Available online at www.sciencedirect.com

Earth and Planetary Science Letters 222 (2004) 1–15

www.elsevier.com/locate/epsl

Frontiers

The hazard of near-Earth asteroid impacts on earth

Clark R. Chapman*

Southwest Research Institute, Suite 400, 1050 Walnut St., Boulder CO 80302, USA

Received 15 December 2003; received in revised form 14 February 2004; accepted 4 March 2004

Abstract

Near-Earth asteroids (NEAs) have struck the Earth throughout its existence. During epochs when life was gaining a foothold ~ 4 Ga, the impact rate was thousands of times what it is today. Even during the Phanerozoic, the numbers of NEAs guarantee that there were other impacts, possibly larger than the Chicxulub event, which was responsible for the Cretaceous–Tertiary extinctions. Astronomers have found over 2500 NEAs of all sizes, including well over half of the estimated 1100 NEAs >1 km diameter. NEAs are mostly collisional fragments from the inner half of the asteroid belt and range in composition from porous, carbonaceous-chondrite-like to metallic. Nearly one-fifth of them have satellites or are double bodies. When the international telescopic Spaceguard Survey, which has a goal of discovering 90% of NEAs >1 km diameter, is completed, perhaps as early as 2008, nearly half of the remaining impact hazard will be from land or ocean impacts by bodies 70–600 m diameter. (Comets are expected to contribute only about 1% of the total risk.) The consequences of impacts for civilization are potentially enormous, but impacts are so rare that worldwide mortality from impacts will have dropped to only about 150 per year (averaged over very long durations) after the Spaceguard goal has, presumably, ruled out near-term impacts by 90% of the most dangerous ones; that is, in the mid-range between very serious causes of death (disease, auto accidents) and minor but frightening ones (like shark attacks). Differences in perception concerning this rather newly recognized hazard dominate evaluation of its significance. The most likely type of impact events we face are hyped or misinterpreted predicted impacts or near-misses involving small NEAs.

Keywords: asteroids; near-Earth; craters; impact; impact hazard; mass extinctions

1. Why are near-Earth asteroids important?

Although interplanetary space is very empty by human standards, Earth is in a ‘‘cosmic shooting gallery’’, as anyone looking up into clear, dark skies can witness: several meteors can be seen flashing across the heavens per hour—cometary and asteroidal dust grains disintegrating in the upper atmosphere. They are accompanied by a size spectrum [1] of ever larger, increasingly less common, bodies up to at least several tens of kilometers in diameter. Although occasional recovered meteorites are from the Moon and Mars (presumably other bodies are also represented by exotic celestial debris), the vast majority of near-Earth objects (NEOs) are asteroids or comets, or their smaller fragments or disintegration products

---

* Tel.: +1-303-546-9670; fax: +1-303-546-9687.

E-mail address: cchapman@boulder.swri.edu (C.R. Chapman).

0012-821X/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2004.03.004

called "meteoroids" (which are called "meteors" while in the atmosphere and "meteorites" when on the ground).

There is scientific consensus that the planets grew, in part, from the accumulation of much smaller objects called "planetesimals" [2]. When the epoch of planetary accretion was largely over, numerous planetesimals remained in orbit around the Sun. By convention, those in and inside of Jupiter's orbit are called "asteroids" and those farther out "comets", although each group is subdivided into specific orbital classes; comets generally have more volatiles than the more rocky or metallic asteroids, although primitive asteroids could be volatile-rich at depth. The dominant asteroid reservoirs are in a large torus called the main asteroid belt and in two groups of "Trojans" averaging 60° ahead of and behind Jupiter in its orbit. The chief known comet reservoirs are the Kuiper Belt and associated scattered disk (beyond Neptune's orbit) and the much more distant spherical halo of comets, called the "Oort Cloud".

Comets, asteroids and meteoroids slowly leak from these reservoirs, generally due to chaotic dynamics near planetary resonances (distances from the Sun where a small body has an orbital period that is a simple fraction of the orbital period of a planet), facilitated by collisions and other minor orbital perturbations (e.g., the Yarkovsky Effect, which is a force on a small body due to asymmetric re-radiation of absorbed sunlight on the warmer "afternoon" side of a spinning asteroid [3]). Some dislodged bodies soon arrive in the terrestrial planet zone, becoming NEOs. Comets rapidly disintegrate as their volatiles are exposed to the Sun. Near-Earth asteroids (NEAs), especially those with orbital aphelia (farthest point from the Sun of an elliptical orbit) remaining out in the asteroid belt, continue to suffer occasional collisional fragmentation. NEAs are in comparatively transient orbits, typically encountering the Sun, or more unusually a terrestrial body, or being ejected from the solar system on hyperbolic orbits, on timescales of a few million years; they are continually being replenished from their reservoirs. There may be roughly equal numbers of comets and NEAs among NEOs larger than several kilometers in diameter, and comets and asteroids may be roughly equal sources of meteor-producing interplanetary dust particles (see [4] for a critical evaluation). But throughout the enormous size range that yields recovered meteorites up to NEAs that threaten civilization, the asteroid belt's inner half is the overwhelmingly dominant reservoir [5]. Therefore, comets, which are estimated to contribute only 1% of the total risk [6], are not emphasized in this review.

This impact environment has existed for the past 3.5 Gyr, according to the terrestrial crater record as well as the lunar chronology derived from associating datable lunar samples with cratered units on the Moon. Generally, the average Earth/Moon impact rate has varied little more than a factor of two during that time, although brief spikes in cratering rate (e.g., by a "comet shower") must have happened (e.g., [7]). Prior to 3.8 Ga, the impact environment was very different. About a dozen huge lunar basins formed from the time of Nectaris (dated at 3.90–3.92 Ga, although possibly as old as 4.1 Ga) until the last one (Orientale) at ~ 3.82 Ga, implying an abrupt decay and cessation of whatever source of objects produced that Late Heavy Bombardment (LHB). (About twice as many observable basins, and presumably others now erased, formed before Nectaris, but it is controversial whether there was a lull in impact rate before a "cataclysm" [8] or instead a generally high bombardment rate persisted since lunar crustal solidification, followed by a rapid decline from ~ 3.9 to ~ 3.82 Ga [9].) In any case, there can be no remnant today of any such short-lived population and, presumably, other now-decayed populations of NEOs may have existed during the first aeon of Earth's existence, due to rearrangements or late formations of planets, which could have stirred up small-body populations [10] or due to tidal or collision break-ups of an Earth-approaching body. Whatever else might have happened, the observed lunar LHB alone would have subjected the Earth, for ~ 50 Myr, to a bombardment rate *thousands* of times that of today, with pivotal implications for the origin and early evolution of life.

Even at the low modern impact rate, impacts happen often enough to affect profoundly the evolution of life (e.g., the Chicxulub impact 65 Myr ago, dominantly responsible for the K–T mass extinction). Because of the comparatively short timespan of human lives and even of civilization, the importance of impacts as a modern hazard is debatable. Below, I argue that the impact hazard is significant in the context of other man-made and natural hazards that society takes seriously, although impacts are obviously far less important than the chief issues affecting our lives. Of course, NEAs have other vital virtues. They and their accompanying meteoroids bring samples from far-flung locations in the solar system to terrestrial laboratories for analysis and they leave traces in ancient impact craters and basins on the Earth and the Moon, permitting broad insights into primordial and recent processes operating in the inner solar system. In the future, NEAs may provide way-stations for astronauts en route to Mars or elsewhere; they also may provide raw materials for utilization in space.

2. Historical recognition of the impact hazard

Ideas that comets might be dangerous date back at least to the 17th century, when Edmond Halley is said to have addressed the Royal Society and speculated that the Caspian Sea might be an impact scar [11]. The physical nature of comets remained poorly understood, however, until the mid-20th century. The first NEA (Eros) was not discovered until 1898 and the first NEA that actually crosses Earth's orbit (Apollo) was not found until 1932. By the 1940s, three Earth-crossing NEAs had been found, their basic rocky nature and relationship to meteorites was appreciated, and it was possible to estimate, albeit crudely, their impact rate [12]. The actual damage that a NEA impact might cause on Earth was concretely described by Baldwin [13], a leading advocate for the impact origin of lunar craters. Later, Öpik [14] (who understood both orbital dynamics and impact physics) proposed that NEA impacts might account for mass extinctions in the Earth's paleontological record. Around the same time, Shoemaker [15] firmly established the impact origin of Meteor Crater in Arizona.

