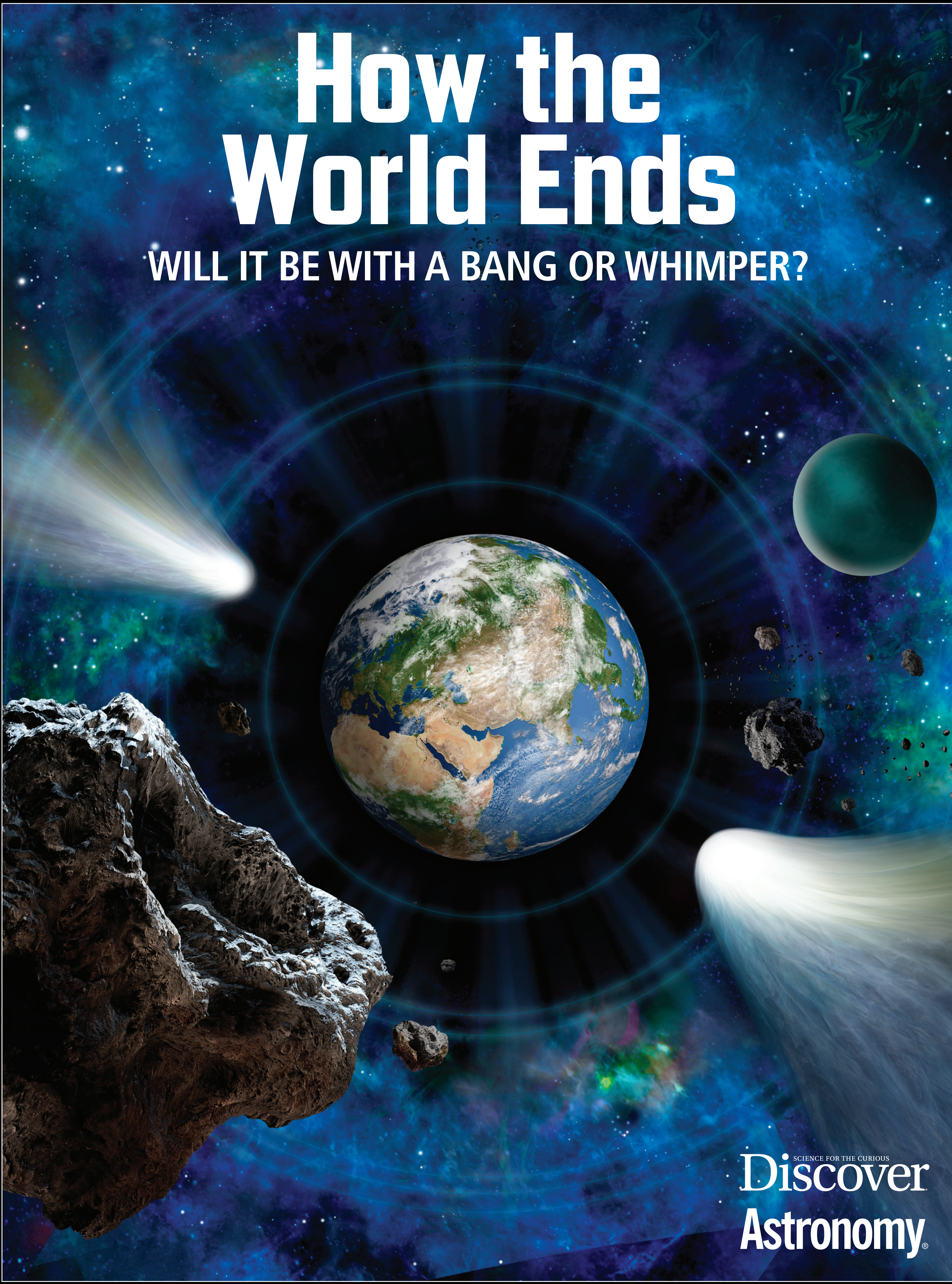
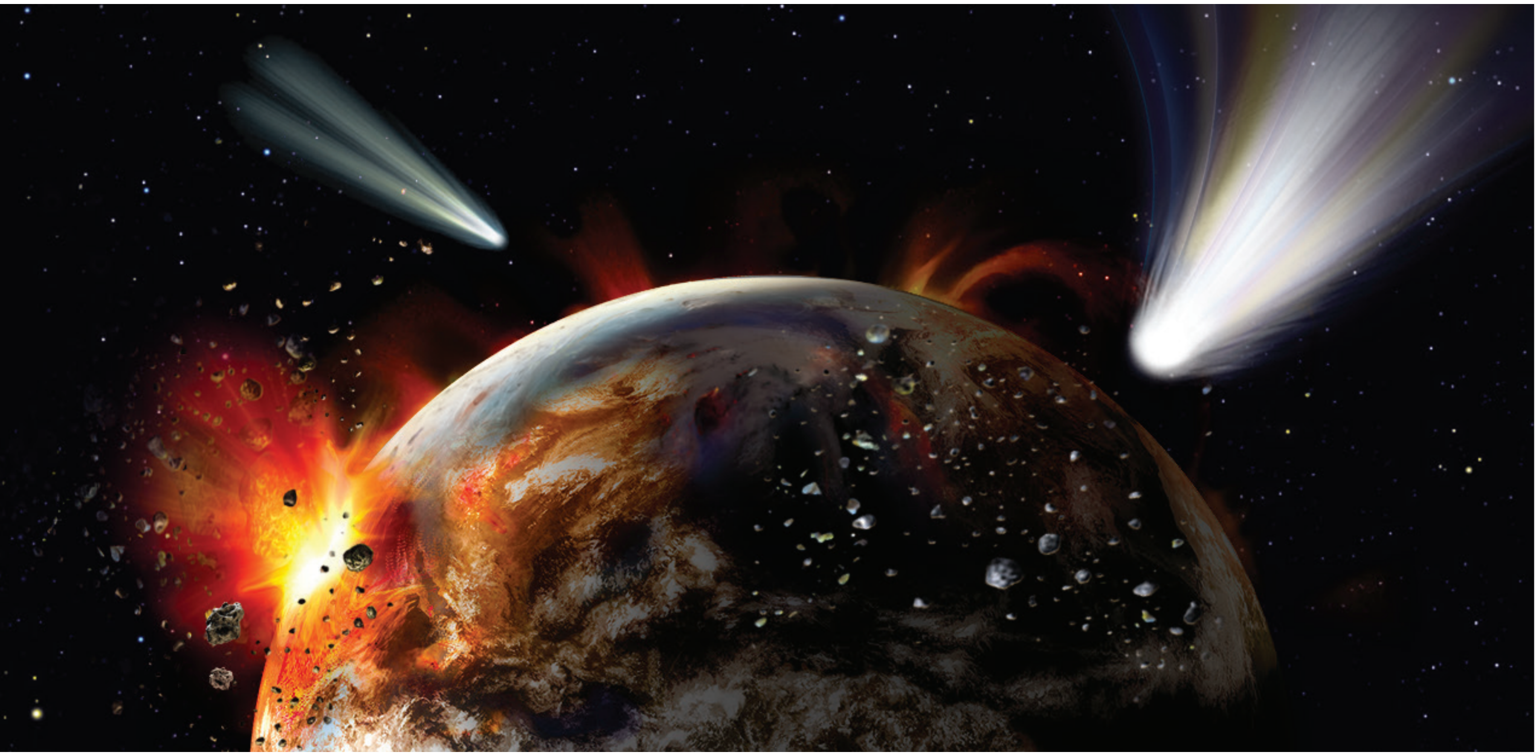


ROEN KELLY/DISCOVER

20 Ways the World Could End

Are we in danger of being erased from the universe? Here we look at the factors that could doom humanity: natural disasters, human-triggered cataclysms, willful self-destruction, and greater forces directed against us.

