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FOREWORD BY ARTHUR C. CLARKE

ROGUE ASTEROIDS AND DOOMSDAY COMETS

THE SEARCH FOR THE MILLION MEGATON MENACE THAT THREATENS LIFE ON EARTH

DUNCAN STEEL

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The Search for the Million Megaton Menace That Threatens Life on Earth

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Foreword by Arthur C. Clarke

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Rogue Asteroids and Doomsday Comets

Foreword

I began the "Sources and Acknowledgments" of my recent factually based novel, *The Hammer of God*, with the words "My involvement with the subject of asteroid impacts is now beginning to resemble a DNA molecule: The strands of fact and fiction are becoming inextricably entwined." *Rogue Asteroids and Doomsday Comets*, of course, adds to that involvement, providing another twist to the entanglement.

Back in 1973, I opened *Rendezvous with Rama* with an account of an impact upon the Earth in 2077 and its awful consequences. Duncan Steel has repeated those words, which still ring true, here in Chapter 11. Two decades ago, we knew comparatively little about the effects of asteroids and comets upon our environment—for example, the Tunguska event of 1908 was a mystery: How could it have left no crater if it were a fragment of a comet?—but research in the intervening two decades has shown that, to a large extent, I got it right. I suggested there that humankind would be spurred into starting a perennial surveillance program to ensure that, post-2077, such an event would never again occur. That program I entitled Spaceguard. In serving on NASA's International Near-Earth Object Detection Workshop (a mouthful of a name for any committee), Steel pointed out that in *Rendezvous with Rama* I had foreseen the type of search program that the committee had been charged by Congress with recommending, although I had based my fictional search on radar methods rather than optical scanning. It was flattering that *The Spaceguard Survey* was adopted as the title for that recommendation.

In between times, remarkable leaps have been made in our understanding of impacts and how they affect life on Earth. Probably the greatest single impetus helping to make this a respectable subject of study was the publication in 1980 of the startling theory that the mysterious sudden demise of the dinosaurs was due to a massive asteroid impact. That hypothesis, developed by Nobel laureate Luis Alvarez and his geologist son, Walter, was based upon their discovery of a huge anomaly in the amount of the rare metal iridium in the geological stratum from the time of the extinction—rare on Earth, but not so rare in meteorites. That development is described herein, along with the more recent ideas that indicate that there have been many mass extinctions in the past few hundred million years caused by such impact catastrophes. To add another twist to the DNA molecule, my only *non*-science fiction novel, *Glide Path* (1963), is dedicated to "Louie and his colleagues." In the closing years of the war, I was responsible for running the prototype ground control approach (GCA) unit, which he invented, though we did not actually meet until ten years later.

Because the subject was now respectable, and suitable for discussion in works of fact as well as fiction, magazine stories aplenty started to appear. In May 1992, I was flattered to receive a letter from *Time* magazine asking me to write a short story for their special "Beyond the Year 2000" edition, to "give readers a snapshot of life on Earth in the next millennium." This was only the second piece of fiction to appear in *Time*, being preceded by a story from Alexander Solzhenitzyn, published in 1969.

With the just-completed *Spaceguard Survey* report in my hands, I had the factual material available in order to provide a sound basis for my story, which duly appeared (see *Time* magazine, Fall 1992, volume 140, number 27). But that short story was not the end of it.

Duncan Steel and I were born in the same county, Somerset in western England, which explains our similar accents. In the middle of 1992, my brother Fred had organized a space festival in the town of my birth, Minehead, to celebrate my 75th year, and Steel came back from Australia to give a presentation about the real-life Spaceguard. That, among other things, convinced me that *The Hammer of God* should be a full novel. This was brought home by a message that Steel sent me soon after he had returned to Australia and I to Sri Lanka. The chronology I spell out in the factual part of *The Hammer of God*, but briefly Steel's message pointed out that the recently rediscovered Comet Swift-Tuttle might be coming back to strike the Earth in 2126. The excitement engendered in the world's media over this possibility—possible with the state of our knowledge then, although we now know that the comet will miss our planet by two weeks—was more than enough to convince me that readers would be interested in a full novel. I was excited as well, because in *Rendezvous with Rama* I had set the arrival of the hypothetical Kali in the year 2110, just sixteen years ahead of the real Comet Swift-Tuttle.

If there is interest in a fictional account of humankind being saved from a calamitous impact, then surely there must also be interest in the facts upon which my writings are based. In this volume, Steel sets out those facts as we understand them today. The statistics are worrying in some respects. Many might say, "But we know of no one that has died from an asteroid impact." That's true, but then who has ever died from a thermonuclear explosion? Surely no one would claim that *they* are not dangerous?