Despite the prescience of these early planetary science pioneers, it was not only a cultural but a scientific shock when Mariner 4's first photographs of the Martian surface revealed it to be covered by craters [16]; a decade later, Mariner 10 found the same on Mercury. Although some fictional accounts of impact catastrophes were published in the 1970s, it was not until 1980/1981 that two events crystallized in the minds of many scientists both the dramatic effects on Earth history and the modern threat posed by impacts. First was publication [17] of the Alvarez et al.'s hypothesis for the K–T boundary and second was a Snowmass, CO, NASA-sponsored workshop entitled "Collision of Asteroids and Comets with the Earth: Physical and Human Consequences", chaired by Eugene Shoemaker. In 1979 and 1980, the Voyagers first encountered Jupiter and Saturn, demonstrating that cratered surfaces extended from Mercury at least out through the giant planets' satellite systems. After a quarter century of space exploration, the particulars of a few NEAs, a few craters on the Earth, and the familiar cratered lunar surface had been linked and generalized to the solar system as a whole. Like any other planet, Earth's surface certainly has been bombarded over the aeons by the same cosmic projectiles.

Even after discovery of the Chicxulub impact structure in Mexico and its temporal simultaneity with the Cretaceous–Tertiary (K–T) boundary and mass extinctions [18], it has taken some earth scientists a while to recognize and accept the statistical inevitability that Earth is struck by asteroids and comets. Each impact, occurring on timescales of tens to hundreds of Myr, liberates tens of millions to billions of megatons (Mt, TNT-equivalent) of energy into the fragile ecosphere, which *must* have had dramatic consequences every time. A few researchers still consider the Chicxulub impact to be only one of several contributing factors to the K–T extinctions (e.g., [19]) and direct evidence firmly linking other mass extinctions to impacts is so far either more equivocal than for the K–T, or altogether lacking. Some geoscientists still think of asteroid impacts as ad hoc explanations for paleontological changes and they resist the logic that earlier, even greater impact catastrophes surely occurred. If the great mass extinctions are not attributed to impacts (e.g., explained instead by episodes of volcanism or sea regressions), one must ask how the huge impacts that must have occurred failed to leave dramatic evidence in the fossil record.

A new thread in public awareness of the modern impact hazard developed in the late 1980s when advanced telescopic search techniques identified NEAs passing by the Earth at distances comparable to that of the Moon. Such "near misses" made headlines and also inspired an aerospace organization and the U.S. Congress to mount a political mandate that NASA examine the impact threat and methods for mitigating it. This led to the definition [20] (and redefinition [21] after the dramatic 1994 impacts of Comet Shoemaker-Levy 9 fragments into Jupiter) of the Spaceguard Survey, which NASA formally endorsed in 1998 and committed to discovering 90% of NEAs >1 km diameter within one decade. (Spaceguard is a network of professional observatories, dominated by two 1-m aperture telescopes near Socorro, NM, operated by MIT Lincoln Laboratory (LINEAR), plus amateur and professional observers who follow up the discoveries in order to refine knowledge of NEA orbits.) As larger NEAs are discovered and their orbital paths extrapolated ahead one century are found to pose zero danger of impact, then we are safer: only the remaining, undiscovered asteroids pose a threat. In 2000, the British government established a Task Force on Potentially Hazardous NEOs, which led to a report [11] and the establishment of the first governmental organization solely devoted to the impact hazard, the NEO Information Centre. Most recently, as the Spaceguard Survey approaches its goal, NASA tasked a new group (NEO Science Definition Team, SDT) to advise on possibilities of extending NEA searches down to smaller sizes; it reported [6] in August 2003.

Funding for research on the modern impact hazard has been minimal, so much of the thinking has taken place in the context of conferences and committee studies rather than comprehensive research programs; reports from these activities, some published as "grey literature", others in professional series, constitute the chief sources of information on the topic [6,11,20–26]. An extensive literature exists on the role of impacts in Earth's geological and paleontological history; the most recent compendium [27] is the fourth in a series of "Snowbird Conferences", which commenced in 1981 soon after the publication [17] of the Alvarez et al.'s hypothesis. The dynamical and physical properties of NEAs were recently reviewed in several chapters of "Asteroids III" [28].

3. Physical and dynamical properties of NEAs

NEAs are defined, somewhat arbitrarily, as asteroids whose perihelia (closest orbital distance to the Sun) are < 1.3 AU (1 AU = the mean distance of Earth from the Sun). About 20% of NEAs are currently in orbits that can approach the Earth's orbit to within < 0.05 AU; these are termed potentially hazardous objects (PHOs). In terms of their origin and physical nature, PHOs are no different from other NEAs; they just happen to come close enough to Earth at the present time so that close planetary encounters could conceivably perturb their orbits so as to permit an actual near-term collision, hence they warrant careful tracking. The Spaceguard search programs (chiefly LINEAR; Lowell Observatory's LONEOS in Flagstaff, AZ; Jet Propulsion Laboratory's Near-Earth Asteroid Tracking [NEAT] in Maui and on Mt. Palomar, CA; and Spacewatch on Kitt Peak, AZ [29]) continue to discover a new NEA every few days. As of February 2004, nearly 2670 NEAs were known (of which nearly 600 were PHOs), which compares with only 18 when the 1981 Snowmass conference met. The census is believed to be complete for NEAs >3 km diameter. The estimated number of NEAs >1 km in diameter (the size for which NASA established Spaceguard's 90% completeness goal by 2008) is ~ 1100 ± 200 [6], of which about 55% had been found by early 2004. As shown in Fig. 1, there is a roughly power-law increase in numbers of NEAs with decreasing size (differential power law exponent = – 3.35) down to the billion-or-so NEAs ≥ 4 m diameter; 4 m constitutes the annual impact event on Earth with an energy ~ 5 kt [30]. Frequencies are least secure, with the uncertainties approaching an order of magnitude, for NEAs too rare to be witnessed as bolides (brilliant meteors) but too small to be readily discovered telescopically, e.g., ~ 10–200 m diameter. This includes objects of the size (~ 50 m) that produced the dramatic 15 Mt Tunguska lower atmospheric explosion in Siberia as recently as 1908. The expected frequency of Tunguskas is less than once per thousand years; it is odd that the last one was so recent. An alternative possibility is that the destruction of thousands of square kilometers of forest was accomplished by a blast much less energetic than 15 Mt, due to a more common, smaller object (see appendix 4 in [6]).

The observed distribution of NEO orbits (characterized by semi-major axis *a*, eccentricity *e* and inclination *i*), after correction for observational biases in discovery, has been modeled in terms of source regions for these bodies within and beyond the aster-

