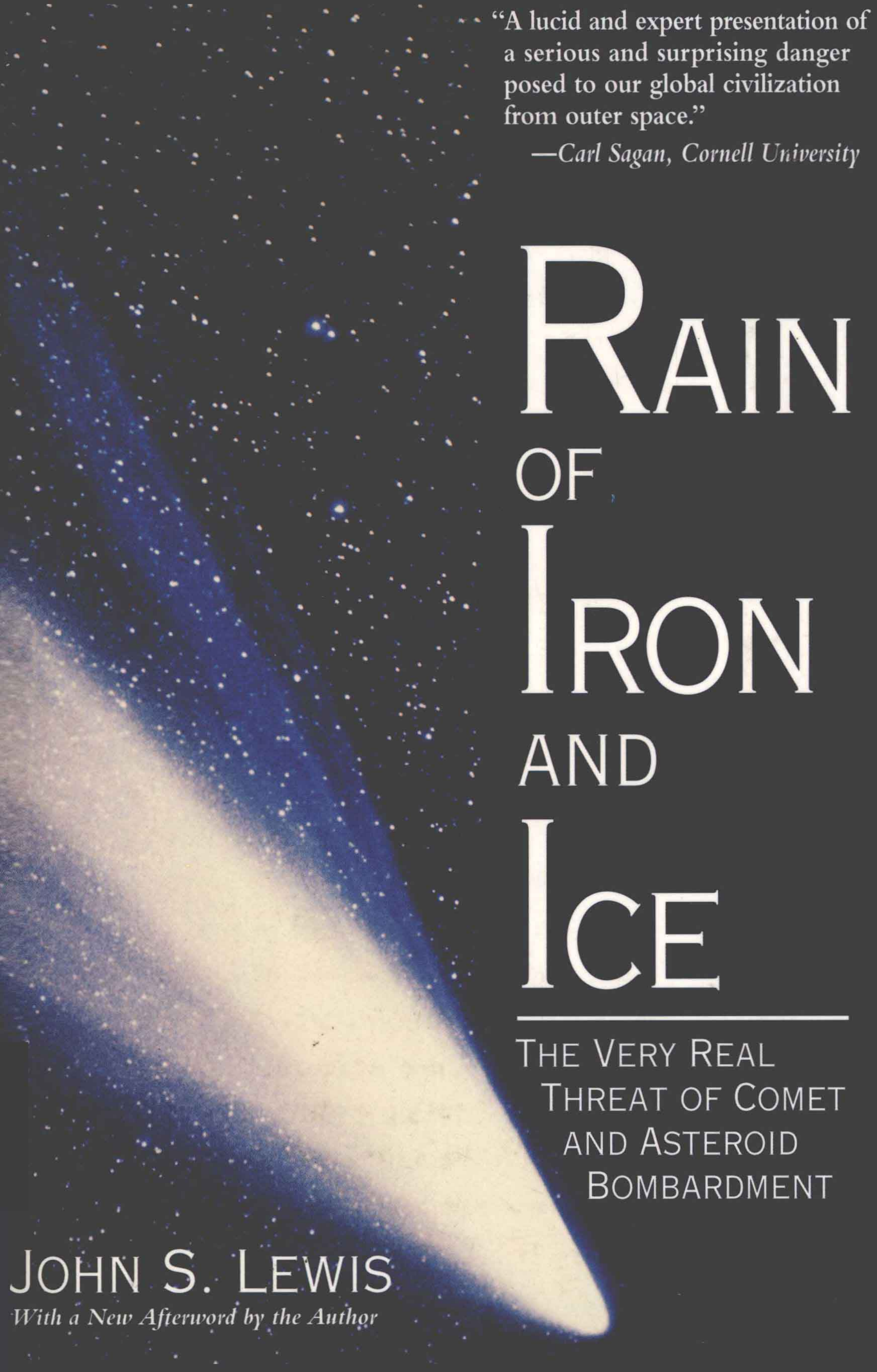

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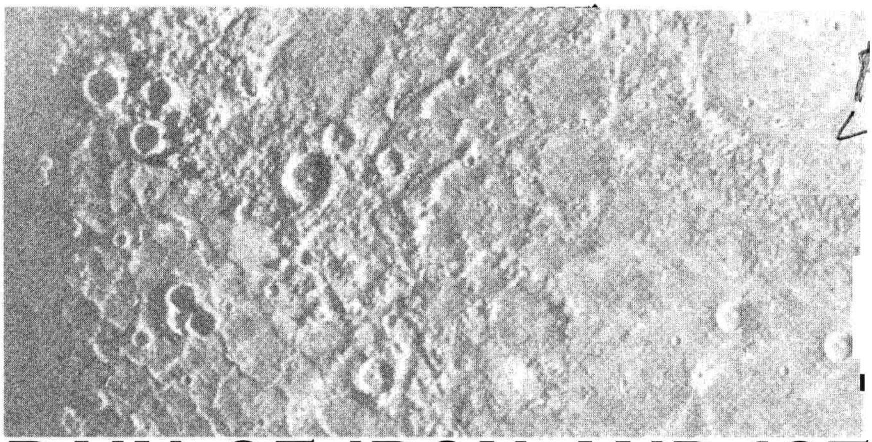
—*Carl Sagan, Cornell University*

Rain of Iron and Ice

The Very Real Threat of Comet and Asteroid Bombardment

John S. Lewis

With a New Afterword by the Author



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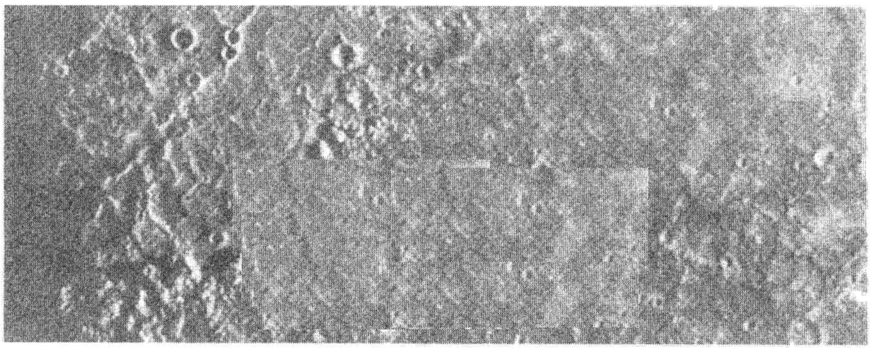

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RAIN OF IRON AND ICE

To my wife,

Ruth Margaret Adams Lewis

and

to my best friend

Peg,

who,

fortunately,

are one and the same person.

Deux ou trois pages auraient suffi pour la Vérité;
les passions firent des Livres.

ACADÉMIE ROYALE DES SCIENCES,
Paris. Histoire (1710)

TRANSLATION:
Two or three pages suffice to convey the truth;
it is passions that make books.

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RAIN OF IRON AND ICE

CONTENTS

INTRODUCTION

It was a warm, clear afternoon in the capital. The bustle of metropolitan commerce and tourism filled the streets. Small sailing vessels dotted the sheltered waters within sight of the government buildings, riding on a soft southerly breeze. The Sun sparkled on the gentle swells and wakes, lending a luminous glow to the poppies and tulips nodding in the parks along the water's edge. All was in order. But suddenly the sky brightened as if with a second, more brilliant Sun. A second set of shadows appeared; at first long and faint, they shortened and sharpened rapidly. A strange hissing, humming sound seemed to come from everywhere at once. Thousands craned their necks and looked upward, searching the sky for the new