Finally, I cannot resist the temptation to gloat over two other statements that I have made in my publications. First, with regard to the Tunguska event, in part of this book Steel describes how his view of the hazard of asteroids and comets differs from the mainstream belief of scientists working in the area, and in particular how he sees relatively small objects in the Taurid meteoroid stream as posing the major risk. Back in 1980, in *Arthur C. Clarke's Mysterious World*, I pointed out that the Tunguska object was quite likely a member of that stream, a suggestion for which I am pleased to see I am duly credited in Chapter 9!

Second, as I write, the astronomical world waits with bated breath for the impacts of the fragments of Periodic Comet Shoemaker-Levy 9 on Jupiter. Some have suggested—in error—that those impacts might be enough to cause nuclear fusion to initiate in the core of that planet, turning it into a second sun. Precisely such an event, though with a somewhat different scenario, was the climax of *2010: Odyssey II*, splendidly rendered in the movie version. Though I do not for a moment believe that this will actually happen* (Jupiter would have to possess ten times its present mass to become a sun, and that of any comet is quite negligible), I am not averse to generating a little alarm. For the case of impacts upon the Earth, a little alarm is what is needed to get Spaceguard funded and under way, thus helping to guarantee that humankind will see not just 2001, but 3001 as well.

ARTHUR C. CLARKE

Colombo, Sri Lanka
June 1994

*Author's Note: What actually transpired in these phenomenal Jovian impacts (see Epilogue) entirely confirmed Clarke's predictions.

Preface

My intention in writing this book has been to present the facts and our scientific beliefs (and uncertainties) about the terrestrial impact hazard due to comets and asteroids in an easily understood way. I strongly believe that this is such an important subject that the public needs to be properly informed so that educated decisions may be made about how we should be addressing this hazard. Clearly, I am of the opinion that this is a problem that can and should be not only tackled, but also solved, because the future of the human race and all other forms of life on Earth may very well depend on doing so. Inaction at this stage is simply an indulgence in a game of Russian roulette, whether or not we know that the gun is pointing at us, and whether or not we realize that the trigger is being pulled. For the first time since life began on Earth, a species has the ability to ensure that life continues without a repeat of the impact-induced mass extinctions that have occurred in the past and will almost certainly recur in the future unless we intervene.

I have not intended to give a complete bibliography or to cite every single original reference that has provided a building block, no matter how small, to the citadel of knowledge on this topic; to have done so would have added considerably to the length of this book and would have been of little or no interest to most readers. I have, however, given references to some of the most pertinent or unusual publications that the keen reader may want to access, and have included suitable review papers for those who may want to pursue the details. The majority of the works cited should be intelligible to the interested layperson. For the reader who wants to delve even deeper, there is practically no limit to the amount of time that might be spent on following up the latest information on asteroids and comets. Original research papers running to many thousands of pages are published on this topic every year in a wide variety of scientific journals.

Of necessity, a book such as this contains certain technical terms with which the reader might not be familiar. These have been described, so far as is possible, in the Glossary or are defined as they are introduced in the main text. Although the reader will certainly be familiar with, for example, the word *comets*, the discussion in the Glossary might be of use in developing an understanding of how comets fit into the general scenario. It is hoped that unnecessary jargon has been largely excluded.

A large number of people have assisted me at various stages of the preparation of this book, either directly, with answers to my requests for information, or indirectly in discussions that may at the time have been seemingly unrelated. I have tried to make a list that is as complete as possible, but it is virtually certain that I have left someone out—my apologies. Anyway, I have much appreciated, in no particular order, the help of Rob McNaught, Brian Marsden, Graff Williams, Victor Clube, David Asher, Mark Bailey, Gerhard Hahn, Graeme Waddington, Bill Napier, Annette Callow, Russell Cannon, Robyn Shobbrook, Arthur C. Clarke, Stephen Bain, Paul Davies, Ken Russell, Tony Beresford, Gene and Carolyn Shoemaker, David Levy, Tom Gehrels, Bob Dean, Roy Antaw, Rhonda Martin, Malcolm Hartley, Gordon Garradd, Paul Cass, Lewis Jones, Graham Elford, Colin Keay, Herb Zook, Glo Helin, Jim Scotti, David Rabinowitz, Gennadij Andreev, Richard Grieve, Janice Smith, John Campbell, Alan Gilmore, Pam Kilmartin, Andrew Taylor, Jack Baggaley, David Morrison, Clark Chapman, Steve Ostro, Alan Harris, Don Yeomans, David Nicholls, Vic Gostin, Jim Klimchuk, Paul Thomas, Chris Chyba, Kevin Zahnle, Chris McKay, Sidney van den Berg, Michael Rampino, Shin Yabushita, Ichiro Hasegawa, Andrea Carusi, Robert Jedicke, Ted Bowell, Giovanni Valsecchi, Howard Jones, Tony McDonnell, Rick Binzel, Paul Almond, John Hanson, Aletha Jones, and, of course, my wife Helen and son Harrison, for whom asteroid 5263 Arrius is named.