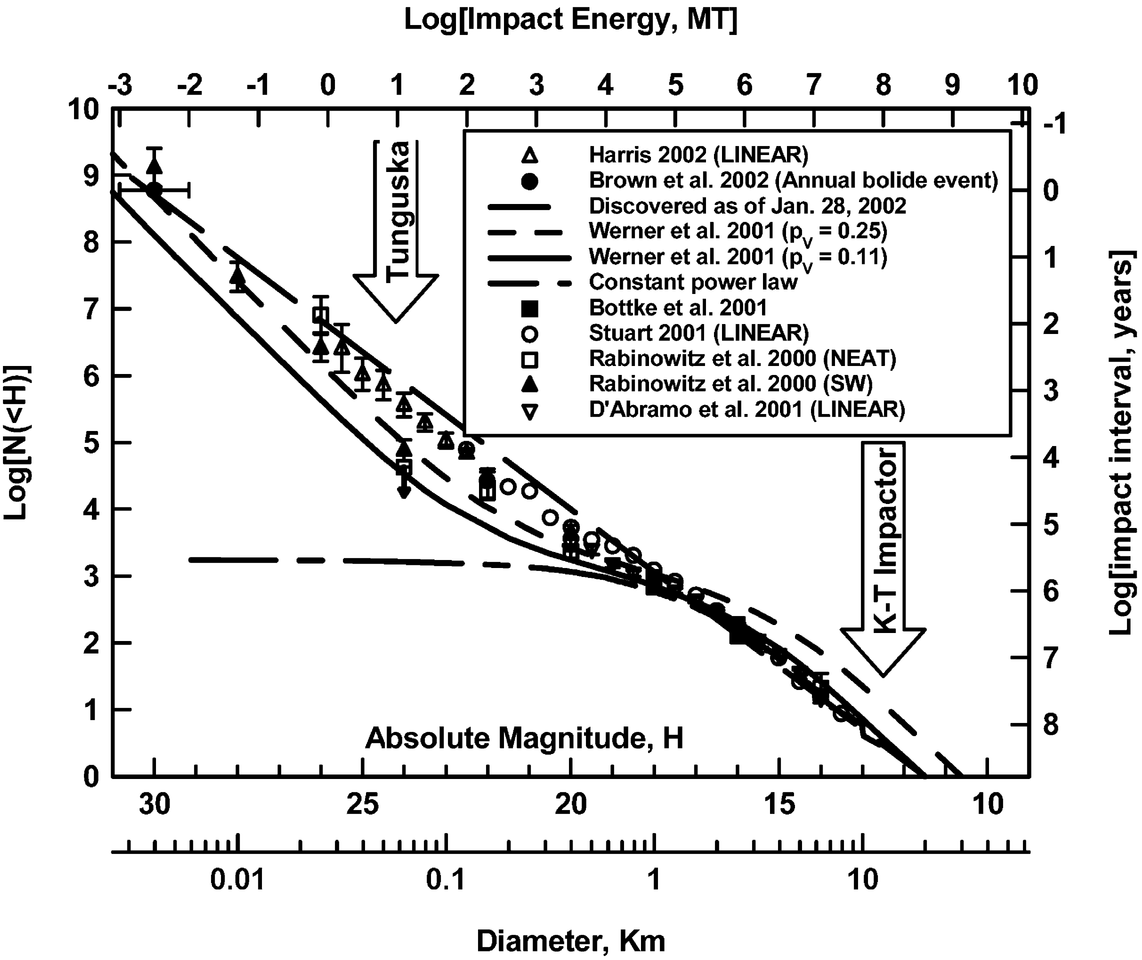


Fig. 1. Size distribution for cumulative number N of NEAs larger than a particular size, estimated in several ways, chiefly from telescopic search programs [6]. H is the stellar magnitude of an asteroid at 1 AU distance from both the Sun and the Earth (courtesy of A. Harris).

oid belt [5]. The result is that 37 ± 8% are derived from the ν_6 secular resonance (involving the precession rate of Saturn's orbit), which shapes the inner edge of the asteroid torus; 23 ± 9% come from the 3:1 resonance with Jupiter (where an asteroid orbits the Sun three times during 1 Jovian year), near 2.5 AU. And 33 ± 3% are derived from hundreds of weaker resonances throughout the asteroid belt (weighted toward the inner belt), in which asteroids gradually drift (by the Yarkovsky Effect) into numerous, weak orbital commensurabilities (ratios of orbital periods) involving Mars, Jupiter, and Saturn; they then chaotically diffuse, often becoming Mars-crossing and finally, after a few tens of Myr, NEAs. Lastly, 6 ± 4% come from the short-period, Jupiter-family comet population (most of these are dormant, inactive comets, but a few have shown cometary activity). The contribution of long-period or new comets (e.g., from the Oort Cloud) to the threatening NEO population has recently [6] been assessed to be very low (~ 1%). Smaller, meteorite-sized bodies are also derived from the inner half of the asteroid belt, by similar dynamical mechanisms, although the Yarkovsky Effect is more important for smaller bodies, which accumulate much of their measured exposures to cosmic rays while moving within the asteroid belt rather than after they are in short-lived orbits that cross terrestrial planet orbits [31].

Mineralogical compositions of NEAs are assessed from absorption bands and other spectral signatures in reflected visible and near-infrared sunlight, after accounting for modification of the optical properties of surface minerals by the solar wind and micrometeoroid bombardment (“space weathering”, [32]). These spectra are summarized by a colorimetric taxonomy [33]; the majority are divided between low-albedo types inferred to resemble carbonaceous chondritic meteorites and moderate-albedo types inferred to resemble ordinary chondrites and other stony meteorites. There are some more exotic types, like nickel–iron (metallic) meteorites and basaltic achondrites. Such inferences have been augmented by radar reflection [34] (which is especially sensitive to metal content) and confirmed by more detailed close-up examination of the large NEA, Eros, by the NEAR Shoemaker spacecraft [35,36]. Briefly, NEA colors and spectra, and inferred compositions, appear in proportions similar to those for asteroids in the inner half of the asteroid belt [37], consistent with the calculations of main-belt source regions for NEAs summarized above. Thus, accounting for physical processes (like weeding out of weak materials by the Earth’s atmosphere), there appears to be compatibility between the compositions of inner-main-belt asteroids, NEAs and the meteorites that fall to Earth. No doubt, some NEAs are made of materials too weak to survive atmospheric passage; these might be dormant or dead comets or unevolved, primitive asteroids, and would be important targets for future investigations by spacecraft.

Our appreciation of the physical configurations of NEAs has undergone a revolution in the past decade. Although it was surmised several decades ago that some NEAs might be double (double craters are common on the Earth, and to varying degrees on the Moon, Venus and Mars [38,39]), only lately has it become clear that nearly 20% of NEAs have satellites or are double bodies. Definitive proof comes from radar delay-Doppler mapping [34] (see Fig. 2). But as adaptive optics and other modern techniques (including analysis of “eclipsing binary” lightcurves) discover common asteroid duplicity also among main-belt asteroids, Trojans, and Kuiper Belt objects [40], it is clear that small bodies must no longer be assumed to be simple objects. Several independent modes of formation are required to explain all of the double or satellite-containing small-body systems. But break-up by tidal disruption during close passage to a planet (as exemplified by Comet Shoemaker-Levy 9’s break-up in 1992 [41]) seems to be the chief process accounting for the high fraction of NEO satellites and double bodies [40,42]. Clearly, the potential for a threatening NEA to have one or more satellites may complicate a deflection operation.

Tidal break-up is facilitated by another geophysical attribute of NEAs. Long ago, it was proposed [43] that larger main-belt asteroids might be “rubble piles” because inter-asteroidal collisions sufficiently energetic to fragment them would be insufficient to launch the fragments onto separate heliocentric orbits; instead, the pieces would reaccumulate into a rubble pile. It is now clear, from advanced modelling, that

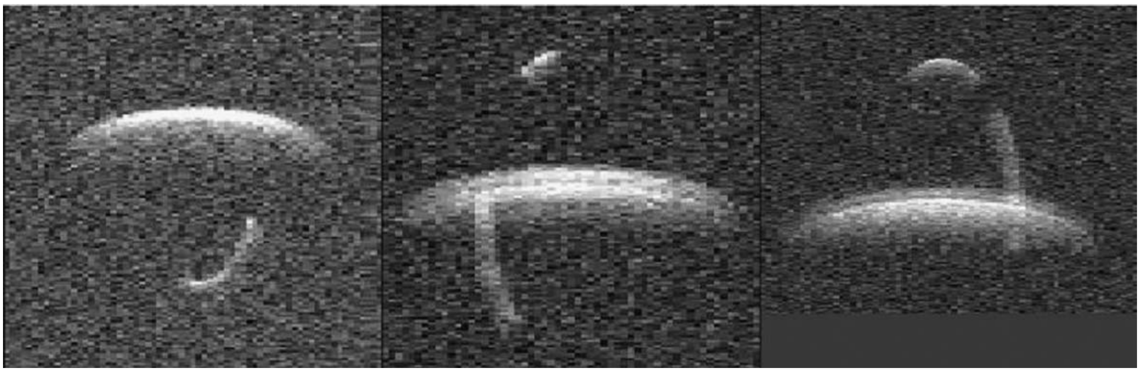


Fig. 2. Three radar delay-Doppler “images”, taken over several hours, of the binary asteroid 1999 KW4. The motion of the satellite is evident. Such radar presentations should not be interpreted literally as an image. Nevertheless, it is evident that a smaller object is orbiting the main body (courtesy of Steve Ostro).

most asteroids, including those of sub-kilometer sizes, should be rubble piles or at least battered and badly fractured [42]. Lightcurves confirm that most NEAs >200 m diameter are weak or cohesionless, while smaller ones are monolithic "rocks". No NEA larger than 200 m (nor any main-belt asteroid) rotates faster than ~ 2.2 h, at which a cohesionless, fragmental body would fly apart by centrifugal force. However, all of the nearly dozen NEAs < 200 m diameter with measured lightcurves have spin periods < 2 h, ranging downward to just a couple minutes [44]. Clearly, the latter are strong, monolithic rocks, while larger NEAs are rubble piles, susceptible to disaggregation by tidal forces during a close passage to Earth or another large planet. Numerical simulations [42] show that some such tidal encounters result in double bodies or a dominant body with one or more satellites.

