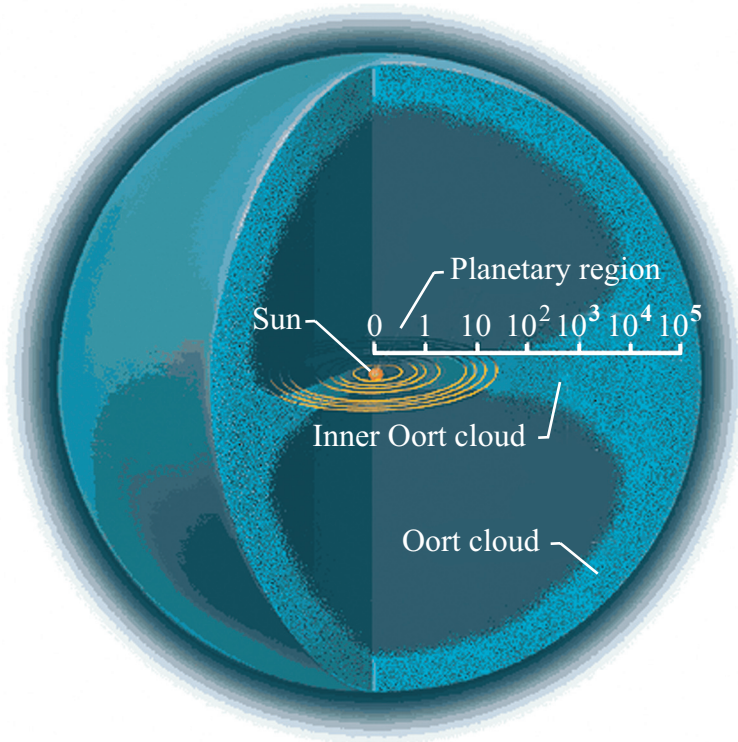


Figure 2. Oort cloud (image courtesy of The Electronic Universe Project, University of Oregon).

the number that should be observed based on the expected steady-state distribution of Oort cloud comets. Dynamic studies generally predict that there should be many more comets than we currently observe, unless some physical mechanism acts to reduce the intrinsic brightness of these objects during subsequent perihelial returns. This phenomenon is often referred to as comet “fading” and has been a vital assumption in comparing the observed and predicted orbits of LPCs (ref. 20)

There are several possible explanations for this discrepancy, and ultimately the answer to this paradox may be that a combination of several mechanisms is responsible. One explanation is that some comets disrupt as they travel through the inner solar system. From an impact hazard standpoint, the important question is whether they disintegrate into very small particles, such as dust, or do the nuclei fragment into smaller, but significant, “cometesimals” that cannot be easily observed with Earth-based telescopes. Comet C/1999 S4 (LINEAR) provided a valuable example of how important space-based observations can be for NEO detection. As it passed through perihelion, intense solar heating triggered a massive disruption of the comet’s nucleus around July 26, 2000. Initial Earth-based observations, using 2-m class telescopes, showed a diffuse cloud of dust and gas, indicating that the comet had completely vaporized (ref. 21). On August 5, 2000, the Hubble Space Telescope conclusively showed that the comet has broken into a swarm of more than a dozen minicomets, some tens of meters in diameter (ref. 22). Subsequent observations with the 8.2-m European Southern Observatory Very Large Telescope (VLT) also showed the remnants of the comet nucleus. As the fragments faded from view, it was not possible to ascertain whether or not they continued to disintegrate completely. Comet Shoemaker-Levy 9, which was much larger than Comet C/1999 S4, broke into many large well-defined fragments from tidal stresses as it passed within 100000 km of Jupiter. Although we have direct evidence that some comets disrupt or fragment, a second possibility is that some LPC nuclei are structurally capable of remaining intact and simply stop outgassing, resulting in either extinction or dormancy. Comets may deplete their volatile

gases and evolve into asteroid-like bodies, with some being captured into short-period orbits while others return on long-period trajectories. If this is another possible fate of LPCs, the very real concern exists that there may be impacting objects that have never been previously observed, have extremely low albedos (≈ 0.02), and never brighten significantly. It is also very possible that both of these mechanisms are responsible for the lack of observed SPCs. If a large cometary body was to disrupt into a collection of significant size fragments that later become extinct or dormant, the ability for any detection system to discover them would be taxed considerably. Because comets and asteroids might form a continuous spectrum of planetary bodies rather than two distinct types, it is very possible that the above mechanisms, as well as others, could explain the lack of observed comets. Finally, another possibility is that the flux of LPCs is not constant (see discussion in next section) and that we are currently in a period of relatively low LPC flux. Drawing definitive conclusions for extremely long-term processes based on a constrained set of observations is always a difficult task.

