2

Target Earth: Present, Past, and Future

Current studies of Earth and the solar system have demonstrated clearly that impact events are a definite part of the present as well as the past. The multiple impacts of Comet Shoemaker-Levy 9 on Jupiter in July 1994 (*Spencer and Mitton,* 1995) provided the entire world with an awesome demonstration that, even 4.5 b.y. after formation of the solar system, the cosmic bombardment process in still going on, and the catastrophic effects produced by the impacts on Jupiter provided a graphic — and disturbing — example of what might happen if a similar object should strike Earth instead.

Several features of the present solar system demonstrate that impact events — both actual and potential — are part of the current state of Earth as well: (1) the Earth is accompanied in the solar system by thousands, possibly millions, of randomly moving kilometer-sized objects, some of which could collide with the Earth in the future; (2) small extraterrestrial objects are continually colliding with Earth, and larger ones have struck it in the recent past.

2.1. COMETS AND ASTEROIDS: THE KILLER NEIGHBORS?

The Earth is accompanied in the solar system by many other solid objects. In addition to the planets and moons, the solar system contains a large amount of lesser cosmic debris, objects ranging from microscopic dust particles to objects tens of kilometers in size, each of which moves in its own orbit around the Sun. In the size range of interest for impact events, from a few tens of meters up through tens of kilometers in size, two kinds of objects can be distinguished: asteroids and comets.

2.1.1. Asteroids

Asteroids are small, rocky bodies, regarded as the fragments of small objects (*planetesimals*) that existed in the inner solar system when the solar system formed, but were not swept up by growing planets (*Binzel et al.,* 1989). Most asteroids are a few kilometers to a few tens of kilometers in size. A few are larger; Ceres, the largest known, has a diameter of about 1000 km, or about the size of the state of Texas. Several thousand asteroids more than a kilometer across have been discovered, and millions of smaller ones almost certainly exist. Most asteroids, especially the largest ones, are located in the **asteroid belt**, a zone between the orbits of Mars and Jupiter, and most asteroids — but not all — tend to stay there, safely out of range of Earth.

2.1.2. Comets

Comets are also small objects, typically tens of kilometers in diameter. In contrast to the rocky asteroids, comets contain a significant amount of volatile ices in addition to rocky material (*Wilkening*, 1982; *Newburn et al.,* 1991). The evaporation of these icy compounds when comets pass through the inner solar system and approach the Sun creates the long, shining tails that make comets such striking objects in history and superstition. Because they contain so much low-temperature material, scientists suspect that comets have probably formed as small bodies in the cold outer solar system.

Comets are divided into two types, based on the shape of their orbit and on how long they take to make one revolution around the sun. *Short-period comets,* such as Comet Encke and Comet Halley, orbit the Sun in ≤200 years. However, most short-period comets have orbital periods of only a few years and travel on small, nearly circular orbits like those of planets and asteroids. *Long-period comets,* like the recently observed Comet Hale-Bopp, may take thousands of years to complete a single orbit, and they travel on highly elongate orbits that take them far beyond Pluto and perhaps 10% of the distance to the nearest star. It has been argued, both on theoretical grounds and from observations of the orbits of long-period comets, that the entire solar system is in fact surrounded, at a distance of about 50,000 AU, by a vast cloud containing billions of comets (*the Oort Cloud*), from which comets are occasionally perturbed (perhaps by passing stars) into orbits that carry them down into the inner solar system toward the Sun. A similar accumulation of small icy objects, the *Kuiper Belt,* may exist beyond the orbit of Neptune and may actually be the source of the short-period comets that enter the solar system (*Rahe et al.,* 1994).

2.1.3. Close Encounters

There is nothing that isolates the Earth from these small but fast-moving objects. Any time the orbit of a comet or asteroid crosses the orbit of the Earth, a collision is possible. The majority of asteroids, whose orbits lie within the asteroid belt between Mars and Jupiter, remain at great distances from the Earth and pose no danger to it. But not all asteroids remain there. Even within the asteroid belt, the orbits of individual asteroids can be changed by close encounters with Mars or Jupiter, or by low-velocity collisions with other asteroids. These random perturbations can put asteroids into new orbits, some of which enter the inner solar system and cross the orbits of the inner planets. More than 150 **near-Earth asteroids (NEAs)** with diameters of ≥1 km, whose orbits approach or cross the orbit of the Earth, have already been discovered, and several hundred more are believed to exist.