Small-scale surface properties of small, nearly gravitationless NEAs, below the resolution of radar delay-Doppler mapping, remain conjectural, except for Eros, which was imaged down to cm-scales near NEAR Shoemaker's landing site. Pre-NEAR Shoemaker predictions about the small-scale structure of Eros' surface were dramatically incorrect [45,46]: unlike the lunar regolith, small (< 10 m diameter) craters are very rare on Eros, whereas boulders and rocks are extremely common. The character of surficial soils and regoliths on smaller NEAs is difficult to predict, but it is important, as all proposed deflection technologies (and mining operations) would have to interact with an NEA's surface, whether to attach a device, burrow into the object, or affect the surface remotely (e.g., by neutron bomb detonation or laser ablation). Probably, the surfaces of rapidly spinning small bodies < 200 m diameter are composed of hard rock (or metal), with only an extremely thin layer of surficial particulates (e.g., bound by electrostatic forces).

4. Past history of impacts on Earth

I now discuss briefly, from a planetary science perspective, the role of impacts on the geological and biological history of our planet. By considering the past, I set the stage for the modern impact hazard. Clearly, impacts dominated the early geological evolution of the surface of our planet until at least 3.8 Ga. It is almost equally incontrovertible that impacts have continued to interrupt more quiescent evolution of our planet's ecosphere well into the Cenozoic; such impacts will continue, even though other processes (e.g., plate tectonics, volcanism, weathering and erosion) are now more important than localized impacts in shaping geomorphology.

About 170 impact craters have been recognized on Earth [47], and perhaps double that number according to private, commercial records. They range from recent, small (tens to hundreds of meters in diameter) impact craters to multi-hundred km structures expressed in the geologic record although lacking crater-like morphology, which has been eroded away. Published ages for some of these impact scars are precise, but others are poorly characterized and often turn out to be erroneous (raising doubts about alleged periodicities in impact rates). The Earth's stratigraphic history is increasingly incomplete for older epochs, but the virtual total loss of datable rocks back toward 4 Ga is consistent with the inferences from the lunar LHB that Earth was pummeled by a couple lunar-basin-forming projectiles every Myr for 50–100 Myr, which would have boiled away any oceans and completely transformed the atmospheric, oceanic and crustal environment of the planet. Additionally, *thousands* of K–T boundary level events, one every 10,000 years, must have had profound repercussions.

The LHB would certainly have "frustrated" the origin of life on Earth [48,49]. Yet, some impacting projectiles might have contributed life-enhancing, volatile-rich substances to our planet. Moreover, impacts necessarily eject small fractions of excavated materials at greater than escape velocity. Any simple, extant lifeforms might survive in such ejecta (orbiting in geocentric or heliocentric orbits), and "re-seed" life upon re-impacting Earth after terrestrial environments had relaxed from the violent aftereffects of such impacts [50,51]. As I noted above, the Earth's impact environment became similar to today's by ~ 3.5 Ga. Dozens of K–T level impacts would have happened since that time, several of which were at least an order-of-magnitude even more devastating. Momentous events, like "Snowball Earth" [52,53], have been hypothesized to have occurred in pre-Phanerozoic times; the inevitable cosmic impacts must be considered as plausible triggers for such dramatic climatic changes, or their cessation, during those aeons.

During the Phanerozoic, there must have been several K–T (or greater) impact events, roughly equaling the number of major mass extinctions recorded in the fossil record. Only the K–T boundary extinction is now accepted as being largely, or exclusively, due to impact (the formation of Chicxulub). Evidence accumulates that the greatest mass extinction of all, the Permian–Triassic event, was exceptionally sudden [54] and is associated with evidence for impact [55], but generally the search for evidence as robust as what proved the impact origin of the K–T has been unproductive. Perhaps the K–T impact was exceptionally efficient in effecting extinction (e.g., because of the composition of the rocks where it hit, or if it were an oblique impact or augmented by accompanying impacts). However, straightforward evaluations of the expected physical [56] and biological [57] repercussions of massive impacts suggest that any such impact should result in such extreme environmental havoc that a mass extinction would be plausible, although conditions may cause consequences to vary from impacts of similar magnitude [58].

I have argued [59] that impacts must be exceptionally more lethal globally than any other proposed terrestrial causes for mass extinctions because of two unique features: (a) their environmental effects happen essentially instantaneously (on timescales of hours to months, during which species have little time to evolve or migrate to protective locations) and (b) there are compound environmental consequences (e.g., broiler-like skies as ejecta re-enter the atmosphere, global firestorm, ozone layer destroyed, earthquakes and tsunami, months of ensuing ‘‘impact winter’’, centuries of global warming, poisoning of the oceans). Not only the rapidity of changes, but also the cumulative and synergistic consequences of the compound effects, make asteroid impact overwhelmingly more difficult for species to survive than alternative crises. Volcanism, sea regressions, and even sudden effects of hypothesized collapses of continental shelves or polar ice caps are far less abrupt than the immediate (within a couple of hours) worldwide consequences of impact; lifeforms have much better opportunities in longer-duration scenarios to hide, migrate, or evolve. The alternatives also lack the diverse, compounding negative global effects. Only the artificial horror of global nuclear war or the consequences of a very remote possibility of a stellar explosion near the Sun could compete with impacts for immediate, species-threatening changes to Earth's ecosystem. Therefore, since the NEA impacts inevitably happened, it is plausible that they—and chiefly they alone—caused the mass extinctions in Earth's history (as hypothesized by Raup [60]), even though proof is lacking for specific extinctions. What other process could possibly be so effective? And even if one or more extinctions *do* have other causes, the largest asteroid/comet impacts during the Phanerozoic cannot avoid having left traces in the fossil record.

5. The impact hazard: consequences for society in the 21st century

Cosmic projectiles rain down on us, ranging from the frequent flashes of meteoroids, to less frequent meteorite-producing bolides, to the even less common A-bomb level upper-atmospheric explosions recorded by Earth-orbiting surveillance satellites, to the historically rare Tunguska-level events, and finally to the still rarer but potentially extremely destructive impacts of bodies >100 m diameter, which must be considered not in terms of their frequency but instead in terms of their low but finite *probabilities* of impacting during the timeframe that is important to us, our children, and our grandchildren—the 21st century.

The statistical frequency of impacts by bodies of various sizes is fairly well known (Fig. 1). Less well understood are the physical and environmental consequences of impacts of various sizes. The most thorough evaluation of the environmental physics and chemistry of impacts is by Toon et al. [56]; later research has elucidated the previously poorly understood phenomena of impact-generated tsunami [6,61,62]. I have evaluated numerous impact scenarios (see [63]), emphasizing their potential consequences on human society, which are even less well understood than environmental effects. The most comprehensive analysis of the risks of NEA impacts is that of the NASA NEO Science Definition Team (SDT) [6].