DUNCAN STEEL

Coonabarabran, Australia
December 1994

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Fiddling While Rome Burns

It is difficult to overstate the almost unimaginable energy that is released when a massive asteroid or comet hits the Earth. Merely stating that the explosive power is far greater than all the world's nuclear arsenals combined does not properly convey matters. The reader may think that such combined power might simply result in a larger area being flattened than that which a nuclear bomb devastates. Instead of the holocaust wreaked in the few square kilometers of central Hiroshima, for example, we might imagine all the buildings in the metropolis of Los Angeles being toppled. In fact, the impact of a large asteroid or comet is quite different from that. Were one to land in Southern California, for example, all of Los Angeles along with several kilometers of the rock from the Earth's crust beneath it would be picked up and largely vaporized, lumps raining down on Hawaii and New York an hour or so later. Not that Honolulu or New York City would be left standing by then. Phenomenal seismic shocks following the impact would have already shaken them flat.

This is a terrifying scenario, certainly. But how likely is it? Scars left on the Earth's surface suggest it is far from science fiction. There are, in fact, many enormous craters on the surface of the Earth that have been conclusively identified as the fossils of just such impacts. The best-known crater in the world is Meteor Crater in northern Arizona. Twelve hundred meters wide, 170 meters deep, and 5 kilometers in circumference, Meteor Crater is the surviving scar from an iron meteorite thumping into the plains thereabouts around 50,000 years ago in a cataclysmic explosion that liberated energy equivalent to 20 million tons (Mt) of TNT. To put that number into perspective, consider that the explosion that formed Meteor Crater was equivalent to almost 2,000 times the power of the bombs dropped on Hiroshima and Nagasaki.

Impressive as it is, Meteor Crater is a relative newcomer, and a pipsqueak as craters go. Just a few years ago, another large impact scar—180 kilometers across—was identified on the Yucatán Peninsula in Mexico. The impact that left this crater is thought to have been capable of such damage that scientists theorize it provides the answer to the long-standing mystery concerning the cause of the dinosaur extinction 65 million years ago. Based on evidence in the fossil record, it seems that the environmental disaster wreaked by this impact was of such global proportions that it caused the extinction of a large fraction of the species then extant, including the dinosaurs, and heralded the beginning of the Tertiary era, and, of course, the ascendancy of the mammals. We will learn more about this crater, and this theory, later in the book. We will also see that the geological record shows plentiful evidence of other global environmental upheavals that can be linked to large impacts by asteroids and comets. It is only in recent years, however, that we have known how to identify much of this evidence.

The irony is that after spending billions of dollars sending men to the Moon and studying the craters there, we have at last realized that there are plenty of craters to study that are accessible at a rather more modest cost. There is, however, good reason that more craters haven't been identified sooner. For decades, maps of South Australia have shown a 35-kilometer-wide dry salt pan called Lake Acraman, but it was only in 1986 that geologists realized that this is the residual basin surviving from a colossal impact about 600 million years ago, forming a crater 90 kilometers across. The true nature of the lake was unrecognized for so long because the telltale signs of an impact have been worn away. Over the past 600 million years, the effects of wind, rain, and ice have gradually chipped away at the shape of the original crater. Other remnants of the impact were, however, left in the geological record some distance away. The collision that created the crater also caused a shower of rock to be disgorged from the site, which then rained down more than 300 kilometers away in a region where the mountains known as the Flinders Ranges now stand. At the time, that region was occupied by a shallow sea, so that the ejected rock accumulated in the sediment laid down there over eons, eventually buckling up to form the mountain range. We have been able to identify Lake Acraman as a crater because of the ejected rock fragments found in the Flinders, which are so different from the predominant local geology but are identical with the rocks at Lake Acraman.

Indeed, due to the obscurity of many of the craters on Earth, much of our initial knowledge about how craters are formed came not from the study of terrestrial craters, but from evidence gathered from studies of the lunar surface. If the Earth could be said to be pockmarked by craters, then the Moon appears to have had a more severe dose of the same ailment. Even a brief peek through a very modest telescope, or a perusal of satellite images, indicates that our lunar companion has suffered numerous and frequent impacts over the eons. In fact, the Moon's surface is so saturated with craters in many areas that any new incoming asteroid or comet will almost surely obliterate an old crater in order to produce a new one.