BY **COREY S. POWELL, DIANE MARTINDALE**



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We've had a good run of it. In the 500,000 years Homo sapiens has roamed the land we've built cities, created complex languages, and sent robotic scouts to other planets. It's difficult to imagine it all coming to an end. Yet 99 percent of all species that ever lived have gone extinct, including every one of our hominid ancestors. In 1983, British cosmologist Brandon Carter framed the "Doomsday argument," a statistical way to judge when we might join them. If humans were to survive a long time and spread through the galaxy, then the total number of people who will ever live might number in the trillions. By pure odds, it's unlikely that we would be among the very first hundredth of a percent of all those people. Or turn the argument around: How likely is it that this generation will be the one unlucky one? Something like one fifth of all the people who have ever lived are alive today. The odds of being one of the people to witness doomsday are highest when there is the largest number of witnesses around—so now is not such an improbable time.

Human activity is severely disrupting almost all life on the planet, which surely doesn't help matters. The current rate of extinctions is, by some estimates, 10,000 times the average in the fossil record. At present, we may worry about snail darters and red squirrels in abstract terms. But the next statistic on the list could be us.

NATURAL DISASTERS

1 Asteroid impact Once a disaster scenario gets the cheesy Hollywood treatment, it's hard to take it seriously. But there is no question that a cosmic interloper will hit Earth, and we won't have to wait millions of years for it to happen. In 1908 a 200-foot-wide comet fragment slammed into the atmosphere and exploded over the Tunguska region in Siberia, Russia, with nearly 1,000 times the energy of the atomic bomb dropped on Hiroshima. Astronomers estimate similar-sized events occur every one to three centuries. Benny Peiser, an anthropologist-cum-pessimist at Liverpool John Moores University in England, claims that impacts have repeatedly disrupted human civilization. As an example, he says one killed 10,000 people in the Chinese city of Chi'ing-yang in 1490. Many scientists question his interpretations: Impacts are most likely to occur over the ocean, and small ones that happen over land are most likely to affect unpopulated areas. But with big asteroids, it doesn't matter much where they land. Objects more than a half-mile wide—which strike Earth every 250,000 years or so—would touch off firestorms followed by global cooling from dust kicked up by the impact. Humans would likely survive, but civilization might not. An asteroid five miles wide would cause major extinctions, like the one that may have marked the end of the age of dinosaurs. For a real chill, look to the Kuiper belt, a zone just beyond Neptune that contains roughly 100,000 ice-balls more than 50 miles in diameter. The Kuiper belt sends a steady rain of small comets earthward. If one of the big ones headed right for us, that would be it for pretty much all higher forms of life, even cockroaches.

2 Gamma-ray burst If you could watch the sky with gamma-ray vision, you might think you were being stalked by cosmic paparazzi. Once a day or so, you would see a bright flash appear, briefly outshine everything else, then vanish. These gamma-ray bursts, astrophysicists recently learned, originate in distant galaxies and are unfathomably powerful—as much as 10 quadrillion (a one followed by 16 zeros) times as energetic as the sun. The bursts probably result from the merging of two collapsed stars. Before the cataclysmal event, such a double star might be almost completely undetectable, so we'd likely have no advance notice if one is lurking nearby. Once the burst begins, however, there would be no missing its fury. At a distance of 1,000 light-years—farther than most of the stars you can see on a clear night—it would appear about as bright as the sun. Earth's atmosphere would initially protect us from most of the burst's deadly X rays and gamma rays, but at a cost. The potent radiation would cook the atmosphere, creating nitrogen oxides that would destroy the ozone layer. Without the ozone layer, ultraviolet rays from the sun would reach the surface at nearly full force, causing skin cancer and, more seriously, killing off the tiny photosynthetic plankton in the ocean that provide oxygen to the atmosphere and bolster the bottom of the food chain. All the gamma-ray bursts observed so far have been extremely distant, which implies the events are rare. Scientists understand so little about these explosions, however, that it's difficult to estimate the likelihood of one detonating in our galactic neighborhood.

3 Collapse of the vacuum In the book *Cat's Cradle*, Kurt Vonnegut popularized the idea of "ice-nine," a form of water that is far more stable than the ordinary kind, so it is solid at room temperature. Unleash a bit of it, and suddenly all water on Earth transforms to ice-nine and freezes solid. Ice-nine was a satirical invention, but an abrupt, disastrous phase transition is a possibility. Very early in the history of the universe, according to a leading cosmological model, empty space was full of energy. This state of affairs, called a false vacuum, was highly precarious. A new, more stable kind of vacuum appeared and, like ice-nine, it quickly took over. This transition unleashed a tremendous amount of energy and caused a brief runaway expansion of the cosmos. It is possible that another, even more stable kind of vacuum exists, however. As the universe expands and cools, tiny bubbles of this new kind of vacuum might appear and spread at nearly the speed of light. The laws of physics would change in their wake, and a blast of energy would dash everything to bits. "It makes for a beautiful story, but it's not very likely," says Piet Hut of the Institute for Advanced Studies in Princeton, New Jersey. He says he worries more about threats that scientists are more certain of—such as rogue black holes.

4 Rogue black holes Our galaxy is full of black holes, collapsed stellar corpses just a dozen miles wide. How full? Tough question. After all, they're called black holes for a reason. Their gravity is so strong they swallow everything, even the light that might betray their presence. David Bennett of Notre Dame University in Indiana managed to spot two black holes recently by the way they distorted and amplified the light of ordinary, more distant stars. Based on such observations, and even more on theoretical arguments, researchers guesstimate there are about 10 million black holes in the Milky Way. These objects orbit just like other stars, meaning that it is not terribly likely that one is headed our way. But if a normal star were moving toward us, we'd know it. With a black hole there is little warning. A few decades before a close encounter, at most, astronomers would observe a strange perturbation in the orbits of the outer planets. As the effect grew larger, it would be possible to make increasingly precise estimates of the location and mass of the interloper. The black hole wouldn't have to come all that close to Earth to bring ruin; just passing through the solar system would distort all of the planets' orbits. Earth might get drawn into an elliptical path that would cause extreme climate swings, or it might be ejected from the solar system and go hurtling to a frigid fate in deep space.

5 Giant solar flares Solar flares—more properly known as coronal mass ejections—are enormous magnetic outbursts on the sun that bombard Earth with a torrent of high-speed subatomic particles. Earth's atmosphere and magnetic field negate the potentially lethal effects of ordinary flares. But while looking through old astronomical records, Bradley Schaefer

of Yale University found evidence that some perfectly normal-looking, sunlike stars can brighten briefly by up to a factor of 20. Schaefer believes these stellar flickers are caused by superflares, millions of times more powerful than their common cousins. Within a few hours, a superflare on the sun could fry Earth and begin disintegrating the ozone layer (see #2). Although there is persuasive evidence that our sun doesn't engage in such excess, scientists don't know why superflares happen at all, or whether our sun could exhibit milder but still disruptive behavior. And while too much solar activity could be deadly, too little of it is problematic as well. Sallie Baliunas at the Harvard-Smithsonian Center for Astrophysics says many solar-type stars pass through extended quiescent periods, during which they become nearly 1 percent dimmer. That might not sound like much, but a similar downturn in the sun could send us into another ice age. Baliunas cites evidence that decreased solar activity contributed to 17 of the 19 major cold episodes on Earth in the last 10,000 years.