Although giant impacts are very rare, when the threshold for globally destructive effects is exceeded

(NEAs >1.5–3 km diameter) then the potential mortality is unprecedentedly large, so such impacts dominate mortality [64], perhaps 3000 deaths per year worldwide, comparable with mortality from other significant natural and accidental causes (e.g., fatalities in airliner crashes). This motivated the Spaceguard Survey. Now the estimated mortality is somewhat lower, ~ 1000 annual deaths [6] due to somewhat lower estimates of the number of NEAs >1 km diameter and somewhat higher estimates of the threshold size for destructive global effects. Since most of that mortality has been eliminated by discovery of 55% of NEAs >1 km diameter and demonstration that none of them will encounter Earth in the next century, the remaining global threat is from the 45% of yet-undiscovered large NEAs plus the minor threat from comets. Once the Spaceguard Survey is complete, the residual global threat will be < 100 annual fatalities worldwide, see Table 1 [6].

The SDT [6] also evaluated two other sources of mortality due to NEO impactors smaller than those that would cause global effects: (a) impacts onto land, with local and regional consequences analogous to the explosion of a bomb and (b) impacts into an ocean, resulting in inundation of shores by the resulting tsunamis. The SDT evaluated fatalities for land impacts using (a) a model for the radius of destruction by impactors >150 m diameter [65] that survive atmospheric penetration with most of their cosmic velocity (although 220 m may be more nearly correct [66]) and (b) a map of population distribution across the Earth. A thorough analysis of the tsunami hazard [67], based on reanalysis of wave and run-up physics combined with analysis of coastal populations, provided an estimated number of "people affected per year" by impact-generated tsunami. As the SDT notes, historically only ~ 10% of people in an inundation zone die, thanks to advance warning and evacuation. Hence, in Table 1, which summarizes mortality from land impacts, ocean impacts, and globally destructive impacts, I divide the SDT's estimated tsunami hazard by a factor of 10.

Table 1
Estimated annual worldwide deaths from impacts

	Overall hazard	Residual hazard			
	Total	Total	Land	Tsunami	Global
Minimum	363	36	28	5	3
Nominal	1090	155	51	16	88
Maximum	3209	813	86	32	695

In Table 1, the "overall hazard" is that posed by nature, before the Spaceguard Survey started to certify that a fraction of NEAs (more larger ones than smaller ones) will not hit. The "residual hazard" (see Fig. 3) is what is expected after about 2008. Whereas non-global impacts constitute < 10% of the natural impact hazard, they are nearly half of the residual hazard. The land-impact hazard is chiefly due to bodies 70–200 m diameter (indeed, the chances are better than 1% that such an impact will kill ~ 100,000 people during the 21st century; larger bodies, 150–600 m are mainly responsible for the somewhat smaller tsunami hazard.

The SDT's main goal was to derive the cost–benefit ratio for building an augmented Spaceguard Survey, so they emphasized property damage rather than mortality, which gives greater weight to destruction by tsunamis compared with land impacts. On that basis, they calculated the costs of various ground- and space-based telescope systems that might retire 90% of the residual non-global impact hazard in the next decade or two. The SDT's final recommendation was to proceed, beginning in 2008, with what they calculated would be a cost-effective 7–20-year program, costing between US\$236 and US\$397 million, designed to discover 90% of PHOs >140 m diameter.

It is subjective to compare the impact hazard, given its inherent low-probability high-consequence character, with other societal hazards. I consider mortality rather than property damage as being more central to fears of impacts. But neither mortality nor economic loss estimates provide a good forecast of how societies respond to different kinds of hazards. The ~ 3000 deaths from the terrorist attacks of September 11, 2001 had dramatic national and international consequences (involving economics, politics, war, etc.), while a similar number of U.S. highway fatalities during the same month were hardly noticed, except by family members and associates of the deceased. Risk perception expert Paul Slovic believes that asteroid impacts have many elements of a "dreadful" hazard (being perceived as being involuntary, fatal, uncontrollable, catastrophic and increasing [increasing in news reports,

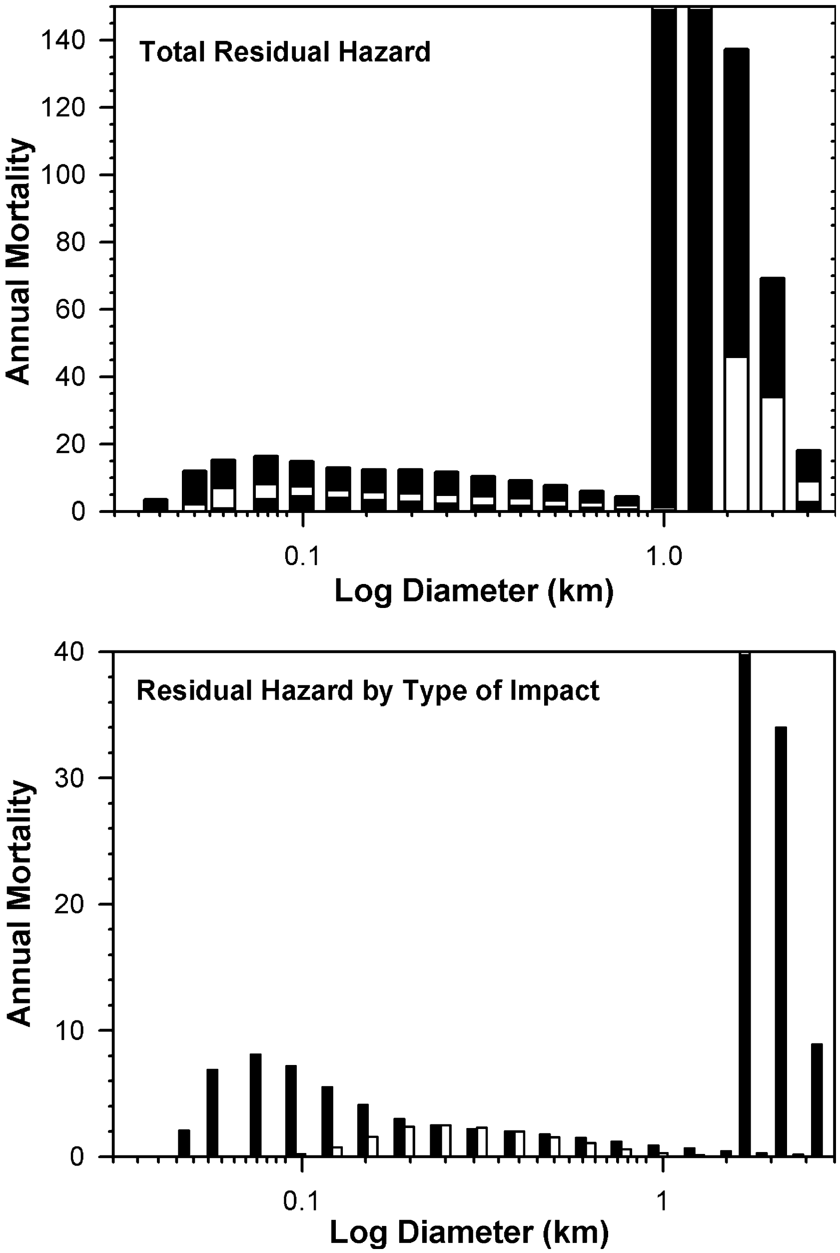


Fig. 3. Top: Minimum (lower dark bars), nominal (white bars) and maximum (upper dark bars) estimates of deaths per year (averaged over long durations) for the total residual impact hazard as a function of impactor diameter. Bottom: The nominal (white) bars in the top graph are broken down by type of impact. The three tall black bars on the right represent the globally destructive impacts. The remaining black bars show land impacts while the white bars show tsunami mortality. (Based on the data from the SDT [6]).

anyway]), like terrorism or nuclear threats, in contrast with more mundane hazards that may be more serious measured by objective criteria [67]. Society often spends much—even orders of magnitude—more per life saved to reduce “dreadful” hazards than mundane ones. For this reason, efforts to reduce the impact hazard and to plan for mitigation (e.g., evacuation of ground zero, storing food supplies in order to survive a global agricultural disaster or developing capabilities to deflect a threatening NEO) may be perceived by many citizens as money well spent. On the other hand, Slovic's public opinion polls show that many others regard the impact hazard as being trivial.