In the outer solar system, far beyond Pluto, similar perturbations, perhaps caused by passing stars, may nudge comets out of the distant Oort Cloud and put them onto highly elliptical orbits that also enter the inner solar system and may cross Earth's orbit. Eventually, over millions of years or more, some of the asteroids or comets that repeatedly cross Earth's orbit will collide with it. There is nothing to stop them.

2.2 IN OUR TIME: SMALL CATASTROPHES

Even at this moment, collisions of extraterrestrial objects with Earth are occurring by the billions. Steadily and quietly, Earth itself accumulates about 100 tons of extraterrestrial material every day (*Taylor,* 1992, pp. 176–177; *Love and Brownlee,* 1993). Almost all this material enters Earth's atmosphere as small particles (from microscopic dust to the size of golf balls); these objects burn up in the atmosphere to produce visible streaks of light (**meteors** or "**shooting stars**") in the night sky.

Among extraterrestrial objects in the solar system, small objects (<1 cm) are much more abundant than larger ones, but larger objects, even though rarer, also strike Earth. Some tens of objects, ranging in size from a few tens of centimeters to a few meters and weighing from a few kilograms to a few tons, also collide with Earth every year. Most of these objects are rocky or metallic fragments of asteroids, and they are large enough and solid enough to survive passage through Earth's atmosphere. As they pass through the atmosphere, their outer parts burn off, they slow down, they hit the ground at relatively low velocities, and they remain reasonably intact, becoming **meteorites**.

Earth shows evidence of many small extraterrestrial collisions in the present, but its recent past shows that even larger objects have struck (or barely missed) Earth during just the last few decades.

In 1947, an iron meteorite about 3 m across and weighing perhaps 100 tons entered the atmosphere above the Sikhote-Alin region of Siberia (Russia), broke up in midflight, and showered the region below with thousands of chunks of metal (*Krinov,* 1966, Chapter 4). Because the original object broke up in the atmosphere, the resulting smaller fragments were slowed down and produced no major damage on impact. The kinetic energy of the original object, equivalent to about 4000 tons [4 **kilotons** (**kT**)] of TNT, was dissipated harmlessly in the atmosphere and by the low-velocity impacts on the ground.

In 1972, an object about 10 m across skimmed through the atmosphere above the western United States, leaving a bright trail that was seen and photographed, before it bounced out into space again. Had it struck Earth's surface instead, it would have released energy equivalent to that of several atomic bombs, sufficient to destroy a large city (*Weaver,* 1986, pp. 416–417; *Morrison,* 1992, p. 7).

In 1908, an even larger object, perhaps 30–50 m across, exploded in the sky above the Tunguska River of Siberia (Russia), producing an air blast that was detected around the world and flattened about 2000 km^2 of forest (an area more than half the size of Rhode Island) (*Krinov,* 1966, Chapter 3; *Chyba et al.,* 1993). The energy released was equivalent to about 15 million tons [15 **megatons** (**MT**)] of TNT. Fortunately, even this large object was broken up by pressure waves generated during its passage through the atmosphere, and its kinetic energy was released as a huge explosion several kilometers above the ground. If the object had survived to strike the ground intact, it would have produced a crater about 1 km in diameter [about the size of Barringer Meteor Crater (Arizona)] and devastated much of the surrounding countryside (*Kring,* 1997). (The timing of the Tunguska event was also fortunate. If the object had entered the atmosphere only a few hours later, the blast would have occurred over the city of St. Petersburg, Russia, and would probably have destroyed the city.)

Earth's situation in space, together with the observed record of the present and recent past, demonstrates that there is nothing unusual or nonuniformitarian about extraterrestrial impacts, even large ones. In fact, impacts are like other uniformitarian processes such as earthquakes and volcanic eruptions: there are lots of small ones and relatively few large ones. The small ones occur frequently, cause little damage, and tend to be ignored. The larger ones are much rarer, but they are the ones that do all the damage.

2.3. THE PROBLEMS OF PREDICTION: HOW BIG, HOW OFTEN?

2.3.1. Ingredients of Catastrophe

Collisions of large extraterrestrial bodies with Earth are rare, but they are far more destructive than the impacts of smaller objects. Larger and heavier objects not only possess more kinetic energy than smaller ones, but they are also less affected by Earth's atmosphere. They are not slowed down, they survive intact to the ground, and their entire original kinetic energy is delivered to Earth's surface. Objects no more than a few tens of meters across may be massive enough (and coherent enough, especially if they are iron meteorites) to pass through the atmosphere without being slowed and to strike the ground at their original cosmic velocities.