6 Reversal of Earth's magnetic field Every few hundred thousand years Earth's magnetic field dwindles almost to nothing for perhaps a century, then gradually reappears with the north and south poles flipped. The last such reversal was 780,000 years ago, so we may be overdue. Worse, the strength of our magnetic field has decreased about 5 percent in the past century. Why worry in an age when GPS has made compasses obsolete? Well, the magnetic field deflects particle storms and cosmic rays from the sun, as well as even more energetic subatomic particles from deep space. Without magnetic protection, these particles would strike Earth's atmosphere, eroding the already beleaguered ozone layer (see #5). Also, many creatures navigate by magnetic reckoning. A magnetic reversal might cause serious ecological mischief. One big caveat: "There are no identifiable fossil effects from previous flips," says Sten Odenwald of the NASA Goddard Space Flight Center. "This is most curious." Still, a disaster that kills a quarter of the population, like the Black Plague in Europe, would hardly register as a blip in fossil records.

7 Flood-basalt volcanism In 1783, the Laki volcano in Iceland erupted, spitting out three cubic miles of lava. Floods, ash, and fumes wiped out 9,000 people and 80 percent of the livestock. The ensuing starvation killed a quarter of Iceland's population. Atmospheric dust caused winter temperatures to plunge by 9 degrees in the newly independent United States. And that was just a baby's burp compared with what the Earth can do. Sixty-five million years ago, a plume of hot rock from the mantle burst through the crust in what is now India. Eruptions raged century after century, ultimately unleashing a quarter-million cubic miles of lava—the Laki eruption 100,000 times over. Some scientists still blame the Indian outburst, not an asteroid, for the death of the dinosaurs. An earlier, even larger event in Siberia occurred just about the time of the Permian-Triassic extinction, the most thorough extermination known to paleontology. At that time 95 percent of all species were wiped out.

Sulfurous volcanic gases produce acid rains. Chlorine-bearing compounds present yet another threat to the fragile ozone layer—a noxious brew all around. While they are causing short-term destruction, volcanoes also release carbon dioxide that yields long-term greenhouse-effect warming.The last big pulse of flood-basalt volcanism built the Columbia River plateau about 17 million years ago. We're ripe for another.

8 Global epidemics If Earth doesn't do us in, our fellow organisms might be up to the task. Germs and people have always coexisted, but occasionally the balance gets out of whack. The Black Plague killed one European in four during the 14th century; influenza took at least 20 million lives between 1918 and 1919; the AIDS epidemic has produced a similar death toll and is still going strong. From 1980 to 1992, reports the Centers for Disease Control and Prevention, mortality from infectious disease in the United States rose 58 percent.

ROEN KELLY/DISCOVER

Old diseases such as cholera and measles have developed new resistance to antibiotics. Intensive agriculture and land development is bringing humans closer to animal pathogens. International travel means diseases can spread faster than ever. Michael Osterholm, an infectious disease expert who recently left the Minnesota Department of Health, described the situation as "like trying to swim against the current of a raging river." The grimmest possibility would be the emergence of a strain that spreads so fast we are caught off guard or that resists all chemical means of control, perhaps as a result of our stirring of the ecological pot. About 12,000 years ago, a sudden wave of mammal extinctions swept through the Americas. Ross MacPhee of the American Museum of Natural History argues the culprit was extremely virulent disease, which humans helped transport as they migrated into the New World.

HUMAN-TRIGGERED DISASTERS

9 Global warming The Earth is getting warmer, and scientists mostly agree that humans bear some blame. It's easy to see how global warming could flood cities and ruin harvests. More recently, researchers like Paul Epstein of Harvard Medical School have raised the alarm that a balmier planet could also assist the spread of infectious disease by providing a more suitable climate for parasites and spreading the range of tropical pathogens (see #8). That could include crop diseases which, combined with substantial climate shifts, might cause famine. Effects could be even more dramatic. At present, atmospheric gases trap enough heat close to the surface to keep things comfortable. Increase the global temperature a bit, however, and there could be a bad feedback effect, with water evaporating faster, freeing water vapor (a potent greenhouse gas), which traps more heat, which drives carbon dioxide from the rocks, which drives temperatures still higher. Earth could end up much like Venus, where the high on a typical day is 900 degrees Fahrenheit. It would probably take a lot of warming to initiate such a runaway greenhouse effect, but scientists have no clue where exactly the tipping point lies.

10 Ecosystem collapse Images of slaughtered elephants and burning rain forests capture people's attention, but the big problem—the overall loss of biodiversity—is a lot less visible and a lot more serious. Billions of years of evolution have produced a world in which every organism's welfare is intertwined with that of countless other species. A recent study of Isle Royale National Park in Lake Superior offers an example. Snowy winters encourage wolves to hunt in larger packs, so they kill more moose. The decline in moose population allows more balsam fir saplings to live. The fir trees pull carbon dioxide out of the atmosphere, which in turn influences the climate. It's all connected. To meet the demands of the growing population, we are clearing land for housing and agriculture, replacing diverse wild plants with just a few varieties of crops, transporting plants and animals, and introducing new chemicals into the environment. At least 30,000 species vanish every year from human activity, which means we are living in the midst of one of the greatest mass extinctions in Earth's history. Stephen Kellert, a social ecologist at Yale University, sees a number of ways people might upset the delicate checks and balances in the global ecology. New patterns of disease might emerge (see #8), he says, or pollinating insects might become extinct, leading to widespread crop failure. Or as with the wolves of Isle Royale, the consequences might be something we'd never think of, until it's too late.

11 Biotech disaster While we are extinguishing natural species, we're also creating new ones through genetic engineering. Genetically modified crops can be hardier, tastier, and more nutritious. Engineered microbes might ease our health problems. And gene therapy offers an elusive promise of fixing fundamental defects in our DNA. Then there are the possible downsides. Although there is no evidence indicating genetically modified foods are unsafe, there are signs that the genes from modified plants can leak out and find their way into other species. Engineered crops might also foster insecticide resistance. Longtime skeptics like Jeremy Rifkin worry that the resulting superweeds and superpests could further destabilize the stressed global ecosystem (see #9). Altered microbes might prove to be unexpectedly difficult to control. Scariest of all is the possibility of the deliberate misuse of biotechnology. A terrorist group or rogue nation might decide that anthrax isn't nasty enough and then try to put together, say, an airborne version of the Ebola virus. Now there's a showstopper.