6. Three representative scenarios of NEA consequences

I briefly summarize three scenarios (drawn from many more in [63]), which illustrate the breadth of issues that must be confronted in managing potential consequences of NEA impacts. For each impact disaster scenario, I consider the nature of the devastation, the probability that the event will happen, the likely warning time, the possibilities for post-warning mitigation, the nature of issues to be faced in after-event disaster management, and—of most practical interest—what can be done *now* to prepare in advance.

6.1. 2–3 km diameter civilization destroyer

A million-megaton impact, even though ∼ 100 times less energetic than the K–T impact, would probably destroy civilization as we know it. The dominant immediate global effect would be sudden cooling, lasting many months, due to massive injection of dust into the stratosphere following impact. Agriculture would be largely lost, worldwide, for an entire growing season. Combined with other effects (a firestorm the size of India, destruction of the ozone layer, etc.), it is plausible that billions might die from collapse of social and economic institutions and infrastructure. No nation could avoid direct, as well as indirect, consequences of unprecedented magnitude. Of course, because civilization has never witnessed such an apocalypse, predictions of consequences are fraught with uncertainty.

As discussed earlier, few bodies of these sizes remain undiscovered, so the chances of such an event are probably < 1-in-100,000 during the next century. The warning time would almost certainly be long, in the case of a NEA, but might be only months in the case of a comet. With years or decades of advance warning, a technological mission might be mounted to deflect the NEA so that it would miss the Earth; however, moving such a massive object would be very challenging. In any case, given sufficient warning, many immediate fatalities could be avoided by evacuating ground zero and longer-term casualties could be minimized by storing food supplies to survive the climate catastrophe. Susceptible infrastructure (transportation, communications, medical services) could be strengthened in the years before impact. However, no preparation for mitigation is warranted for such a rare possibility until a specific impact prediction is made and certified. The only advance preparations that might make sense would be *at the margins* of disaster planning developed for other purposes: considering such an apocalypse might foster "out-of-the-box" thinking about how to define the outer envelope of disaster contingencies, and thus prove serendipitously useful as humankind faces an uncertain future.

6.2. Once-in-a-century mini-Tunguska atmospheric explosion

Consider a 30–40-m office-building-sized object striking at 100 times the speed of a jetliner. It would explode ∼ 15 km above ground, releasing the energy of ∼ 100 Hiroshima-scale bombs. Weak structures would be damaged or destroyed by the blast wave out to 20 km. The death toll might be hundreds; although casualties would be far higher in a densely populated place, they would much more likely be zero (i.e., if the impact were in the ocean or a desolate location). Such an event is likely to occur in our grandchildren's lifetime, although most likely over the ocean rather than land. Even with the proposed augmented Spaceguard Survey, it is unlikely that such a small object would be discovered in advance; impact would occur without warning. Since it could occur literally anywhere, there are no location-specific kinds of advance measures that could or should be taken, other than educating people (perhaps especially military forces that might otherwise mistake the event as an intentional attack) about the possibilities for such atmospheric explosions. In the lucky circumstance that the object is discovered years in advance, a relatively modest space mission could deflect such a small body, preventing impact [26].

6.3. Prediction (or media report) of a near-term impact

This NEA scenario is the one most likely to become an urgent issue for public officials. Indeed, such events have already happened. The problem, which can develop within hours in the 24-h global news media, is that something possibly real about a NEA is twisted by human fallibility and/or hyperbole. Hypothetical examples include: (a) a prediction, a few days in advance, of an actual near-miss ("just" 60,000 km from Earth) by a >100-m asteroid, which might be viewed with alarm by a distrustful public who would still fear an actual impact; (b) the reported (or mis-reported) prediction by a reputable (but mistaken or misquoted) astronomer that a huge impact will occur on a specific day in the future in a particular country, resulting in panic for several days until the report is withdrawn; or (c) a prediction, officially endorsed by an entity like the International Astronomical Union, of a one-in-a-few-hundred impact *possibility* on a specific date decades in the future (Torino Scale = 2; see below), which because of circumstances cannot be refined for months. On January 13/14, 2004, some NEA experts believed for a few hours that there was a 10–25% chance that a just-detected NEA, 30 m in size, would strike the Earth's northern hemisphere just a few days later [68]; a public announcement of this possible "mini-Tunguska" was being considered, but then an amateur astronomer made observations that discounted any imminent impact and the real object was later verified as being much farther away.

Ways to eliminate instances of hype and misunderstanding involve public education about science, critical thinking and risk; familiarizing science teachers, journalists and other communicators with the impact hazard might be especially effective. One approach that has evolved since a 1999 conference in Torino (Turin), Italy, is promulgation of the Torino Scale [63,69,70], which attempts to place impact predictions into a sober, rational context (on a 10-point Richter-like scale, predicted impact possibilities usually rate a 0 or 1, and are unlikely to exceed 4 during our lifetimes).

7. Evaluation of the modern impact hazard

Unlike other topics in astronomy (except solar flares and coronal mass ejections), only the impact hazard presents serious practical issues for society. Contrasting with most practical issues involving meteorology, geology and geophysics, the impact hazard is both more extreme in potential consequences and yet so rare that it has not even been experienced in more than minor ways in historical times. It has similarities to natural hazards in that its practical manifestations mainly involve familiar destructive processes, such as fire, high winds, earthquakes, falling debris and floods. The impact hazard also ranks with other natural disasters in the mid-range of risks of death [67]: much less important than war, disease, famine, automobile accidents or murder but much more important than shark attacks, botulism, fireworks accidents or terrorism. Yet, impacts differ from natural disasters because the hazard is mainly not location-dependent (impacts happen anywhere, not just along faults, although ocean impact effects are amplified along coastlines) and there are no precursor or after-shock events.

There are also similarities and differences compared with terrorism and other human-caused calamities. Like terrorism, the impact hazard is "dreadful" (in Slovic's nomenclature), it seems to strike randomly (at least unexpectedly) in time and location, and few have been (or, in my estimation, are likely to be) killed, although in each case many *could* be killed. Dissimilar attributes include the essential "act of God" nature of impacts, whereas terrorism involves willful acts of evil, inspiring retribution. Also, we can probably *do something* about most impact threats, whereas terrorism and threats of nuclear war are dealt with by such imperfect human endeavors as diplomacy. Another disproportionate comparison involves past public expenditures: hundreds of billions of dollars are being allocated to the war on terrorism compared with a few million spent annually on the impact hazard (mostly funding the Spaceguard Survey).

The practical, public implications and requirements of the impact hazard are characterized by its *uncertainty* and "iffy" nature. Yet, the chief scientific evaluations of the hazard, and thus (because of the subject's popularity) its public promulgation in the news, is skewed with respect to reality. In the last few years, many peer-reviewed papers have been published (often with popular commentaries and even CNN crawlers) about how many >1-km NEAs there are, ranging from lows of ~ 700 [71] to highs approaching 1300. Yet far less attention is paid (although not quite none at all (e.g., [72]) to the much greater uncertainties in environmental effects of impacts. And there is essentially no serious, funded research concerning the largest sources of uncertainty—those concerning the psychology, sociology and economics of such extreme disasters—which truly determine whether this hazard is of academic interest only or, instead, might shape the course of history. For example, many astronomers and geophysicists, who are amateurs in risk perception and disaster management, assume that "panic" is a probable consequence of predicted or actual major asteroid impacts. Yet some social scientists (e.g., [73]) have concluded that people rarely panic in disasters. Such issues, especially in a post-September 11th terrorism context, could be more central to prioritizing the impact hazard than anything earth and space scientists can do. If an actual Earth-targeted body is found, it will be the engineers and disaster managers whose expertise will suddenly be in demand.