The origin of the lunar craters was a matter of dispute among astronomers through the ages, and their cause has only recently been settled, lending crucial support to the theories of the effects of impacts on Earth. Even at the start of the Apollo program just three decades ago, it was still the favored idea among many geologists and astronomers that the origin of the lunar craters was volcanic action, despite the fact that evidence from telescopic studies should have made it clear that impacts must have been responsible. For example, many craters show a central uplift or spike reminiscent of the surface profile in a cup of coffee after a sugar cube has been dropped into it—a rebound occurs, the coffee spurting upward. In the case of the huge energies and pressures generated in a big impact, the rock target behaves for a while as a fluid, but is then frozen into this characteristic rebound form—a sure sign of an impact crater.

The case was sealed, however, when the Apollo rock samples were inspected. First, metamorphism in the rocks, which is indicative of the phenomenal pressures generated in impacts, was identified immediately. In addition, study of the rocks showed that they were pitted and cratered throughout by telltale signs of energetic impacts; that is, dust particles too small to be seen with the eye had zapped into the Moon, causing tiny craters, around and within which the rock was melted to leave a glassy surface. Slightly larger projectiles, perhaps the size of a pinhead or more, had produced craters with dimensions of thimbles; such projectiles are called *meteoroids*. Indeed the whole of the lunar surface had clearly been turned over many times by relatively small impacts by such meteoroids, from pinhead to basketball size, a process that selenologists call *gardening*. And this process is still going on today on the Moon.

This discovery led to the obvious question: So why, apparently, didn't (and doesn't) a similar steady bombardment happen on Earth? Why was the Earth not similarly saturated with craters and why are we not constantly assailed by meteoroids? A quite simple calculation shows that the number of impacts per unit area of the Earth should, in fact, be about twice that of the Moon, because the Earth's larger gravity should pull more impactors in as they orbit the Sun. According to that calculation, the Earth should have 25 to 30 times the number of craters in total. Where are they? As in the case of the Lake Acraman crater, we now know that most of the craters formed on Earth must have been obscured. And as for the steady bombardment of meteoroids, we are shielded from them by the Earth's atmosphere.

The reasons that Earth craters are not obvious, and that we are not daily peppered with meteoroids like buckshot, are explained by the very different environment here on the Earth, compared with the Moon. We are well aware that the terrestrial water and oxygen supplies have made it possible for life to proliferate here and for you to be able to sit and read this book. But the air is also responsible for protecting us from the small meteoroids that would otherwise rain down, and the water is accountable for obliterating much of the evidence of large impacts that would otherwise have made clear to us our finite mortality—as a species, if not as individuals.

Meteoroids hit the lunar surface unimpeded by any atmosphere; shooting stars cannot be seen from the Moon. And once meteoroids strike the Moon, the craters that are produced remain as scars for eons, obliterated only if another chance impact happens in the same location. The Moon also has no rain or wind to erode away the craters. It has no continental drift and no active volcanoes, which have also played a part in obliterating or obscuring the craters on Earth.

The Moon has an environment friendly to incoming meteoroids, asteroids, and comets in that they reach the surface intact. The converse is true of Earth. A meteoroid approaching the Earth, maybe the size of a nut and bolt, starts to heat up as it meets the upper atmosphere. At an altitude of 120 kilometers, where the atmospheric density is only one ten-millionth of that at the surface, friction causes this heating, pounding the material into gas particles. By 100 kilometers' altitude, the material has heated up so intensely that it is not only melting, but also boiling off, producing a glowing trail, which you may witness as a shooting star. By 80 kilometers, there is practically nothing left of the meteoroid, and the shooting star has had its short burst and dies out, usually after just two or three seconds.

The larger the meteoroid, of course, the deeper it may penetrate into the atmosphere. Given a suitable composition (nickel-iron), density (high, around eight times that of water), a shallow-entry angle (so that it slows gradually, having a longer path through the upper atmospheric layers), and a low entry speed (11 kilometers per second being the lowest possible), a meteoroid the size of a basketball may reach the surface, although only a fist-sized chunk might remain. This could perhaps cause some damage or even injury—there have been a few cases in recorded history of humans being hit, and property damage occurs about once a year on average.