NEO Impact Flux and Showers

Estimates for the impact flux from comets and asteroids are based on a variety of data, including cratering data (particularly the Moon and Mars), current NEO discovery efforts, and declassified U.S. Department of Defense data from space-based, earthward looking infrared sensors. Between 1975 and 1992, these sensors detected 136 meteoroid fireballs with observed energies between 1 and 10 kilotons (kt) (ref. 23). These objects are small and do not normally survive entry through the atmosphere to reach Earth, but they create upper atmospheric explosions that can be detected. These observations provide important information for bounding the number of asteroids larger than a certain size. The population estimates are based on observational data, so a potential for biases exists in the impact flux for any given size and type of object.

NEOs are removed from the solar system on timescales of 10 to 100 million years (ref. 3). This is accomplished via collisions and gravitational interactions with the planets. As mentioned earlier, the NEA population is constantly being replenished by main belt asteroids perturbed into Earth-approaching orbits. The collision of main belt asteroids and the gravitational influence of Jupiter can send new asteroids toward Earth. Additionally, some NEAs may be extinct comet nuclei so their populations may be altered by several mechanisms.

The flux of LPCs may also vary over time due to tidal forces associated with periodic movement of the solar system through the galactic disk and impulsive perturbations to the Oort cloud. The formation of large impact craters during the last 220 million years appears to have 4 apparent pulses at approximately 2, 35, 65, and 99 million years ago, with a best-fit period of 32 million years. Although the possibility of a periodic astronomical disturbance mechanism exists, the current hypotheses regarding possible sources are either improbable or only cause a weak periodic modulation of the comet flux (ref. 24). These comet showers are most likely random events resulting from the close passage of stars through the Oort cloud. Two significant Earth cratering events, the 100-km crater in Popigai (Siberia) and the 90-km Chesapeake Bay crater (Virginia), occurred nearly synchronously 35.6 million years ago. Analysis of the flux of extraterrestrial helium-3 in pelagic limestone deposits indicates that both impacts likely occurred during a short-lived burst of LPCs in the late Eocene epoch. Helium-3 is an isotope that rarely occurs on Earth but is common in interplanetary dust particles. Although several mechanisms could be responsible for the observed increases in the helium-3 flux, the most likely explanation is that they were the result of a comet shower from an isolated impulsive Oort cloud perturbation (ref. 25). It is likely that comet showers in the last 100 million years have been no more intense than 30 times the combined background flux of comet nuclei and asteroids. Although the flux of LPCs is not expected to change significantly in the foreseeable future, a shower of LPCs could result in the most challenging protection effort imaginable. Large

numbers of LPCs entering the inner solar system for the first time each year would require an extremely coordinated detection effort to determine if any objects were a threat. Not only would the probability of an impact during the first perihelial passage be greatly increased, but the threat of impact from smaller cometary fragments would be a problem. The ability to accurately determine the orbits of LPCs would not only assist with the threat of direct collision, but would also permit the more accurate tracking of comet fragments.

The fact that the population and flux of NEOs are not constants emphasizes the need for a continuous detection capability. It is not sufficient to undertake a campaign to search down to a limiting size and then stop observing. This need for continuous monitoring is absolutely critical for LPCs, where we will likely only have one opportunity to identify an impactor.

Unknown Objects and Orbit Classes

Due to limitations in current Earth-based NEO search campaigns, certain classes of minor planets could remain undiscovered and result in an impact without prior warning. Obviously, NEOs too faint (small and/or low albedo) to be observed with ground-based telescopes would be missed by an Earth-based detection system. Additionally, asteroids in fairly long periods or resonant orbits could be missed during a finite search period. One class of hypothesized asteroids could be similar to Atens or the unproven IEAs. IEAs would have aphelia that just reach to the Earth's orbit. Presently, their aphelia could coincide with Earth's aphelion. Therefore, this class of NEOs would not be currently visible in the night sky, and search strategies based on searching near solar opposition would be incapable of detecting them. Hence, we currently have no data regarding the population of this theoretical orbital class. As an IEA's line of apsides precess with respect to Earth's orbit, its orbit could become Earth-crossing. By the time an impacting asteroid in this orbital class became observable, it would allow for little, if any, warning time. An inadequate space-based system could suffer from similar problems as Earth-based systems, but a properly deployed space-based system could more easily identify this class of objects. Two possible approaches for detecting this orbital class would be to make observations near the Sun's observed position, or from an orbit significantly interior to that of the Earth. Placing the system at the Earth-Sun L1 Lagrange point would permit constant monitoring, but placing the system in a heliocentric orbit different than the Earth's orbit would only allow periodic coverage due to the differences in the orbital periods.