12 Particle accelerator mishap Theodore Kaczynski, better known as the Unabomber, raved that a particle accelerator experiment could set off a chain reaction that would destroy the world. Surprisingly, many sober-minded physicists have had the same thought. Normally their anxieties come up during private meetings, amidst much scribbling on the backs of used envelopes. Recently the question went public when London's Sunday Times reported that the Relativistic Heavy Ion Collider (RHIC) on Long Island, New York, might create a subatomic black hole that would slowly nibble away our planet. Alternately, it might create exotic bits of altered matter, called strangelets, that would obliterate whatever ordinary matter they met. To assuage RHIC's jittery neighbors, the lab's director convened a panel that rejected both scenarios as pretty much impossible. Just for good measure, the panel also dismissed the possibility that RHIC would trigger a phase transition in the cosmic vacuum energy (see #3). These kinds of reassurances follow the tradition of the 1942 "LA-602" report, a once-classified document that explained why the detonation of the first atomic bomb almost surely would not set the atmosphere on fire. The RHIC physicists did not, however, reject the fundamental possibility of the disas-

ters. They argued that their machine isn't nearly powerful enough to make a black hole or destabilize the vacuum. Oh, well. We can always build a bigger accelerator.

13 Nanotechnology disaster Before you've even gotten the keyboard dirty, your home computer is obsolete, largely because of incredibly rapid progress in miniaturizing circuits on silicon chips. Engineers are using the same technology to build crude, atomic-scale machines, inventing a new field as they go called nanotechnology. Within a few decades, maybe sooner, it should be possible to build microscopic robots that can assemble and replicate themselves. They might perform surgery from inside a patient, build any desired product from simple raw materials, or explore other worlds. All well and good if the technology works as intended. Then again, consider what K. Eric Drexler of the Foresight Institute calls the "grey goo problem" in his book *Engines of Creation*, a cult favorite among the nanotech set. After an industrial accident, he writes, bacteria-sized machines, "could spread like blowing pollen, replicate swiftly, and reduce the biosphere to dust in a matter of days." And Drexler is actually a strong proponent of the technology. More pessimistic souls, such as Bill Joy, a cofounder of Sun Microsystems, envision nano-machines as the perfect precision military or terrorist tools.

14 Environmental toxins From Donora, Pennsylvania, to Bhopal, India, modern history abounds with frightening examples of the dangers of industrial pollutants. But the poisoning continues. In major cities around the world, the air is thick with diesel particulates, which the National Institutes of Health now considers a carcinogen. Heavy metals from industrial smokestacks circle the globe, even settling in the pristine snows of Antarctica. Intensive use of pesticides in farming guarantees runoff into rivers and lakes. In high doses, dioxins can disrupt fetal development and impair reproductive function—and dioxins are everywhere. Your house may contain polyvinyl chloride pipes, wallpaper, and siding, which belch dioxins if they catch fire or are incinerated. There are also the unknown risks to think about. Every year NIH adds to its list of cancer-causing substances—the number is up to 218. Theo Colburn of the World Wildlife Fund argues that dioxins and other, similar chlorine-bearing compounds mimic the effects of human hormones well enough that they could seriously reduce fertility. Many other scientists dispute her evidence, but if she's right, our chemical garbage could ultimately threaten our survival.

WILLFUL SELF-DESTRUCTION

15 Global war Together, the United States and Russia still have almost 19,000 active nuclear warheads. Nuclear war seems unlikely today, but a dozen years ago the demise of the Soviet Union also seemed rather unlikely. Political situations evolve; the bombs remain deadly. There is also the possibility of an accidental nuclear exchange. And a ballistic missile defense system, given current technology, will catch only a handful of stray missiles—assuming it works at all. Other types of weaponry could have global effects as well. Japan began experimenting with biological weapons after World War I, and both the United States and the Soviet Union experimented with killer germs during the cold war. Compared with atomic bombs, bioweapons are cheap, simple to produce, and easy to conceal. They are also hard to control, although that unpredictability could appeal to a terrorist organization. John Leslie, a philosopher at the University of Guelph in Ontario, points out that genetic engineering might permit the creation of "ethnic" biological weapons that are tailored to attack primarily one ethnic group (see #11).

16 Robots take over People create smart robots, which turn against us and take over the world. Yawn. We've seen this in movies, TV, and comic books for decades. After all these years, look around and still—no smart robots. Yet Hans Moravec, one of the founders of the robotics department of Carnegie Mellon University, remains a believer. By 2040, he predicts, machines will match human intelligence, and perhaps human consciousness. Then they'll get even better. He envisions an eventual symbiotic relationship between human and machine, with the two merging into "post-biologicals" capable of vastly expanding their intellectual power. Marvin Minsky, an artificial-intelligence expert at MIT, foresees a similar future: People will download their brains into computer-enhanced mechanical surrogates and log into nearly boundless files of information and experience. Whether this counts as the end of humanity or the next stage in evolution depends on your point of view. Minsky's vision might sound vaguely familiar. After the first virtual-reality machines hit the marketplace around 1989, feverish journalists hailed them as electronic LSD, trippy illusion machines that might entice the user in and then never let him out. Sociologists fretted that our culture, maybe even our species, would whither away. When the actual experience of virtual reality turned out to be more like trying to play Pac-Man with a bowling ball taped to your head, the talk died down. To his credit, Minsky recognizes that the merger of human and machine lies quite a few years away.

17 Mass insanity While physical health has improved in most parts of the world over the past century, mental health is getting worse. The World Health Organization estimates that 500 million people around the world suffer from a psychological disorder. By 2020, depression will likely be the second leading cause of death and lost productivity, right behind cardiovascular disease. Increasing human life spans may actually intensify the problem, because people have more years to experience the loneliness and infirmity of old age. Americans over 65 already are disproportionately likely to commit suicide. Gregory Stock, a biophysicist

at the University of California at Los Angeles, believes medical science will soon allow people to live to be 200 or older. If such an extended life span becomes common, it will pose unfathomable social and psychological challenges. Perhaps 200 years of accumulated sensations will overload the human brain, leading to a new kind of insanity or fostering the spread of doomsday cults, determined to reclaim life's endpoint. Perhaps the current trends of depression and suicide among the elderly will continue. One possible solution—promoting a certain kind of mental well-being with psychoactive drugs such as Prozac—heads into uncharted waters. Researchers have no good data on the long-term effects of taking these medicines.

A GREATER FORCE IS DIRECTED AGAINST US

18 Alien invasion At the SETI Institute in Mountain View, California, a cadre of dedicated scientists sifts through radio static in search of a telltale signal from an alien civilization. So far, nothing. Now suppose the long-sought message arrives. Not only do the aliens exist, they are about to stop by for a visit. And then . . . any science-fiction devotee can tell you what could go wrong. But the history of human exploration and exploitation suggests the most likely danger is not direct conflict. Aliens might want resources from our solar system (Earth's oceans, perhaps, full of hydrogen for refilling a fusion-powered spacecraft) and swat us aside if we get in the way, as we might dismiss mosquitoes or beetles stirred up by the logging of a rain forest. Aliens might unwittingly import pests with a taste for human flesh, much as Dutch colonists reaching Mauritius brought cats, rats, and pigs that quickly did away with the dodo. Or aliens might accidentally upset our planet or solar system while carrying out some grandiose interstellar construction project. The late physicist Gerard O'Neill speculated that contact with extraterrestrial visitors could also be socially disastrous. "Advanced western civilization has had a destructive effect on all primitive civilizations it has come in contact with, even in those cases where every attempt was made to protect and guard the primitive civilization," he said in a 1979 interview. "I don't see any reason why the same thing would not happen to us."