One particularly impressive meteoroid entry happened on April 9, 1993, when a very bright meteor—what is known as a fireball—was seen by hundreds of people over the south coast of New South Wales in Australia. Most had never seen anything like it before, and it engendered great excitement, to say the least. At the time, I told the media, who were clamoring for information, that such an event might be seen from any one spot only once every few years, maybe once every decade—and then only if you stayed up all night, every night, and kept your eyes open. It was therefore a source of some embarrassment when precisely a week later, an even bigger meteoroid—estimated at about 3 to 4 meters in size—arrived in the atmosphere high above the Queensland border, zipping across the sky on its southerly path across

New South Wales as it turned night into day for a few seconds, eventually petering out at a height of around 18 kilometers above the small city of Dubbo. On its supersonic path, it generated a shockwave felt in Dubbo and throughout the surrounding area to a radius of at least 100 kilometers. By the time that I got through to the main Dubbo police station switchboard 30 minutes later (to tell them what had happened), the operator had logged over a hundred calls from people claiming variously that a bomb had gone off, that a jet had flown just over their rooftops, or that someone or something was smashing into their house—a hundred calls at that station alone, with thousands more received elsewhere. It seems that many of the rest of Dubbo's 30,000 inhabitants were hiding under their beds, and the State Emergency Services had been alerted as houses were shaken to their foundations and windows vibrated. The energy released in the detonation was roughly equivalent to that released by the Hiroshima bomb, so the thought that a bomb had gone off was not so bizarre. This "bomb" went off, however, 18 kilometers above the city, which is close to twice the height at which a jumbo jet flies. And no meteorite reached the ground.

How could a mere lump of rock or ice produce such a gargantuan explosion? The answer is that at a speed of 30 kilometers per second, any solid body has a hundred times more energy available for destructive purposes than if it were made of pure dynamite. That sort of speed is outside the realm of our everyday experience: It is about a thousand times the highway speed limit in most countries and somewhat more than a hundred times the velocity of a jumbo jet. However, it is the speed with which we circle the Sun on planet Earth, imperceptably varying by a few percent between winter and summer. It also happens to be a reasonably good guess at the likely impact speed of an asteroid or comet smashing into our planet.

It is extremely fortunate, therefore, that the vast majority of potential impactors entering the Earth's atmosphere do not reach the ground. Even an asteroid as big as a city block will more than likely detonate high above the surface, and it is not until sizes larger than about 100 meters are reached that there is a strong chance of a cratering event. For 50-meter asteroids, the chance of reaching the surface intact is of the order of 1%.

So how many asteroids are there out there of truly dangerous size? If you walk along a beach and randomly pick up pebbles, you'll find that by far the largest fraction are small in size, with an ever-decreasing number of larger stones: For every one the size your fist, there are ten or twenty the size of your thumb, and maybe fifty the size of your little finger. The same sort of rule applies in space: For every grapefruit-sized meteoroid, there are a dozen apple-sized and a hundred pea-sized meteoroids. But, as we have seen, even a pea-sized meteoroid packs a punch. In fact, about the same punch as a stick of dynamite, using the "hundred times as much energy" rule. On a clear night you may see ten shooting stars (or meteors) per hour, their death throes illuminating the sky as they burn up 100 kilometers above your head. Those are due to meteoroids just the size of a pea. Once an hour you may see an especially bright one, perhaps due to a walnut-sized particle, and once every few hours a dazzling streak as a grapefruit-sized meteoroid meets its end in the tenuous air far above. A basketball-sized lump, giving a real humdinger, which may instantaneously light up the country around you, you'll see maybe once a month if you have the time and the patience. The question is, how long is it between the *big* lumps of rock or ice, which will punch through the atmosphere to wreak havoc below? The answer to that, according to our presently incomplete understanding, is about a century between 50-meter rocks potentially big enough to wipe out a city or even a good-sized European country or a small U.S. state (for example, New Jersey or Connecticut). Correspondingly, it is about 100,000 years between 1-kilometer asteroids and comets, which could kill a large fraction of humankind and send the rest back into a twenty-first-century version of the Dark Ages.

These chances may seem inconsequently slim, but given the evidence we now have that these cataclysmic events have happened in the past, and given a recent proliferation of findings of asteroids and comets that are on course to cross the Earth's path, we must consider very seriously the probability of future impacts. And our estimations need not be in the realm of the purely speculative. Indeed, in 1992, a great news frenzy was set off when a comet, which had been beyond the realm of our telescopes for 130 years, was rediscovered. Calculations of its orbit made at the time showed that it might well collide with the Earth on its next trip around. Nineteenth-century observations of that comet, discovered by American astronomers Lewis Swift and Horace Tuttle in 1862, suggested that it would be back in 1980–82, but it did not appear. Astronomers have known for more than a century that the