Sun. Above them a tremendous white fireball blossomed, like the unfolding of a vast paper flower, but now blindingly bright. For several seconds the fierce fireball dominated the sky, shaming the Sun. The sky burned white-hot, then slowly faded through yellow and orange to a glowering copper-red. The awful hissing ceased. The onlookers, blinded by the flash, burned by its searing heat, covered their eyes and cringed in terror. Occupants of offices and apartments rushed to their windows, searching the sky for the source of the brilliant flare that had lit their rooms. A great blanket of turbulent, coppery cloud filled half the sky overhead. For a dozen heartbeats the city was awestruck, numbed and silent. Then, without warning, a tremendous blast smote the city, knocking pedestrians to the ground. Shuttered doors and windows blew out; fences, walls, and roofs groaned and cracked. A shock wave raced across the city and its waterways, knocking sailboats flat in the water. A hot, sulfurous wind like an open door into hell, the breath of a cosmic ironmaker's furnace, pressed downward from the sky, filled with the endless reverberation of invisible landslides. Then the hot breath slowed and paused; the normal breeze resumed with renewed vigor, and cool air blew across the city from the south. The sky overhead now faded to dark gray, then to a portentous black. A turbulent black cloud like a rumpled sheet seemed to descend from heaven. Fine black dust began to fall, slowly, gently, suspended and swirled by the breeze. For an hour or more the black dust fell, until, dissipated and dispersed by the breeze, the cloud faded from view.