19 Divine intervention Judaism has the Book of Daniel; Christianity has the Book of Revelation; Islam has the coming of the Mahdi; Zoroastrianism has the countdown to the arrival of the third son of Zoroaster. The stories and their interpretations vary widely, but the underlying concept is similar: God intervenes in the world, bringing history to an end and ushering in a new moral order. Apocalyptic thinking runs at least back to Egyptian mythology and right up to Heaven's Gate and Y2K mania. More worrisome, to the nonbelievers at least, are the doomsday cults that prefer to take holy retribution into their own hands. In 1995, members of the Aum Shinri Kyo sect unleashed sarin nerve gas in a Tokyo subway station, killing 12 people and injuring more than 5,000. Had things gone as intended, the death toll would have been hundreds of times greater. A more determined group armed with a more lethal weapon—nuclear, biological, nanotechnological even—could have done far more damage.

20 Someone wakes up and realizes it was all a dream Are we living a shadow existence that only fools us into thinking it is real? This age-old philosophical question still reverberates through cultural thought, from the writings of William S. Burrows to the cinematic mind games of *The Matrix*. Hut of the Institute of Advanced Studies sees an analogy to the danger of the collapse of the vacuum. Just as our empty space might not be the true, most stable form of the vacuum, what we call reality might not be the true, most stable form of existence. In the fourth century B.C., Taoist philosopher Chuang Tzu framed the question in more poetic terms. He described a vivid dream. In it, he was a butterfly who had no awareness of his existence as a person. When he awoke, he asked: "Was I before Chuang Tzu who dreamt about being a butterfly, or am I now a butterfly who dreams about being Chuang Tzu?"

ROEN KELLY/DISCOVER

DARK MATTER'S shadowy effect on Earth

Earth's periodic passage through the galaxy's disk could initiate a series of events that ultimately lead to geological cataclysms and mass extinctions.

by Michael R. Rampino

A shower of comets rains down on Earth while violent volcanic eruptions billow up from below. Both events may follow our planet's passage through dark matter concentrated in the Milky Way's plane and help to trigger extinction events.
DON DIXON FOR *ASTRONOMY*

Do geologists dream of a final theory? Most people would say that plate tectonics already serves as geology's overarching idea. The discovery of plate tectonics 50 years ago was one of the great scientific achievements of the 20th century, but is the theory complete? I think not. Plate tectonics describes Earth's present geology in terms of the geometry and interactions of its surface plates. Geologists can extrapolate plate motions both back in time and into the future, but they cannot yet derive the behavior and history of plate tectonics from first principles.

Although scientists can interpret the history through the lens of what they see today, an important question remains: Why did geologic events — such as hot-spot volcanism, the breakup of continents, fluctuations in seafloor spreading, tectonic episodes, and sea-level oscillations — occur exactly when and where they did? Are they random, or do they follow some sort of a pattern in time or space?

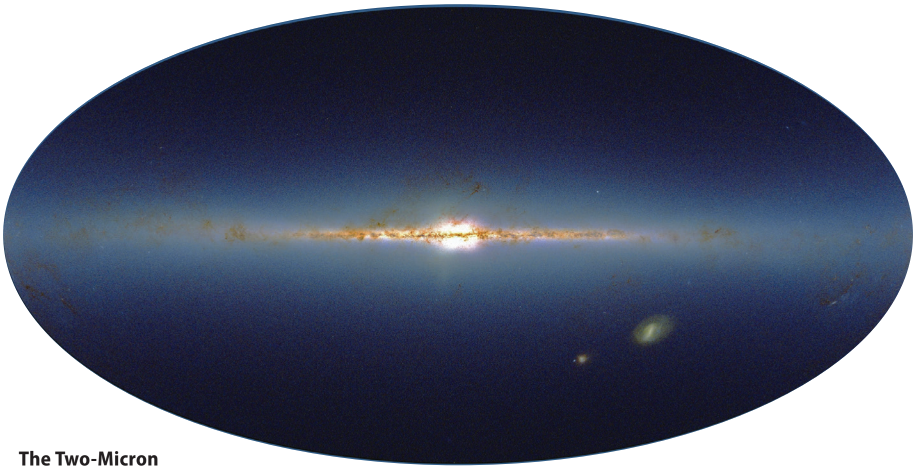
A complete theory of Earth should explain geologic activity in the spatial domain, as plate tectonics does quite well for the present (once you incorporate hot spots), but also in the time and frequency domains. Recent findings suggest to me that geology may be on the threshold of a new theory that seeks to explain Earth's geologic activity in time and space in the context of its astronomical surroundings.

A big impact

The first clue for a cosmic connection came in a 1980 report by Nobel Prize-winning physicist Luis Alvarez and his son Walter, a noted geologist. Working at the University of California, Berkeley, the two suggested that the severe mass extinction of life at the end of the Cretaceous period 66 million years ago was the result of a devastating impact of a large asteroid or comet. This spectacular finding was followed in early 1984 with the remarkable claim by Dave Raup and Jack Sepkoski of the University of Chicago that mass-extinction events followed a 26 million-year cycle.

Could periodic impacts cause periodic extinctions? A number of craters of various sizes and ages mark the location of past impacts, and the estimated ages of several coincide fairly well with mass extinctions. For example, Nobel laureate Harold Urey noted in 1973 that the 56-mile-diameter (90 kilometers) Popigai crater in northern Siberia dates from about 36 million years ago, close to the time of the Late Eocene extinction event.

Cratering specialist Richard Grieve of the Canadian Bureau of Mines and Energy in Ottawa originally compiled the most complete list of terrestrial impact craters. (The ever-growing list is now manintained online.) ➔



The Two-Micron All-Sky Survey revealed what the Milky Way looks like edge-on. Clearly visible is the dark horizontal band marking the galaxy's midplane. Earth's passage through this region every 30 million years or so could initiate a series of events that leads to extinction events on Earth. 2MASS/IPAC/CALTECH

The Earth Impact Database currently contains about 190 documented impact craters, and it includes their sizes, locations, and estimates of their ages. These craters are only a small subset of the actual number of objects that have collided with Earth. Many more impact craters have been so severely eroded and/or covered by sediments that they are difficult to identify. What's more, no craters have been found in the deep ocean, only in shallow areas of the continental shelf. This is not surprising because the ocean floor is young, at most only about 180 million years old, so it should exhibit relatively few craters. And no one knows precisely what kind of structure a large impact into thin ocean crust would leave behind.

Many of the estimates of crater ages are merely rough limits based on the age of the older rocks targeted by the impact, or the age of the first sediments burying the impact structure. But a number of the craters have been dated well enough by studying the decay of the impactor's radioactive elements to make a rigorous statistical analysis of the timing of the impacts. In the mid-1980s, the ages of the best-dated craters in Grieve's list were run through the computer at NASA's Goddard Institute for Space Studies in New York City using a new analysis method, and the impact-crater record showed a significant periodicity of about 30 million years.

At the same time, Walter Alvarez and physicist Richard Muller, also at UC Berkeley, did their own analysis and found a 28 million-year cycle using a somewhat different set of craters. Other researchers have revisited these results over the years, and they are still controversial. But in 2015, my former student Ken Caldeira and I studied more impact structures with improved crater-age data and were able to be more specific. We found that craters and extinctions both seem to occur with the same 26 million-year cycle.