Although it is not necessarily fair to use hypothetical objects to assist in the justification of an NEO detection system, astronomy is a field with numerous examples of how the discovery of previously unknown objects has altered long-standing perceptions. It is very likely that as NEO detection systems significantly improve, the increased capability of these systems will identify new classes of asteroids and comets. One recent discovery highlights this point. In 1997, Asteroid 3753 Cruithne (1986TO) was determined to be a dynamical companion of Earth following a complex "horseshoe" orbit when viewed in a heliocentric reference frame corotating with the Earth (ref. 26). When viewed from this corotating vantage point, the asteroid traces out a kidney bean-shaped orbit once each year with the full cycle of the overlapping horseshoe completed in approximately 375 years. Its high inclination (almost 20°) and eccentricity (0.51) make it an unlikely candidate for being a dynamical companion of the Earth. Although 3753 Cruithne neither orbits the Earth nor follows Earth's orbit around the Sun, it is Earth's only known natural companion other than the Moon. Repeated close approaches with the Earth result in gravitational perturbations that increase the object's period slightly. The object's distance from the Earth varies from approximately 0.1 to 2.5 au. Although horseshoe orbits are a well-known feature of the gravitational three-body problem, 3753 Cruithne's orbit has characteristics never before observed or anticipated using theory or computer simulations. The intricate horseshoe orbit includes a spiraling

motion, a significant inclination relative to the ecliptic, and an overlap at the end of the horseshoe. Prior to 1997, no other near-Earth asteroid had been discovered in a horseshoe orbit. Although this object had been originally discovered in 1986, it was never sufficiently tracked to determine its unprecedented orbit. The object has an absolute magnitude of 15.1 and an estimated diameter of 5 km. Recently, two additional asteroids of unknown size, 1998 UP1 and 2000 PH5, have been determined to be in similar orbital relationships with Earth. In that 3753 Cruithne's orbit has a fairly high inclination, there is no danger of collision with the Earth when it reaches its closest approach of approximately 0.1 au. However, the discovery of such an asteroid raises the question of how many additional undetected asteroid companions exist that could be impact threats. Understanding the characteristics of 3753 Cruithne's orbit and other possible orbital classes provides tremendous benefit in developing and establishing NEO detection strategies.

The Impact Hazard

It is generally believed by scientists that an impact with an asteroid or comet between 1 and 2 km in diameter would have the ability to disturb Earth's climate on a global scale. Although very infrequent, these impacts could result in explosions with the energy equivalent of a million megatons of TNT. The uncertainty regarding the precise threshold diameter is significant, but it is certain that destruction and loss of life unprecedented in human history would result. The predicted and observed effects of Earth impacts have been documented extensively in various reports, such as "The Spaceguard Survey" (ref. 3), and books, such as *Hazards Due to Comets and Asteroids* (ref. 4) and *Cosmic Catastrophes* (ref. 5). Subsequent sections provide a brief summary describing the effects of Earth impacts and emphasize the hazards over the entire range of threat.

Various statistical analyses have been performed to estimate the probability of death or destruction from the impact of a comet or asteroid of a given size, including the recent computer modeling by John S. Lewis in *Comet and Asteroid Impacts on a Populated Earth: Computer Modeling* (ref. 11). The initial goal of CAPS is to identify what is required to protect against LPCs capable of global devastation and smaller impactors capable of regional hazards. Defending against the smallest impactors (≈ 10 -m diameter) capable of severe local destruction is likely to prove an insurmountable task in the foreseeable future, from both technological and economic standpoints. However, if a viable approach for cataloging smaller NEOs (50- to 100-m diameter) can be developed, it is possible that the approach could be applicable to even smaller objects. A general outline of the comet and asteroid impact hazard is provided subsequently in ascending order of destructive power, followed by a few examples of the indirect hazards that could accompany even a relatively small impact event. It is important to realize that the kinetic energy released during an impact is proportional to the mass of the impacting NEO (which is proportional to the cube of the object's diameter) and the square of its relative velocity. The explosive yield of an impact is usually expressed in megatons (Mt) or kilotons (kt), where $1 \text{ Mt} = 4.184 \times 10^{15}$ joules of energy. As mentioned previously, NEO densities can vary by a factor of 40 when comparing metallic asteroids with the lowest density assumed for comet nuclei. The mean velocity of NEAs relative to the Earth is approximately 21 km/s while LPCs have higher velocities with a mean of approximately 55 km/s (ref. 13).