Many thought it was the end of the world. . . .

Reconstruction of events in Constantinople, A.D. 472

Earth, like its sister planets, experiences an erratic but unceasing rain of comets and asteroids which has profoundly affected its geological and biological history and which exposes its inhabitants to continuous risk of disaster. From time to time, enormous explosions affect the entire surface of Earth, excavating huge craters and making the biosphere briefly hostile to life. Much more frequently, small impactors have a devastating local effect similar to that of a multimegaton nuclear airburst.

Awareness of this danger dates back to the earliest human records. Mythology fairly drips with frightening allusions to cometary omens, celestial serpents, fiery dragons, mass disasters inflicted from above, entire cities destroyed by "lightning bolts," and the fall of alien materials from the skies. But myths, however often they may be based on actual events, have been filtered through countless generations of retelling, editing, and reinterpretation. Millennia after all eyewitnesses to these events have died, taking with them almost all of the circumstantial evidence of names, dates, places, and observed phenomena, the stories survive largely as cautionary tales, transmitted for their moral value and mythic grandeur. Their worth as firsthand accounts has been all but destroyed—but the fear, the horror, the raw emotional impact, have remained intact. The original eyewitnesses did not understand the phenomena they saw, and those who passed the stories down through the centuries neither understood nor observed any such events themselves. It is hard to doubt that the ancients witnessed countless events that are relevant to our story, but it is difficult to reconstruct these events from their lingering echoes in myth.

Although a general human awareness of cosmic bombardment can be traced back to ancient times, our ability to understand and predict these devastating events is of recent vintage. Fortuitously, a number of exciting but seemingly unrelated twentieth-century discoveries in many different fields of science have converged into a single vast drama; a kind of all-enveloping detective story in which we all are players. This story tramples traditional disciplinary boundaries and exposes time-honored philosophical principles to direct experimental tests. Our understanding of astronomy, geology, and biology is illuminated by this new insight: we see Earth's surface not in quasi-mystical terms as a uniquely sheltered refuge for life, but as a part of the fabric of the solar system, subject like other bodies to rare, cataclysmic change. The origin and fate of species are, we find, linked to events unknown to Darwin. The dominance of the human race, of mammals, of land life, the very existence of life on this planet may be consequences of our bombardment history.

It was not easy for the experts of earlier centuries to accept that Earth is constantly showered by rocky debris from asteroids and comets. Reports of meteorite falls by peasants were treated with ultimate disdain by "authorities" who derived their knowledge of nature not from observation and experiment, but from reading the dogma of Aristotle, Galen, Ptolemy, and the sages of the Church. It was only in the philosophical and political wake of the American and French Revolutions that such reports were sought out and analyzed by the real authorities: scientists who knew that their knowledge and understanding were imperfect, and who believed that both could be improved, perhaps even perfected, by diligent recourse to observation and critical analysis. The stories of several meteorite falls before 1800 are discussed in chapter 1 as illustrations of the great cultural change from the scholastic world of medieval Europe to the empirical world of the Age of Reason and of the changing of the guard at the Citadel of Truth and Traditional Wisdom.