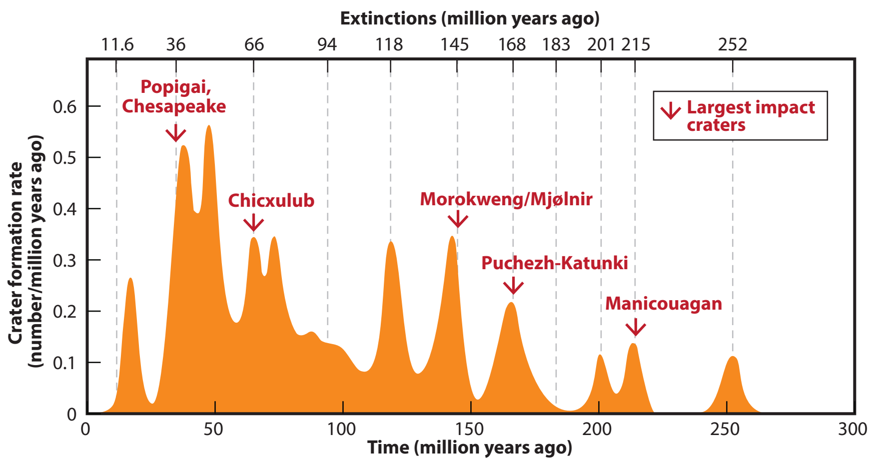
These analyses of crater ages convinced me that many of the impacts were periodic. Still, it begged the question of where they were coming from. There were two possibilities: Earth-crossing asteroids originally from the asteroid belt between the orbits of Mars and Jupiter, or icy comets from the distant Oort Cloud that surrounds the Sun. We doubted that asteroids could have pelted Earth in regular cycles. That left the Oort Cloud comets, which number in the trillions. In the early 1980s, astronomer Jack Hills of Los Alamos National Laboratory in New Mexico calculated that a passing star could induce gravitational perturbations that would shake up the loosely bound Oort Cloud comets at the edge of the solar system. This would cause large numbers of these icy bodies to fall into the inner solar system, producing a comet shower, where some could strike Earth. Hills even suggested that such a comet shower could have caused the demise of the dinosaurs. But if comet showers were the culprits, why would they show a cycle of 26 million to 30 million years?

A galactic connection

It seemed natural to search for any cosmic cycles that have a period of about 30 million years. One in particular stands out. The solar system oscillates with respect to the midplane of the disk-shaped Milky Way Galaxy with a period of about 60 million years. The Sun's family passes through this plane twice each period, or once every 30 million years or so. The solar system behaves like a horse on a carousel — as we go around the disk-shaped galaxy, we bob up and down through the disk, passing through its densest part roughly every 30 million years.

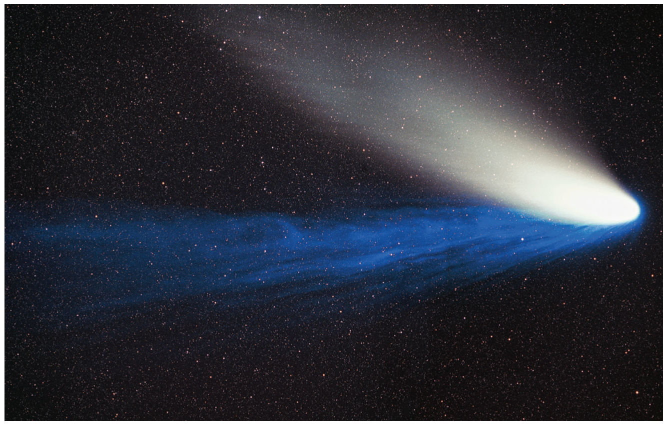
Considering possible errors in dating the extinctions and the craters, as well as the uncertainties in the galactic period, the three cycles seemed to agree. Surely, it is too much of a coincidence that the cycle found in mass extinctions and impact craters should turn out to be one of the fundamental periods of our galaxy. The idea seemed almost too pretty to be wrong. But people searching for cycles have been fooled before, and we still had to answer

An impact on extinctions



The crater formation rate ebbs and flows with time, though most often it peaks close to the time of an extinction event. The highlighted events indicate the six largest impacts during the past 260 million years. *ASTRONOMY*: ROEN KELLY, AFTER RAMPINO, CALDEIRA, AND PROKOPH

The edge-on spiral NGC 1055 in Cetus reveals the thick bands of gas and dust that pervade a typical spiral galaxy's disk. The mass concentrated there can jostle distant comets and send them hurtling toward their stars. ESO



Comet Hale-Bopp mesmerized observers when it passed through the inner solar system in 1997. This first-time visitor from the distant Oort Cloud had a nucleus some 37 miles (60 km) across — big enough to cause catastrophic damage if it hit Earth. Similar comets of the past may have initiated mass extinctions. GERALD RHEMANN

the question: How does this cycle of movement lead to periodic perturbations of the Oort Cloud comets?

Obviously, whatever object or objects was causing a periodic gravitational perturbation strong enough to disturb Oort Cloud comets would have to be quite massive. Hills had suggested that a star could do the trick. However, close encounters with stars should not take place as often as once every 30 million years. Massive interstellar clouds of gas and dust might be a better alternative. A close encounter with a large cloud, say one with a mass greater than 10,000 times that of the Sun, also could deliver a comet shower.

A large fraction of our galaxy's normal matter resides in a flattened disk. Using computer simulations of galactic motion, physicist John Matese at the University of Louisiana and his colleagues calculated that the Oort Cloud would be especially vulnerable to gravitational perturbations caused by galactic tides — in essence, the pull of gravity of all the mass concentrated in the midplane. And a comparison of the estimated times when the solar system crossed the galactic plane with the times of impacts and mass extinctions showed potential correlations.

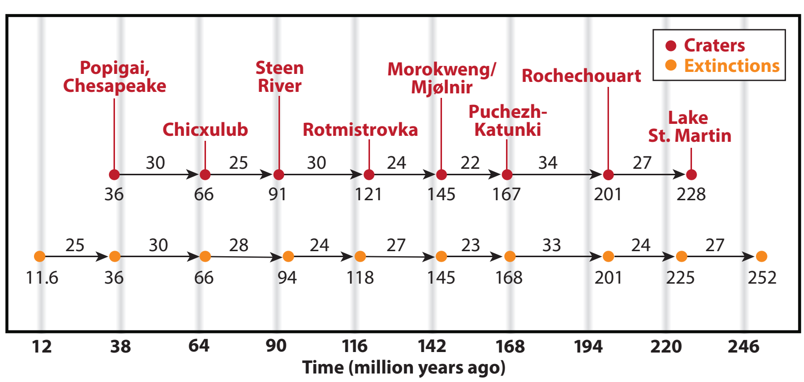
A dark matter connection?

More recently, in 2014, astrophysicists Lisa Randall and Matthew Reece at Harvard University suggested that the largest gravitational perturbations of the Oort Cloud could be from an invisible thin disk of exotic dark matter. Astronomers believe dark matter — a mysterious form of matter that interacts only through the gravitational force — accounts for about 85 percent of all the matter in the universe. Amazingly, all the visible matter in planets, stars, nebulae, and galaxies makes up only 15 percent of the total.