I have noted the primacy of psychological perceptions in characterizing the impact hazard. Since impact effects (other than the spectacle of meteors and occasional meteorite falls) have never been experienced by human beings now alive, we can relate to this hazard only theoretically. Since it involves very remote possibilities, the same irrationality applies that governs purchases of lottery tickets or re-building in 100-year floodplains just after a recent 100-year flood. Because society fails to apply objective standards to prioritizing hazard mitigation funding, it is plausible that the residual risks of this hazard might be altogether ignored (the Spaceguard Survey has been cheap, but it becomes increasingly costly to search for the remaining, small NEAs); or society may instead over-react and give "planetary defense" more priority than battling such clear-and-present dangers as influenza. Yet, contrasting with the irrational perceptions of the impact hazard, it potentially can be mitigated in much more concrete ways than is true of most hazards. An impact can be predicted in advance in ways that remain imperfect [70] but are much more reliable than predictions of earthquakes or even storms, and the components of technology exist—at affordable costs given the consequences of an actual impact—to move any threatening object away and avoid the disaster altogether. In contrast with the dinosaurs, human beings have the insight and capability to avoid extinction by impacts.

Acknowledgements

I thank Chris Koeberl, Rick Binzel and Larry Nittler for helpful reviews. Preparation of this review was assisted by the Alan Harris, David Morrison and members of the B612 Foundation. ***[AH]***

References

[1] Z. Ceplecha, Meteoroids: an item in the inventory, in: T.W. Rettig, J.M. Hahn (Eds.), Completing the Inventory of the Solar System, Astron. Soc. Pac. Conf. Ser., vol. 107, 1996, pp. 75–84.

[2] S.J. Weidenschilling, Formation of planetesimals and accretion of the terrestrial planets, Space Sci. Rev. 92 (2000) 295–310.

[3] W.F. Bottke Jr., D. Vokrouhlický, D.P. Rubincam, M. Brož, The effect of Yarkovsky thermal forces on the dynamical evolution of asteroids and meteoroids, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, pp. 395–408.

[4] S.F. Dermott, D.D. Durda, K. Grogan, T.J.J. Kehoe, Asteroidal dust, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, pp. 423–442.

[5] W.F. Bottke, A. Morbidelli, R. Jedicke, J.-M. Petit, H.F. Levison, P. Michel, T.S. Metcalfe, Debiased orbital and absolute magnitude distribution of the near-Earth objects, Icarus 156 (2002) 399–433.

[6] Near-Earth Object Science Definition Team, Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters, NASA Office of Space Science, Solar System Exploration Div., Washington, DC, 2003, 154 pp., http://neo.jpl.nasa.gov/neo/neoreport030825.pdf.

[7] T.S. Culler, T.A. Becker, R.A. Muller, P.R. Renne, Lunar

impact history from $^{40}Ar/^{39}Ar$ dating of glass spherules, Science 287 (2000) 1785–1788.

[8] G. Ryder, Mass flux in the ancient Earth–Moon system and benign implications for the origin of life on Earth, J. Geophys. Res. 107 (E4) (2002) 5022 (doi: 10.1029/2001JE001583).

[9] W.K. Hartmann, Megaregolith evolution and cratering cataclysm models—lunar cataclysm as a misconception (28 years later), Meteorit. Planet. Sci. 38 (2003) 579–593.

[10] J.E. Chambers, J.J. Lissauer, A. Morbidelli, Planet V and the origin of the lunar Late Heavy Bombardment, Bull.-Am. Astron. Soc. 33 (2001) 1082.

[11] H. Atkinson, C. Tickell, D. Williams (Eds.), Report of the Task Force on Potentially Hazardous Near Earth Objects, British National Space Centre, London, 2000, 54 pp.

[12] F. Watson, Between the Planets, The Blakiston Co., Philadelphia, 1941, 222 pp.

[13] R.B. Baldwin, The Face of the Moon, Univ. Chicago Press, Chicago, 1949, 239 pp.

[14] E.J. Öpik, On the catastrophic effect of collisions with celestial bodies, Ir. Astron. J. 5 (1958) 36.

[15] E.M. Shoemaker, Impact mechanics at Meteor Crater, Arizona, in: B.M. Middlehurst, G.P. Kuiper (Eds.), The Moon Meteorites and Comets, Univ. Chicago Press, Chicago, 1963, pp. 301–336.

[16] R.B. Leighton, B.C. Murray, R.P. Sharp, J.D. Allen, R.K. Sloan, Mariner IV photography of Mars: initial results, Science 149 (1965) 627–630.

[17] L.W. Alvarez, W. Alvarez, F. Asaro, H.V. Michel, Extraterrestrial cause for the Cretaceous–Tertiary extinction, Science 208 (1980) 1095–1108.

[18] A.R. Hildebrand, W.V. Boynton, Proximal Cretaceous–Tertiary boundary impact deposits in the Caribbean, Science 248 (1990) 843–847 (see also);
A.R. Hildebrand, W.V. Boynton, Cretaceous ground zero, Nat. Hist. (6) (1991) 47–53;
G.T. Penfield, Pre-Alvarez impact, Nat. Hist., (6) (1991) 4.

[19] J.D. Archibald, Dinosaur extinction: changing views, in: J.G. Scotchmoor, D.A. Springer, B.H. Breithaupt, A.R. Fiorillo (Eds.), Dinosaurs: The Science Behind the Stories, American Geological Institute, 2002, pp. 99–106.

[20] D. Morrison (Ed.), The Spaceguard Survey: Report of the NASA International Near-Earth Object Detection Workshop, NASA, Washington, DC, 1992, http://impact.arc.nasa.gov/reports/spaceguard/index.html.

[21] E.M. Shoemaker (Ed.), Report of the Near-Earth Objects Survey Working Group, NASA, Washington, DC, 1995, http://impact.arc.nasa.gov/reports/neoreport/index.html.

[22] G.H. Canavan, J.C. Solem, J.D.G. Rather (Eds.), Proceedings of the Near-Earth-Object Interception Workshop, Los Alamos Natl. Lab. LA-12476-C, Los Alamos NM, 1993, 296 pp.

[23] Proceedings of the Planetary Defense Workshop, Lawrence Livermore Natl. Lab. CONF-9505266, Livermore CA, 1995, 513 pp.

[24] T. Gehrels (Ed.), Hazards due to Comets and Asteroids, Univ. Arizona Press, Tucson, 1994, 1300 pp.

[25] J.L. Remo (Ed.), Near-Earth Objects: The United Nations International Conference, Annals of the New York Academy of Sciences, vol. 822, 632 pp.

[26] M.J.S. Belton (Ed.), Mitigation of Hazardous Comets and Asteroids, Cambridge Univ. Press, Cambridge, 2004, in press.

[27] C. Koeberl, K.G. MacLeod (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond, Geological Soc. America, Boulder CO, Special Paper, vol. 356, 746 pp.

[28] W.F. Bottke Jr., A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, 785 pp.

[29] G.H. Stokes, J.B. Evans, S.M. Larson, Near-Earth asteroid search programs, in: W.F. Bottke Jr., A. Cellino, P. Binzel, R.P. Binzel (Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, pp. 45–54.

[30] P. Brown, R.E. Spalding, D.O. ReVelle, E. Tagliaferri, S.P. Worden, The flux of small near-Earth objects colliding with the Earth, Nature 420 (2002) 294–296.

[31] D. Vokrouhlický, P. Farinella, Efficient delivery of meteorites to the Earth from a wide range of asteroid parent bodies, Nature 407 (2000) 606–608.

[32] C.R. Chapman, Space weathering of asteroid surfaces, Annu. Rev. Earth Planet. Sci. (2004) (in press) doi: 10.1146/annurev.earth.32.101802.120453.

[33] S.J. Bus, F. Vilas, M.A. Barucci, Visible-wavelength spectroscopy of asteroids, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, pp. 169–182.

[34] S.J. Ostro, R.S. Hudson, L.A.M. Benner, J.D. Giorgini, C. Magri, J.-L. Margot, M.C. Nolan, Asteroid radar astronomy, in: W.F. Bottke, A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, pp. 151–168.

[35] J.F. Bell III, et al., Near-IR reflectance spectroscopy of 433 Eros from the NIS instrument on the NEAR mission, Icarus 155 (2002) 119–144.

[36] T.J. McCoy, et al., The composition of 433 Eros: a mineralogical–chemical synthesis, Meteorit. Planet. Sci. 36 (2001) 1661–1672.