If it was difficult to accept that kilogram-sized pieces of rock and iron could fall from the sky, it was vastly harder to contemplate mountain-sized impactors colliding with Earth at speeds of tens of kilometers per second. The first craters studied on Earth, which belonged to active volcanoes, called attention to themselves by means of spectacular eruptions. When other craters, showing different properties, were discovered, it was tempting to attribute them to the same familiar volcanic processes. Indeed, large craters with absolutely no sign of volcanic influence were disingenuously named "cryptovolcanic," meaning that all evidence of volcanic activity was *hidden.* It was only through extensive fieldwork and the recovery of numerous unambiguous meteorite fragments from Meteor Crater in Arizona, as recounted in chapter 2, that the door was opened to recognizing impact cratering as an important terrestrial process.

Early in the twentieth century, while American geologists were coming to grips with impact cratering on Earth, Russian scientists were puzzling over the astonishing event of June 30, 1908. Workers on the Trans-Siberian Railroad witnessed a brilliant daytime fireball burning across the sky to the north. The fireball passed over the northern horizon and had nearly faded from view when the sky was lit by a tremendous flash. A column of smoke and fire shot up above the horizon with astonishing violence. Even at great distances from the blast, many unusual effects were reported. The shock wave of a huge explosion traveled around the world, and dust from the blast lit the skies of western Europe for days afterward. But Russia was then in such a state of political chaos that no expedition could be mustered to search for the impact crater.

In 1927, when the political situation in Siberia had sufficiently settled down, an expedition was sent in to study the expected impact crater in the Tunguska taiga. But, as recounted in chapter 3, no crater was found. Instead, some two thousand square kilometers of boreal forest were devastated by fire and blast effects, attesting to an unprecedentedly powerful aerial explosion. What could possibly have caused such a violent blast? Why was no crater formed? How often do events of this sort, which leave no enduring geological record, happen on Earth? Many answers to these questions were proposed in the following years, but true understanding had to await the arrival of the atomic bomb.

From the time of the first nuclear explosion in New Mexico in 1945, and emphasized by the cruel fate of Hiroshima and Nagasaki, it was obvious that radiant heating by an extremely energetic fireball must have been the culprit at Tunguska. Experiments with atomic and hydrogen bombs in Nevada and Kazakhstan, described in chapter 4, led to a growing understanding of the physical and chemical effects of large explosions. Leaving aside those effects caused solely by nuclear reactions, very large nonnuclear explosions could be expected to produce powerful blast waves, sear the ground near them, and, if the explosion was on or near the surface, excavate a crater. The hot explosion fireball is very buoyant and rises rapidly, generating wind speeds of up to about a third of the speed of sound and forming the familiar mushroom cloud of rising, cooling gases and debris. Nitrogen in the air, heated to temperatures of many thousands of degrees in the fireball, partly burns to make nitrogen oxides, noxious gases that lend a red-brown color to the cooling fireball. Dust is raised by near-surface bursts and lifted to high altitudes by the mushroom cloud. Even modest-sized nuclear explosions can have effects detectable over intercontinental distances.

But full acceptance of the importance of large impacts on Earth had to await the exploration of the solar system by spacecraft. In the 1960s, beginning with the first unmanned missions to the moon, it was found that craters of all sizes were widely but unevenly spread over the entire lunar surface. The volcanic interpretation of lunar craters, popular among geologists early in the twentieth century, faded under the barrage of data from planetary scientists. Chapter 5 relates the discovery of heavy cratering on Mars and Mercury, and the application of these planetary data to interpretation of craters found on Earth by geologists. Application of space techniques to the study of Earth permitted the discovery and identification of many more terrestrial impact craters, and dating of materials returned from the Moon by both manned and unmanned missions permitted us to estimate the rate of cratering on both the Moon and Earth. By 1970 it was proven beyond doubt that impacts of comets and asteroids on Earth were of great importance over the span of geological time. Further, it became natural and timely to search for bodies in threatening orbits.