Typical cosmic velocities are high. The minimum impact velocity for collisions with Earth is 11.2 km/s; this is, by definition, equal to the *escape velocity* for an object launched into space from Earth's surface. The maximum possible impact velocity onto Earth is the sum of two separate velocities: (1) The velocity of the impacting object in its orbit around the Sun (*heliocentric velocity*). This quantity, which can also be thought of as the escape velocity from the solar system, is about 42 km/s at the orbit of Earth. (2) The *orbital velocity* of Earth itself around the Sun, which is about 30 km/s. The maximum possible impact velocity on Earth is the simple sum of these two velocities, or 72 km/s. However, the orbits of Earth and the colliding object will generally be inclined to one another; the two velocities will therefore add geometrically (as a vector sum), producing Earth-encounter velocities (*geocentric velocities*) between these two limits. Typical Earth-encounter velocities for asteroids are 15–25 km/s (*Chyba et al.,* 1994). Comets tend to have higher encounter velocities, e.g., as much as 60 km/s for Comet Halley. At such speeds, these objects carry as much kinetic energy as 20–50× their weight in TNT, and all this energy is released when they strike the Earth.

Because impact velocities are high, the kinetic energy (= $1/2\ mv^2$) of even small objects is also high. A stony meteorite only 6 m in diameter, colliding with the Earth at 20 km/s, releases as much energy [8.3×10^{13} **joules** (**J**) or 20,000 tons (20 kT) of TNT] as an atomic bomb (see Table 2.1). The impact of a larger object, such as a moderate-sized comet or asteroid only a few kilometers across, releases in seconds amounts of energy measured in millions or even billions of MT (1 MT = 10^6 tons of TNT or 4.2×10^{15} J). For comparison, the total energy released by the Earth, through volcanism, earthquakes, and heat flow, is about 1.3×10^{21} J/yr, or about 310,000 MT/yr (*Fowler,* 1993, p. 226). A collision with a modest-sized asteroid thus releases in a few seconds more energy than the entire Earth releases in hundreds or thousands of years. Fortunately for terrestrial life and civilization, these larger catastrophes are rare, even over geological timescales of millions of years.

2.3.2. Uncertain Estimates

But just how rare is "rare"? How often is an impact crater of a given size produced on Earth? How often will bodies of a given size collide with Earth in the future? Scientists attempting to solve these problems for Earth (or any other planet) are faced with three complex and interrelated questions: (1) How often will an extraterrestrial object of a given size strike Earth? (2) How much energy (determined by the object's mass and impact velocity) will be released by the event? (3) How large a crater will be formed by this amount of energy?

Attempting to answer these questions causes major difficulties. Impact is a random process, not a regular one, and it is difficult to make a precise statistical estimate from only a small number of recorded events. The preserved terrestrial crater population is small; worse, it is biased toward younger and larger structures because of erosion and other postimpact processes. Better statistics are available from the more well-preserved lunar and planetary cratering records, but to apply this information to Earth requires corrections for different planetary gravity fields, target characteristics, and the variation of impact rates at different locations within the solar system. Finally, calculations of crater sizes depend on a large number of complicated factors: projectile characteristics (mass, density, physical properties, impact velocity, impact angle), target characteristics (structure, physical properties), the partitioning of the projectile's original kinetic energy into various forms (mechanical, kinetic, seismic, thermal) within the target, and the relationships between impact energy and crater size for various projectiles, targets, and impact velocities.

Efforts to determine impact frequencies date back to before the Apollo program and the planetary missions of the last few decades, and, despite the difficulties, much progress has been made. Many workers have used a large range of different astronomical and planetary data: the present measured impact rate of small bodies on the Earth; the number and sizes of known asteroids and comets; and the number and size of impact craters observed on the better-preserved surfaces of other planets, particularly the Moon, Mars, and (more recently) Venus (for reviews and different examples, see *Taylor,* 1982, Chapter 3; 1992, Chapter 4; *Hörz et al.,* 1991; papers in *Gehrels,* 1994). Other scientists have calculated terrestrial bombardment rates from the small but growing population of preserved terrestrial craters (*Grieve,* 1991; *Grieve and Shoemaker,* 1994; *Grieve and Pesonen,* 1992, 1996; *Shoemaker and Shoemaker,* 1996). The various theoretical problems of energy partitioning and crater size have been extensively addressed in numerous theoretical and laboratory studies (e.g., *O'Keefe and Ahrens,* 1975, 1977, 1993; *Ahrens and O'Keefe,* 1977; papers in *Roddy et al.,* 1977; *Holsapple and Schmidt,* 1982, 1987; for reviews and literature, see also *Melosh,* 1989, Chapter 7).