Many estimates have been made in an attempt to quantify the probable fatalities resulting from the impact of an NEO of a particular size, and most have focused on the asteroid part of the impact problem. Figure 3 shows the average fatalities estimated to occur from an asteroid impact event of a given diameter (adapted in ref. 13 and originally from ref. 3). Our knowledge of the population of potential impactors is not complete and is subject to change. Although the efforts to discover NEAs greater than 1 km in

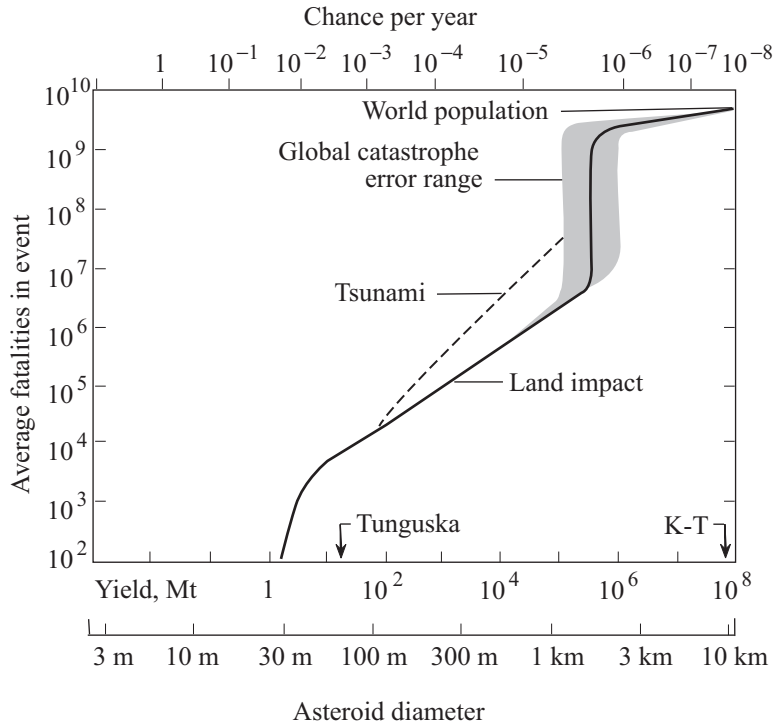


Figure 3. Estimate of averaged fatalities for an asteroid impact versus diameter, explosive yield, and probability per year.

diameter are resulting in many objects smaller than 1 km being detected, only a small percentage of all NEAs have been discovered and cataloged to date. Additionally, the accuracy of the estimated orbits for these known objects varies significantly with the number and quality of the observations. It is the undiscovered asteroids and comets that should warrant much more concern, considering that the likely warning time for one of these objects on an impact trajectory might be as short as a few seconds.

Local Threats

Very small meteorites (stone size) survive entry through Earth’s atmosphere and reach the ground on a fairly regular basis. Contrary to popular belief that no person has ever been killed by a meteorite, historical events indicate death may have resulted from an impact. A large number of historical records appear to describe terrestrial impacts or specifically document their occurrences. A table summarizing the deaths, injuries, and damage from these events is provided in reference 11. On average, over the past 20 years one documented case per year is provided where a small meteorite either hit something or nearly hit a person. Considering that much of the Earth’s surface is unpopulated, these meteorite falls are quite frequent but only capable of damage on an extremely local scale.

Impacts from meteorites approximately 10 m in diameter can result in significant explosions (≈ 10 - to 100-kt yield) that are capable of destroying a town or small city. The Earth is impacted annually by bodies this size, but most are so fragile that they detonate in the upper atmosphere. The population of NEOs of this size is believed to be on the order of 200 million, and the effort required to identify, catalog, and defend against these objects is difficult to comprehend (ref. 11).