The new perspective provided by space exploration gave both scientists and the public a global view of Earth and an appreciation of its environment in the solar system. The recognition of both asteroids with orbits that crossed that of Earth and bodies that actually skimmed through Earth's atmosphere and escaped brought home the intimate association between cosmic and terrestrial events. Chapter 6 recounts the systematic search for Earth-crossing bodies, culminating in the application of modern sensor and computer technology to this problem in the Spacewatch program. The story of the discoveries by these search programs leads naturally into an extrapolation into the near future: How can we best search for threatening objects, and how many can we expect to find?

Another discovery from the early space age was the mechanism responsible for raising intense planet-wide dust storms on Mars. Computer modeling of the effects of dust on the Martian climate showed that large dust burdens in the atmosphere reflected much of the incident sunlight back into space, causing global cooling of the surface. In chapter 7 we see how atmospheric scientists tied together the story of dust storms on Mars and the effects of nuclear weapons to predict that a nuclear war would lift enough dust and soot into Earth's atmosphere to trigger a "nuclear winter." During the several months to one year that the dust remained in the atmosphere, temperatures in continental interiors would plummet, causing global crop failures and mass starvation.

Paleontologists studying the pattern of appearance and disappearance of species in the fossil record have long been aware of abrupt, devastating global extinction events occurring at the ends of geological ages. The greatest of these is at the end of the Permian era, and the second greatest marked the end of the Cretaceous era. In 1981 a team of physicists and geologists headed by Luis Alvarez of Berkeley discovered that a thin, global sediment layer that separates the end of the Cretaceous era (the last period of the age of dinosaurs) from the beginning of the Tertiary era (the start of the age of mammals) contained the unmistakable signature of an asteroid or comet impact. A number of metals, such as iridium, that are very rare in Earth's crust but common in meteorites, were found to be dramatically enriched in that layer. Further, as we discuss in chapter 8, the layer, which is dominantly composed of a very fine-grained clay, was found to contain tiny particles of minerals that had experienced extremely high shock pressures. The layer also contains a large amount of soot, and in some locations a generous admixture of tiny glassy beads called microtektites. The layer is at least a millimeter thick over the entire planet, enough to ensure an intense global nuclear winter, but is considerably thicker at some locations in the Americas. In Haiti it is found in association with, and painted on top of, a rubble layer tens of meters thick. Recently the "smoking gun" has been found: a huge 65-million-year-old crater over two hundred kilometers in diameter, buried under more recent sediments on the north shore of Mexico's Yucatán Peninsula. The end of the Cretaceous era is one of the most interesting and important markers in the geological history of Earth: it is the time of a devastating biological extinction event, in which the pattern of life on the continents and in the oceans changed dramatically in a geological instant.

It is reasonable to ask whether Earth and its twin, Venus, have experienced similar geological histories, but the dense, permanent cloud layer of Venus long frustrated man's efforts to study its surface. The *Magellan* radar-mapping mission was designed to penetrate the dense cloud layer and return detailed radar images of the surface geology. One of the most exciting results of this study of "Earth's twin gone wrong" has been the discovery that, unlike the Moon, Mercury, and even Mars, the number of craters on Venus does not increase rapidly toward smaller sizes: Not only are craters smaller than a few kilometers in diameter extremely rare, but there is a clear tendency for large craters to form pairs and clusters. Chapter 9 relates and interprets the discoveries of the *Magellan* mission regarding the final disintegration of comets and asteroids during high-speed entry into planetary atmospheres. The dense atmosphere of Venus serves as a cushion to not only protect the surface from kilometer-sized impactors, but also decelerate and capture gases released by comets and asteroids as they fragment and burn up. Atmospheric breakup, although less extreme on Earth than on Venus, is still an important factor here, giving us an insight into the nature of Tunguska-type impactors.

In the fall of 1992 a group of radar astronomers were examining Mercury at a time when the relative positions and orientations of Earth and Mercury provided an unusually clear view of the north polar region. Much to the astonishment of the observers, the radar image clearly showed a small, circular, highly reflective region on the floor of a large crater adjacent to the pole. The radar signature of this bright reflective material can be produced by only one known material: ordinary ice. Later observations of the other pole showed another small, bright cap there. Thus Mercury, scorched by the Sun at all other latitudes, almost miraculously has been able to produce and maintain two polar ice caps. Theoretical studies described in chapter 10 suggest that impacts of water-rich asteroids are the most likely source of ices on Mercury, and underline the importance of impacts as a source of atmospheric gases on Venus—and on Earth.