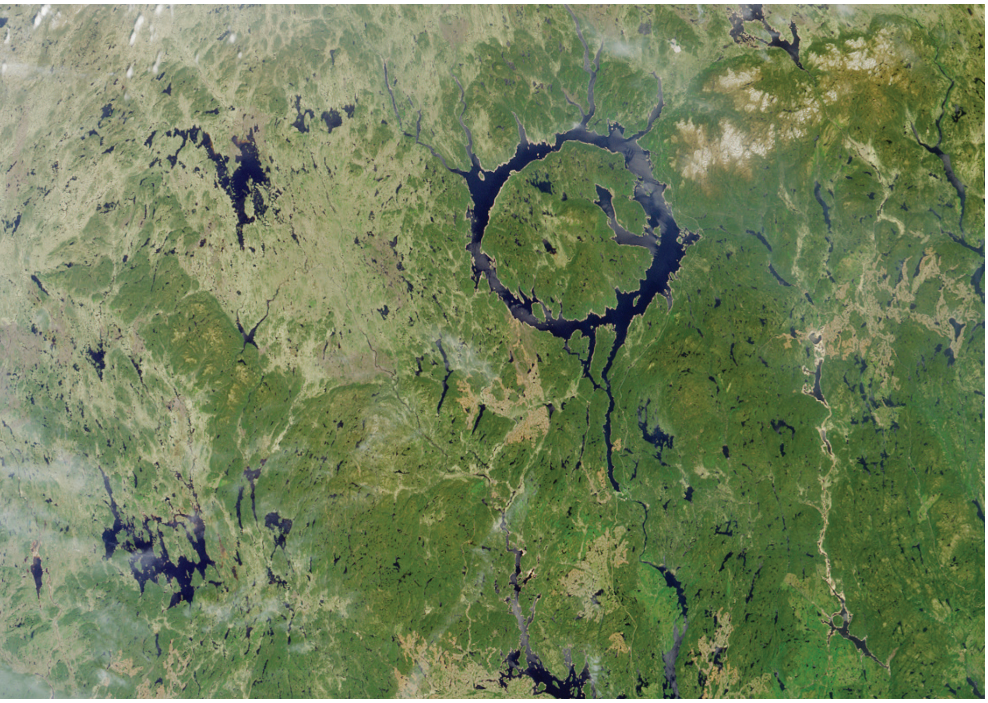
Evidence for dark matter comes mostly from the motions of galaxies. Dark matter explains the fact that stars far from the centers of rotating galaxies have much higher velocities than predicted from the distribution of visible matter alone. Without some additional matter exerting a gravitational pull, the galaxies would fly apart. To explain the "excess velocity" of the stars, scientists think the dark matter likely forms a spherical halo surrounding the galaxies. Evidence for dark matter also comes from galaxy clusters, which require far more matter than what is visible to produce the gravitational forces holding the clusters together. Dark matter also makes its presence known through gravitational lensing. The dark matter halo of a nearby galaxy distorts the light from background galaxies into a ring of mirages around the closer galaxy.

Most astrophysicists believe that dark matter is likely composed of weakly interacting massive particles, or axions. But whatever it is, dark matter does not interact with electromagnetic radiation, so it is difficult to detect. Although scientists infer that dark matter resides in spherical halos surrounding spiral galaxies like our own, Randall and Reece suggested that some dark matter also would be concentrated in a thin disk along the galaxy's midplane.

A match made in the heavens?



The relationship between extinction events nicely tracks with the geological record of major "periodic" craters formed from large comet or asteroid impacts. Here we plot the accepted extinction events (orange circles) and the times between each below the major periodic craters (red circles) and the gaps between them, and compare those with a 26 million-year cycle that started 12 million years ago. *ASTRONOMY*: ROEN KELLY, AFTER RAMPINO, CALDEIRA, AND PROKOPH



Lake Manicouagan in Quebec is the remnant of one of the largest impact features left on Earth. The crater spans about 53 miles (85 km) and resulted from an impact some 215 million years ago.
NASA/GSFC/LaRC/JPL/MISR TEAM

Some researchers predict that such a disk naturally will fragment into smaller, denser clumps. A future test for the existence of a dark matter disk will rely on new data coming from the European Space Agency's Gaia spacecraft, which is measuring the motions of stars in the galactic plane. The behavior of these stars depends on the total mass in the galaxy's disk, which should tell us how much — if any — dark matter is present.

Randall and Reece hypothesize that when the solar system passes through the densely populated galactic midplane, the concentrated gravitational force of the dark and visible mass jostles the Oort Cloud. This sends a shower of comets toward the inner solar system about every 26 million to 30 million years, where some eventually hit Earth. Where are we in this cycle today? We have just crossed the galactic midplane from "below" and remain relatively close to it. And it takes more than a million years for a comet to fall from the distant Oort Cloud into the inner solar system. This puts us in a precarious position, but it is in line with the ages of several young craters and impact-produced ejecta layers in the past 1 million to 2 million years.

Do Earth's cycles match?

But Earth's cosmic connection may go even deeper. The idea of a roughly 30 million-year rhythm in geologic events has a long history in the geological literature. In the early 20th century, W.A. Grabau, an expert on sedimentary strata, proposed that tectonic activity and mountain building drove periodic fluctuations in sea level with an approximately 30 million-year cycle. In the 1920s, noted British geologist Arthur Holmes, armed with a few age determinations from radioactive decay, saw a similar 30 million-year cycle in Earth's geologic activity.

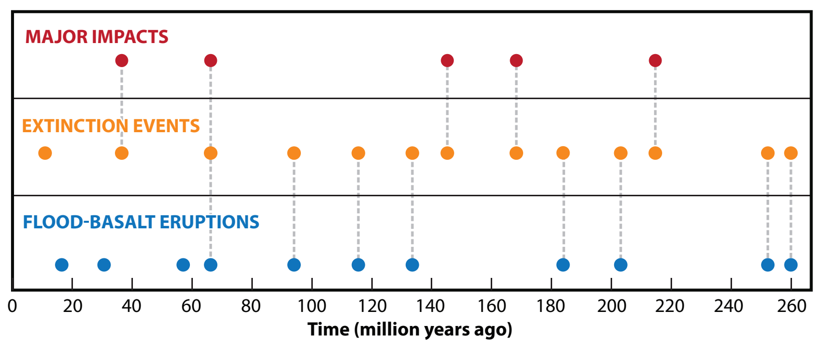
But the idea of periodicity in the geologic record later fell out of favor, and most geologists rejected the notion as simply the human propensity for seeing cycles where there are none. Today, the majority of earth scientists believe that the geologic record preserves the workings of an essentially random system. The geologic community is generally averse to the idea of regular long-term cycles. This is a result, in part, of the many papers over the years that claimed to find one period or another in the geologic record, but which did not survive closer scrutiny.

I spent a lot of time in the library and online searching page by page through the major journals for data sets related to geologic changes in sea level, tectonics, various kinds of volcanism, variations in seafloor spreading rates, extinction events, and indicators of ancient climate shifts. (The last of these show up, for example, in the presence of stagnant oceans depleted in dissolved oxygen or the occurrence of major salt deposits indicating a hot, dry climate.) Eventually, I was able to recognize 77 such documented events in Earth's history over the past 260 million years.

Caldeira, my former student who is now at Stanford University, and I analyzed the new compilation of data and found a strong 26 million- to 27 million-year period of repetition. Richard Stothers at NASA did the same for geomagnetic reversals and detected an approximately 30 million-year cycle. I admit that the reality of these cycles has been much debated, and further statistical tests have produced mixed results. One problem may be that it is difficult to extract cycles from data sets that contain both periodic and nonperiodic events, as would be the case for these geologic events.