Regional Hazards

Objects with diameters larger than a few tens of meters are capable of releasing enormous amounts of destructive energy (multimegaton-class explosions). Fortunately, impacts with objects of sufficient size and composition to survive the heating and stresses imposed during atmospheric entry are much less common. However, they have occurred in the past and will occur in the future. Impacts with objects larger than 50 m, which is generally taken as the limit for atmospheric breakup, occur on the order of a century or hundreds of years. The 50000-year-old Barringer Meteorite Crater (also known as Meteor Crater) in Arizona provides an enduring reminder of this fact. This crater is about 1.2 km in diameter and 175 m deep and was created by a nickel-iron meteorite with a diameter of approximately 45 m. The impact resulted in an explosion with a yield of around 20 Mt (ref. 27). NEAs between 50 and 100 m in diameter are estimated to number in the millions (see fig. 1). Small LPCs (approximately 100 m or less) are much more common than the 1-km class bodies and possibly 10000 times more abundant. These objects may represent a very significant hazard with the mean interval between lethal impacts estimated to be approximately 600 years (ref. 11). Although damage from an object of this size would still be limited on a global scale, an impact near an urban area or coastline could result in considerable loss of life, extensive damage, and economic disruption.

It is important to realize that an object does not need to reach the ground to be destructive. The Earth's atmosphere can effectively protect us from even megaton-class explosions, which disperse and are vaporized before reaching the lower atmosphere. However, an airburst that results in a 276-hPa (4-psi) overpressure at the surface is capable of producing winds of approximately 70 m/s, or 157 mph (ref. 28). These wind velocities are comparable with those of a category 5 catastrophic hurricane (Saffir-Simpson hurricane scale) and can result in massive destruction on the surface. Stony objects ≈ 30 m and LPCs ≈ 60 m in diameter can penetrate the Earth's atmosphere to an altitude that can create a 4-psi shock at the surface (ref. 28). The Tunguska event of 1908, believed to be an aerial explosion of a stony asteroid or comet fragment approximately 50 m in diameter, released up to 20 Mt of energy, the equivalent of 1600 Hiroshima-size bombs, and devastated 2000 km² of Siberian forest. Figure 4 shows the effect that the impact of one of these smaller NEOs could have (adapted from ref. 3). The figure shows the size of the blast field in the Siberian forest compared with Washington, DC. Had the arrival of this object been delayed several hours, it could have impacted in densely populated Europe and had much greater consequences than simply the diminished blast wave that propagated across England. It is not a strict requirement for a comet or asteroid to actually reach the surface to cause extensive destruction, and this event testifies to that fact.

Global Hazard

The size of impactor that would produce deadly and devastating effects of a global scale is not known with great certainty. Many factors, such as where the NEO hits, its relative velocity, and its composition, all contribute to the lethality of the impact. An explosion that releases energy approaching a million megatons of TNT is believed to be capable of producing a global catastrophe. This energy release is achievable with an impact by a comet or asteroid that is between 1 and 2 km in diameter (ref. 3). Even extrapolations based on global nuclear war, our best understood impact analogy, are difficult to quantify when explosions of this magnitude are contemplated. What is known is that the fossil record shows periods of global mass extinctions that have been definitely linked to impact events. The most famous is the Cretaceous-Tertiary (K-T) extinction event 65 million years ago, which resulted from the impact of a 10-km asteroid or comet and created the 170-km Chicxulub crater near the current Yucatan Peninsula. This impact is best known for wiping out the dinosaurs, but it also triggered the extinction of approximately 75 percent of all species on Earth. The massive loss of life was likely caused by a triple punch of