In the spring of 1993 came the astonishing news of the discovery of a peculiar comet-like body called Shoemaker-Levy 9. Photographs showed it to consist of twenty or more radiant pieces in a straight line, embedded inside an extensive bright cloud. A search for the distinctive spectral lines emitted by gases in the supposed comet turned up negative: the diffuse cloud is dust, not gas. As observations of this body accumulated, it was soon determined that Shoemaker-Levy 9 was actually in an extremely elongated elliptical orbit around Jupiter. This was quickly followed by the discovery that its orbit had taken it very close to Jupiter in July 1992, so close that the gravitational (tidal) attraction of Jupiter at the surface of Shoemaker-Levy 9 must have been significantly larger than its own surface gravity. In effect, it was pulled apart by Jupiter's powerful gravity. Even more astonishing, it was found that in its present orbit the entire "string of pearls" would impact on Jupiter in July 1994, causing a spectacular series of gigantic explosions extending over several days. Chapter 11 connects the most recent observations of Shoemaker-Levy 9 to other astronomical lore on the breakup of comets and asteroids, satellites of asteroids, crater clusters on Venus and Earth, and crater chains on Jupiter's giant icy satellites Ganymede and Callisto.

Given the evident importance of impacts on the atmospheric evolution of Venus, and the inevitability of oceanic impacts on Earth, it has become ever more urgent to understand the effects of large impacts on fluid (oceanic and atmospheric) targets. Applying current impact theory to Mars gives a startling result: impacts are capable of removing atmosphere from Mars and ejecting it into space at a speed greater than the planet's escape velocity. Impacts erode the atmosphere irreversibly. Over geological time it is likely that impacts have reduced the mass of the Martian atmosphere by a factor of one hundred. Impacts on Earth differ from those on Mars in that terrestrial impacts have a high likelihood of encountering an ocean. A violent explosion in the ocean will inevitably raise powerful waves, or tsunamis, that can run thousands of kilometers across deep ocean basins with trough-to-crest heights of a few meters and crest-to-crest lengths (wavelengths) of several kilometers. Chapter 12 describes how tsunami waves narrow as they encounter the shallows above continental margins, climbing to heights of hundreds of meters or even kilometers above sea level. Moderate-sized impacts, even in remote oceanic areas with low population densities, may have devastating and lethal effects half a world away.

The effects of comet and asteroid impacts are potentially damaging to life in general, and to human civilization in particular. In the long term, impacts with devastating global effects are very rare, happening in intervals of 10 million years or so. On the scale of a human lifetime, global catastrophes are improbable: the probability of such an event (an impact of 100 million megatons or more) happening during any given generation is less than 0.00001. But *locally* devastating impacts are vastly more common. A mere one hundred megatons can cause severe local destruction, and one-hundred-megaton explosions occur at an average rate of one per millennium. In the twentieth century alone, tens of megatons of explosive power have been liberated in the atmosphere by cosmic impacts. About three-fourths of these impacts struck the oceans and polar regions. The Tunguska event alone was about fifteen megatons, and several other multimegaton events probably occurred in remote, unobserved areas. What are the real hazards from these smaller, much more numerous impactors? Chapter 13 collects eyewitness reports on damage, injuries, and deaths from meteorites and impactor explosions over the past few centuries and discusses the reliability and completeness of the information at our disposal. It also summarizes reports of mysterious aerial explosions over metropolitan areas drawn from newspapers and magazines.

Pulling together all we presently know about the compositions, strengths, orbits, and numbers of comets and asteroids in near-Earth space, we can develop a computer simulation of bombardment activity for a typical century. By running this model for many centuries, we develop a sense not only of the magnitude of the threat to life and property, but also of the extreme randomness and variability of