Even with the large amount of observational, theoretical, and laboratory data now available, the uncertainties in such estimates remain large. Individual estimates of the frequency of impact on Earth for objects of the same size vary by factors of 5–10×, especially for larger objects. (Compare, e.g., the various estimates of *Bottke et al.,* 1994; *Neukum and Ivanov,* 1994; *Grieve and Shoemaker,* 1994.) The material in Table 2.1 presents approximate estimates of terrestrial impact frequencies, energies, and resulting crater sizes. These data represent a combination of various current estimates, but they are only approximate and should be used only for general illustration. The uncertainties, in both the databases and the mathematical models used, are still too great to allow more precise estimates.

TABLE 2.1. **Terrestrial meteorite impact craters: Crater sizes, projectile sizes, frequencies, and comparable terrestrial events.**

Crater Diameter	Approximate Projectile Diameter	Energy (J)	Energy (TNT Equivalent)	Impact Frequency (No. per m.y., Whole Earth)	Mean Impact Interval (T_{mean}, Whole Earth)	Comparable Terrestrial Event
35 m	2 m	2.1 E + 12	500 tons	250,000	4 yr	Minimum damaging earthquake (M = 5) Largest chemical explosion experiment (“Snowball”; Canada, 1964)
75 m	4 m	1.9 E + 13	4,500 tons	69,000	15 yr	Largest chemical explosion (Heligoland Fortifications, 1947)
120 m	6 m	8.3 E + 13	20,000 tons	28,000	35 yr	Atomic bomb explosion (Hiroshima, Japan, 1945)
450 m	23 m	4.2 E + 15	1 MT	2,700	370 yr	“Typical” hydrogen-bomb explosion (1 MT)
1 km	50 m	4.6 E + 16	11 MT	640	1,600 yr	**Wolfe Creek, Australia (D = 0.875 km)** **Pretoria Salt Pan, South Africa (D = 1.13 km)**
1.1 km	55 m	6.2 E + 16	15 MT	540	1,900 yr	**Barringer Meteor Crater, Arizona (D = 1.2 km)** Tunguska explosion, Siberia, Russia (1908) Mt. St. Helens, Washington (1981) (blast only)
1.8 km	90 m	2.5 E + 17	60 MT	230	4,400 yr	San Francisco earthquake (1906) (M = 8.4) Largest hydrogen-bomb detonation (68 MT)
3.1 km	155 m	1.3 E + 18	310 MT	83	12,000 yr	Mt. St. Helens, Washington eruption (1981) (total energy, including thermal)
5 km	250 m	5.7 E + 18	1,400 MT	35	28,500 yr	**Gardnos, Norway (D = 5.0 km)** **Goat Paddock, Australia (D = 5.1 km)**
6.9 km	350 m	1.5 E + 15	3,600 MT	20	51,000 yr	Largest recorded earthquake (Chile, 1960; M = 9.6)
7.2 km	360 m	1.7 E + 15	3,700 MT	18	55,000 yr	Krakatoa volcano eruption (Indonesia, 1883) (Total energy, including thermal)
10 km	500 m	4.6 E + 19	11,000 MT	10	100,000 yr	**Lake Mien, Sweden (D = 9 km)** **Bosumtwi, Ghana (D = 10.5 km)** **Oasis, Libya (D = 11.5 km)**

TABLE 2.1. (continued).

Crater Diameter	Approximate Projectile Diameter	Energy (J)	Energy (TNT Equivalent)	Impact Frequency (No. per m.y., Whole Earth)	Mean Impact Interval (T_{mean}, Whole Earth)	Comparable Terrestrial Event
12.2 km	610 m	8.4 E + 19	20,000 MT	7.1	142,000 yr	Tambora volcano eruption (Indonesia, 1815) (Total energy, including thermal)
20 km	1 km	3.7 E + 20	87,000 MT	2.9	350,000 yr	**Haughton Dome, Canada (D = 20.5 km)** **Rochechouart, France (D = 23 km)** **Ries Crater, Germany (D = 24 km)**
31 km	1.5 km	1.3 E + 21	310,000 MT	1.4	720,000 yr	Total annual energy release from Earth (Heat flow, seismic, volcanic)
50 km	2.5 km	5.8 E + 21	1.3 E + 6 MT	0.22	4.5 m.y.	**Montagnais, Canada (D = 45 km)** **Charlevoix, Canada (D = 54 km)** **Siljan, Sweden (D = 55 km)**
100 km	5 km	4.6 E + 22	1.1 E + 7 MT	0.04	26 m.y.	**Manicouagan, Canada (D = 100 km)** **Popigai, Russia (D = 100 km)**
200 km	10 km	3.7 E + 23	8.7 E + 7 MT	0.007	150 m.y.	Largest known terrestrial impact structures (original diameters 200–300 km) **Sudbury, Canada; Vredefort, South Africa; Chicxulub, Mexico**