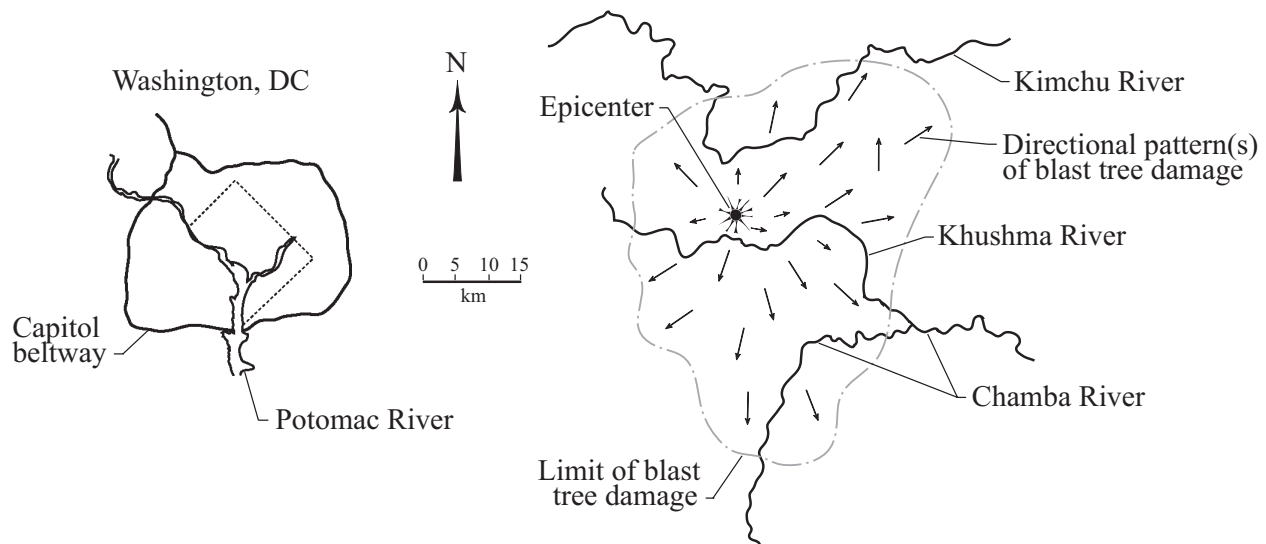


Figure 4. Tunguska impact blast field comparison.

global firestorms, mega-tsunamis, and extensive long-term environmental changes. The shock waves created by such an impact would have triggered massive earthquake and volcanic activity, which would have contributed to the dust and toxic gases released into the atmosphere. In many ways, it is difficult to understand how any species could have survived such conditions. Somehow life on Earth did continue, and this extinction event may very well have allowed for the existence of the human race. Human death and destruction of enormous proportions could be expected from an impact capable of initiating a global catastrophe. Figure 3 shows that a significant fraction of the world's population could die from the direct and indirect effects of a global impact catastrophe.

The Earth is covered with large impact craters. A 1-km-diameter impactor will produce a crater approximately 10 to 15 km in diameter (ref. 3). Currently, there are about 70 known craters larger than 10 km in size, with the largest being the 300-km scar in Vredefort, South Africa (ref. 29). Many more smaller craters have also been identified, but erosion can more easily erase the traces of smaller impact events. Additionally, because approximately 71 percent of the Earth's surface is covered with water, no visible record is available for most impacts.

Indirect Hazards

The enormous heat and acoustical energy directly released from an impact produces destruction that is fairly localized. Depending on the size and location of the impact, the direct effects of an impact may be inconsequential compared with the secondary destruction that could result. Large impacts are expected to affect Earth and its inhabitants on a global scale, but a majority of the damage from smaller impacts may be particularly disproportionate. Outlined in the following sections are some of the possible indirect physical effects of an NEO impact. Additionally, a brief discussion is presented regarding the possibility of lunar surface impacts damaging Earth-orbiting satellites and infrastructure. This is by no means a complete accounting and does not begin to address the very real and important social, economic, and political consequences. The main goal of highlighting some of these secondary destruction mechanisms is to emphasize the breadth of possible effects that need to be considered as part of the impact hazard problem. Because we have not experienced this kind of calamity in modern history, it is possible that the secondary effects could be much more far reaching than we currently realize.

Tsunamis

Tsunamis resulting from the ocean impact of an asteroid or comet may represent the most significant aspect of the impact hazard because most of the Earth's surface is covered with water and a disproportionate number of people inhabit coastal regions. The word tsunami comes from a combination of the Japanese words for harbor (tsu) and wave (nami), because harbors amplify the wave height that reaches the shore. Tsunamis have been recorded for thousands of years and are typically caused by underwater earthquakes, volcanic activity, and landslides. Significant ocean impacts represent a regional hazard that could extend into the realm of global consequences because they can potentially propagate over great distances and wreak havoc on distance shorelines. The United States is particularly vulnerable with both coastlines being highly developed and heavily populated. Additionally, a tsunami can propagate outward from the impact sight at speeds of 750 k/hr (450 mph) and can be barely perceptible in the open ocean, thus making early warning extremely difficult (ref. 30).