[37] R.P. Binzel, D.F. Lupishko, M. DiMartino, R.J. Whiteley, G.J. Hahn, Physical properties of near-Earth objects, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, pp. 255–271.

[38] V.R. Oberbeck, M. Aoyagi, Martian doublet craters, J. Geophys. Res. 77 (1972) 2419–2432.

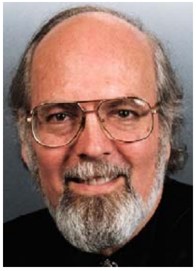
[39] C.M. Cook, H.J. Melosh, W.F. Bottke Jr., Doublet craters on Venus, Icarus 165 (2003) 90–100.

[40] W.J. Merline, S.J. Weidenschilling, D.D. Durda, J.L. Margot, P. Pravec, A.D. Storrs, Asteroids do have satellites, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi, R.P. Binzel (Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, pp. 289–312.

[41] E. Asphaug, W. Benz, Size, density, and structure of Comet Shoemaker-Levy 9 inferred from the physics of tidal breakup, Icarus 121 (1996) 225–248.

[42] D.C. Richardson, Z.M. Leinhardt, H.J. Melosh, W.F. Bottke Jr., E. Asphaug, Gravitational aggregates: evidence and evolution, in: W.F. Bottke Jr., A. Cellino, P. Paolicchi, R.P. Binzel

(Eds.), Asteroids, vol. III, Univ. Arizona Press, Tucson, 2002, pp. 501–515.
[43] C.R. Chapman, The evolution of asteroids as meteorite parent-bodies, in: A.H. Delsemme (Ed.), Comets Asteroids Meteorites: Interrelations, Evolution and Origins, Univ. of Toledo Press, Toledo OH, 1977, p. 265.
[44] R.J. Whiteley, D.J. Tholen, C.W. Hergenrother, Lightcurve analysis of four new monolithic rapidly-rotating asteroids, Icarus 157 (2002) 139–154.
[45] C.R. Chapman, W.J. Merline, P.C. Thomas, J. Joseph, A.F. Cheng, N. Izenberg, Impact history of Eros: craters and boulders, Icarus 155 (2002) 104–118.
[46] C.R. Chapman, What we know and don't know about surfaces of potentially hazardous small bodies, in: M.J.S. Belton (Ed.), Mitigation of Hazardous Comets and Asteroids, Cambridge Univ. Press, Cambridge, 2004, in press.
[47] Earth Impact Database, http://www.unb.ca/passc/ImpactDatabase/, accessed 2003 Dec. 12.
[48] K.A. Maher, D.J. Stevenson, Impact frustration of the origin of life, Nature 331 (1988) 612–614.
[49] N.H. Sleep, K.J. Zahnle, J.F. Kasting, H.J. Morowitz, Annihilation of ecosystems by large asteroid impacts on the early Earth, Nature 342 (1989) 139–142.
[50] N.H. Sleep, K. Zahnle, Refugia from asteroid impacts on early Mars and the early Earth, J. Geophys. Res. 103 (1998) 28529–28544.
[51] J.C. Armstrong, L.E. Wells, G. Gonzalez, Rummaging through Earth's attic for remains of ancient life, Icarus 160 (2002) 183–196.
[52] P.F. Hoffman, A.J. Kaufman, G.P. Halverson, D.P. Schrag, A Neoproterozoic snowball Earth, Science 281 (1998) 1342–1346.
[53] P.F. Hoffman, D.P. Schrag, The snowball Earth hypothesis: testing the limits of global change, Terra Nova 14 (2002) 129–155.
[54] D.H. Erwin, S.A. Bowring, J. Yugan, End-Permian mass extinctions: a review, in: C. Koeberl, K.G. MacLeod (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond, Geological Soc. America, Boulder CO, Special Paper, vol. 356, 2002, pp. 363–383.
[55] A.R. Basu, M.I. Petaev, R.J. Poreda, S.B. Jacobsen, L. Becker, Chondritic meteorite fragments associated with the Permian–Triassic boundary in Antarctica, Science 302 (2003) 1388–1392.
[56] O.B. Toon, K. Zahnle, D. Morrison, R.P. Turco, C. Covey, Environmental perturbations caused by the impacts of asteroids and comets, Rev. Geophys. 35 (1997) 41–78.
[57] D.S. Robertson, M.C. McKenna, O.B. Toon, S. Hope, J.A. Lillegraven, Survival in the first hours of the Cenozoic, Geol. Soc. Amer. Bull. (2004) (in press).
[58] D.A. Kring, Environmental consequences of impact cratering events as a function of ambient conditions on Earth, Astrobiology 3 (2003) 133–152.
[59] C.R. Chapman, Impact lethality and risks in today's world: lessons for interpreting Earth history, in: C. Koeberl, K.G. MacLeod (Eds.), Catastrophic Events and Mass Extinctions: Impacts and Beyond, Geological Society of America, Boulder CO, Special Paper, vol. 356, 2002, pp. 7–19.
[60] D.M. Raup, Bad Genes or Bad Luck? Norton, New York, 1991, 210 pp.
[61] J.G. Hills, C.L. Mader, Tsunami produced by the impacts of small asteroids, in: J.L. Remo (Ed.), Near-Earth Objects: The United Nations International Conference, Annals of the New York Academy of Sciences, vol. 822, 1997, pp. 381–394.
[62] S.R. Chesley, S.N. Ward, A quantitative assessment of the human and economic hazard from impact-generated tsunami, Environ. Hazards (2003) (submitted for publication).
[63] D.M. Morrison, C.R. Chapman, D. Steel, R. Binzel, Impacts and the public: communicating the nature of the impact hazard, in: M.J.S. Belton (Ed.), Mitigation of Hazardous Comets and Asteroids, Cambridge Univ. Press, Cambridge, 2004, in press.
[64] C.R. Chapman, D. Morrison, Impacts on the Earth by asteroids and comets: assessing the hazard, Nature 367 (1994) 33–40.
[65] J.G. Hills, M.P. Goda, The fragmentation of small asteroids in the atmosphere, Astron. J. 105 (1993) 1114–1144.
[66] P.A. Bland, N.A. Artemieva, Efficient disruption of small asteroids by Earth's atmosphere, Nature 424 (2003) 288–291.
[67] D. Morrison, C.R. Chapman, P. Slovic, in: T. Gehrels (Ed.), Hazards due to Comets and Asteroids, Univ. Arizona Press, Tucson, 1994, pp. 59–91.
[68] C.R. Chapman, NEO impact scenarios, American Inst. of Aeronautics and Astronautics 2004 Planetary Defense Conference: Protecting Earth from Asteroids, Garden Grove, Calif. (2004 23 Feb.).
[69] R.P. Binzel, The Torino impact hazard scale, Planet. Space Sci. 48 (2000) 297–303.
[70] C.R. Chapman, The asteroid/comet impact hazard: *Homo sapiens* as dinosaur? in: D. Sarewitz, et al. (Ed.), Prediction: Science, Decision Making, and the Future of Nature, Island Press, Washington, DC, 2000, pp. 107–134.
[71] D. Rabinowitz, E. Helin, K. Lawrence, S. Pravado, A reduced estimate of the number of kilometre-sized near-Earth asteroids, Nature 403 (2000) 165–166.
[72] K.O. Pope, Impact dust not the cause of the Cretaceous–Tertiary mass extinction, Geology 30 (2002) 99–102.
[73] L. Clarke, Panic: Myth or Reality, Contexts (American Sociological Association, Univ. Calif. Press) v. 1 #3 (2002) (http://www.contextsmagazine.org/content_sample_v1-3.php).



Dr. Clark R. Chapman is a planetary scientist at the Boulder, CO, office of Southwest Research Institute. He is past chair of the Division for Planetary Sciences of the American Astronomical Society, first editor of Journal of Geophysical Research-Planets, and has been on the science teams of the Galileo, NEAR-Shoemaker and MESSENGER deep space missions. His PhD (1972) is from the Earth and Planetary Sciences Dept. of MIT.