Atmospheric effects on small projectiles neglected. (In real impacts, projectiles <50 m are probably destroyed in the atmosphere.)
Frequency distributions from *Grieve and Shoemaker* (1994) and *Neukum and Ivanov* (1994).
Spherical projectile: $V = 4/3(\pi)r^3$.
Projectile density = 3500 kg/m^3 (stony meteorite).
Impact velocity = 20 km/s vertical impact.
Crater diameter/projectile diameter is constant, = 20 for all crater sizes.
Crater-forming energy = projectile kinetic energy = $1/2\ mv^2$.
J = joules, m.y. = million years, M = Richter magnitude, E = exponential notation (E + 6 = 1 million, etc.), MT = megatons.
Impact structures shown in boldface type.

Geologically based estimates for the terrestrial impact rate have been obtained from the number of large (D ≥ 20 km) impact structures identified in stable, well-preserved regions of Earth (*Grieve,* 1991; *Grieve and Shoemaker,* 1994; *Shoemaker and Shoemaker,* 1996]. This value, $(5.6 \pm 2.8) \times 10^{-15}$ craters/km^2/yr, is comparable with that deduced from astronomical data (chiefly from crater counts on the Moon's surface), although the stated 50% uncertainty is probably a minimum value. This rate implies that, over the whole Earth, a few (perhaps 1–5) craters of this size (D ≥ 20 km) should be produced every million years or so by the impact of projectiles ≥1–2 km in diameter. In these models, the average impact frequency varies approximately with the inverse square of the crater diameter, implying that about 10 craters of diameter ≥10 km should form in the same million-year period, while a crater ≥100 km in diameter should be formed every 10 m.y. or so. Other models for impact frequencies (e.g., *Neukum and Ivanov,* 1994) yield numbers of craters that are lower by factors of 5–10, especially for larger structures.

Nevertheless, these estimates are useful approximations, and they demonstrate that even very large impacts are not an unusual phenomenon when one thinks in terms of geological periods of time.

2.3.3. An Uncertain Future?

The frequency with which extraterrestrial objects collide with Earth, and the sizes of craters produced by the collisions, are not just interesting scientific problems. They are matters for serious concern about the future of our society, perhaps even of our species. We know that extraterrestrial bodies collide with Earth today, we have demonstrated that they have collided with it in the past, and we must face the fact that they will continue to collide with it in the future. It is not a question of whether such collisions will occur; the only questions are when, how big, and what the effects will be.

The hazards of such future collisions have been discussed in detail elsewhere (*Chapman and Morrison,* 1989, 1994; *Morrison,* 1992; *Gehrels,* 1994; *Verschuur,* 1996). Large impact events are rare, but they cannot be ignored just for that reason. Such events are unpredictable and might happen at any moment. The impact of an object only 50 m across, forming a crater only a kilometers in diameter [e.g., Barringer Meteor Crater (Arizona)], would totally devastate an area of several thousand square kilometers around the impact site (*Kring,* 1997). The probability of a larger event, sufficient to cripple or possibly destroy our current interconnected and technology-dependent civilization, although small, is very real (*Chapman and Morrison,* 1994), and we do not yet know enough to evaluate the danger.

Although much of the concern for assessing and removing impact hazards lies in other areas, particularly social and political, the scientific study of impact events can play a crucial role in understanding and possibly preventing the catastrophic damage that would be caused by a large impact event in the future. The geological structures left by past impact events can give us information about the frequency of large impact events, the sizes of the projectiles, the energy released, and the environmental damage produced over regional or global distances. At the same time, continued observation of the solar system can inventory the existing population of near-Earth asteroids and comets and can help estimate the chances of future collisions. With such data, the threat from extraterrestrial objects can be better evaluated, and people and governments can determine what — if anything — can be done to avoid a catastrophic disaster in the future.