There is a great deal of uncertainty about the effects of impact induced tsunamis in the literature. The two most significant issues concern calculating the initial size of the wave and how the wave dissipates as it travels from the impact site. The energy from an explosion decreases as the square of the distance from the impact increases, but the energy from a radiating coherent ocean wave decreases in proportion to the distance. Some analyses indicate that the impact ocean cavity diameter must be several times wider than the ocean depth at the impact site in order to produce a coherent tsunami capable of traveling great distances. The ratio of cavity diameter to impactor diameter ranges from approximately 40 for a 50-m-diameter impactor to approximately 20 for a 1-km object, assuming an impact velocity of 20 km/s and a density of 3000 kg/m³ (ref. 31). The generated maximum wave heights are highly dependent on the theory and assumptions incorporated in models, and the run-up height (vertical height of the tsunami above sea level at its furthest point) is highly dependent on local topography and the wave's history. Although most simulations confirm that an ocean impact of a 1-km asteroid would generate enormous tsunamis, there is not good agreement on the effect of smaller impacts. Even if the tsunami resulting from a smaller ocean impact dissipates rapidly, an impact near the coast could create devastating local tsunamis, particularly from an LPC with a much higher impact velocity. The run-up height as the wave reaches the coast can be more than an order of magnitude greater than the deepwater wave height, so a 5-m wave could result in a very destructive tsunami over 50 m high (over 15 stories).

Earthquakes and Volcanic Eruptions

Objects of sufficient size and strength to reach the ground are also capable of producing significant seismic disturbances. Even the Tunguska event, which likely did not reach the surface, produced a magnitude 5 earthquake (ref. 28). Although the damage done by an earthquake is highly dependent on the terrain through which the disturbance propagates, it could exceed the blast wave damage. Large impactors, like the K-T event, could conceivably trigger massive earthquakes, which in turn could initiate volcanic eruptions. The combination of these natural disasters could result in much greater global devastation than that which could be attributed directly to the impact explosion.

Misinterpreted Nuclear Strike

Although small impactors (10- to 100-kt yield) would likely cause damage only on a local scale, the possibility exists that the impact could be misinterpreted as an attack using nuclear weapons. Other than the lack of radiation, an impact event would closely resemble a nuclear explosion. If this natural disaster occurred over an area where tense or hostile geopolitical conditions were present, along with presence of nuclear weapons, a retaliatory nuclear exchange could result. Although the probability of such an event is fairly low, it emphasizes that it is not the impact event itself that might be of greatest concern.

Lunar Impacts

The Earth has an atmosphere to effectively protect its surface from smaller impacts, but the Moon lacks such a buffer. Although the Moon is much smaller than the Earth, impacts still occur regularly on the lunar surface. Due to the Moon's low escape velocity (2.376 km/s) and lack of atmosphere, some lunar impact ejecta may leave the Moon's gravitational influence and be expelled into a solar orbit, or captured by the Earth's gravitational field.

The Antarctic Search for Meteorites (ANSMET) Program, which is funded by the Office of Polar Programs of the National Science Foundation, has recovered thousands of meteorites since 1976. An important discovery of ANSMET was that some meteorites were not derived from asteroids, but rather from the lunar and Martian surfaces. Twenty years ago, it was widely believed that any material ejected from a planet-sized body would be vaporized or altered beyond recognition. This paradigm was completely overturned by the discovery of ANSMET meteorite ALH81005, an anorthositic breccia so similar to Apollo lunar highlands samples that all investigators agreed it had to have come from the Earth's Moon. Since that time, ANSMET has recovered six more lunar specimens (ref. 32).

The discovery of lunar meteorites in Antarctica certainly proves that a delivery mechanism exists, but many important questions remain: (1) what size and composition of an impactor is required, (2) how much debris would be captured by the Earth and in what orbits, and (3) how long would an increased debris flux persist. If a significant amount of debris were to be ejected from a lunar impact, it is possible that the resulting debris field could present a significant hazard for satellites orbiting the Earth. Research and analysis in this area of the impact hazard are lacking and require some level of analysis to determine the credibility of this hypothesized hazard. The primary focus for CAPS is Earth defense. However, if lunar impacts are a credible hazard to Earth-orbiting satellites and future in-space infrastructure and lunar outposts, it may be desirable to have at least some CAPS assets located in cislunar space.

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