But if the cycles are real, what could be driving these long-term changes in volcanism, tectonics, sea level, and climate at such regular, if widely spaced, intervals? At first, I thought that the periodic energetic impacts might somehow be affecting deep-seated geological processes. I suggested in a short note in the journal *Nature* that large impacts might so deeply excavate and fracture the crust — to depths in excess of 10 miles (16 km) — that the sudden release

Making a significant connection



Most extinction events in the past 260 million years nearly coincide with either a major impact or a flood-basalt eruption. These events seem to repeat with a period between 26 million and 30 million years. *ASTRONOMY*: ROEN KELLY, AFTER RAMPINO, CALDEIRA, AND PROKOPH

The Piton de la Fournaise volcano on the island Réunion in the western Indian Ocean ranks among the world's most active. It lies above a hot spot in Earth's mantle and exudes low-viscosity lava that flows easily. Even larger eruptions — perhaps triggered by heat from dark matter annihilation in Earth's core — may lead to extinctions. © JULIENGRONDIN | DREAMSTIME.COM

Robust volcanic activity releases vast quantities of basaltic lava that can cover wide areas up to a mile or more deep. This view shows the characteristic stair-step formations in part of the Columbia River Basalt Group in Washington. The area formed from lavas erupted by the Yellowstone hot spot roughly 15 million years ago. WILLIAMBORG/WIKIMEDIA COMMONS

of pressure in the upper mantle would result in large-scale melting. This would lead to the production of massive flood-basalt lavas, which would cover the crater and possibly create a mantle hot spot at the site of the impact. Hot spots could lead to continental breakup, which can cause increased tectonics and changes in ocean-floor spreading rates, and in turn cause global sea levels to fluctuate. Unfortunately, no known terrestrial impact structure has a clear association with volcanism, although some volcanic outpourings on Mars seem to be located along radial and concentric fractures related to large impacts.

Trapped in the core

The potential key to resolving this geological conundrum may come from outer space. Remember that Randall and Reece suggested that Earth passes through a thin disk of dark matter concentrated along the Milky Way's midplane every 30 million years or so. Astrophysicist Lawrence Krauss and Nobel Prize-winning physicist Frank Wilczek of Harvard University, and independently Katherine Freese, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics, proposed that Earth could capture dark matter particles that would accumulate in the planet's core. The number of dark matter particles could grow large enough so that they would undergo mutual annihilation, producing prodigious amounts of heat in Earth's interior.

A 1998 paper in the journal *Astroparticle Physics* (which I am sure few geologists ever read) provided a potential missing link. Indian astrophysicists Asfar Abbas and Samar Abbas (father and son, respectively) at Utkal University also were interested in dark matter and its interactions with our planet. They calculated the amount of energy released by the annihilation of dark matter captured by Earth during its passage through a dense clump of this material. They found that mutual destruction among the particles could produce an amount of heat 500 times greater than Earth's normal heat flow, and much greater than the estimated power required in Earth's core to generate the planet's magnetic field. Putting together the predicted 30 million-year periodicity in encounters with dark matter with the effects of Earth capturing this unstable matter produces a plausible hypothesis for the origin of regular pulses of geologic activity.

Excess heat from the planet's core can raise the temperature at the base of the mantle. Such a pulse of heat might create a mantle plume, a rising column of hot mantle rock with a broad head and narrow tail. When these rising plumes penetrate Earth's crust, they create hot spots, initiate flood-basalt eruptions, and commonly lead to continental fracturing and the beginning of a new episode of seafloor spreading. The new source of periodic heating by dark matter in our planet's interior could lead to periodic outbreaks of mantle-plume activity and changes in convection patterns in Earth's core and mantle, which could affect global tectonics, volcanism, geomagnetic field reversals, and climate, such as our planet has experienced in the past.

These geologic events could lead to environmental changes that might be enough to cause extinction events on their own. A correlation of some extinctions with times of massive volcanic outpourings of lava supports this view. This new hypothesis links geologic events on Earth with the structure and dynamics of the Milky Way Galaxy.

It is still too early to tell if the ingredients of this hypothesis will withstand further examination and testing. Of course, correlations among geologic events can occur even if they are not part of a periodic pattern, and long-term geological cycles may exist apart from any external cosmic connections. The virtue of the galactic explanation for terrestrial periodicity lies in its universality — because all stars in the galaxy's disk, many of which harbor planets, undergo a similar oscillation about the galactic midplane — and in its linkage of biological and geological evolution on Earth, and perhaps in other solar systems, to the great cycles of our galaxy.

Michael R. Rampino *is professor of biology and environmental studies at New York University, and a consultant at NASA's Goddard Institute for Space Studies in New York City. This article is excerpted and adapted from* Cataclysms: A New Geology for the Twenty-First Century *(Columbia University Press, 2017).*

What Would It Take to Wipe Out All Life on Earth?

BY AFAEL ALVES BATISTA, UNIVERSITY OF OXFORD; DAVID SLOAN, UNIVERSITY OF OXFORD

ANDRZEJ PUCHTA/SHUTTERSTOCK

The first exoplanet was spotted in 1988. Since then more than 3,000 planets have been found outside our solar system, and it's thought that around 20 percent of Sun-like stars have an Earth-like planet in their habitable zones. We don't yet know if any of these host life – and we don't know how life begins. But even if life does begin, would it survive?

Earth has undergone at least five mass extinctions in its history. It's long been thought that an asteroid impact ended the dinosaurs. As a species, we are rightly concerned about events that could lead to our own elimination – climate change, nuclear war or disease could wipe us out. So it's natural to wonder what it would take to eliminate all life on a planet.

To establish a benchmark for this, we've been studying what is arguably the world's hardiest species, the tardigrade, also known as the "water bear" for its appearance. Our latest research suggests these microscopic, eight-legged creatures, or their equivalents on other planets, would be very hard to kill off on any planet that was like Earth. The only astrophysical catastrophes that could destroy them are so unlikely there's an insignificant chance of them happening. This extreme survival ability adds weight to the idea that life is hardy enough to be found on other planets less hospitable than our own.

LAST SURVIVORS

Tardigrades are known to survive incredible conditions. Drop the temperature briefly to -272º or raise it to 150º and they go on. Increase atmospheric pressure to more than 1,000 times that at the Earth's surface, or drop it to the vacuum of space and they continue. They can survive for up to 30 years without food or water. They can even withstand thousands of grays (standard doses) of radiation. (Ten grays would be a lethal dose for most humans.)

They live all over the planet but can survive far below the ocean's surface, around volcanic vents at the bottom of the Mariana Trench happily oblivious to the life and death of surface-dwelling mammals. Stripping the ozone layer or upper atmosphere would expose humans to lethal radiation but, at the bottom of the ocean, the water

3D STOCK/SHUTTERSTOCK

overhead would provide shielding.

We wanted to consider what cataclysmic events might be able to finally kill off the hardy tardigrade. What would need to happen to destroy every living thing on the planet? The simplest answer is that the planet's entire oceans would have to boil. On Earth, this would require an incredible amount of energy—5.6 x 10^{26} joules (around a million years' of total human energy production at current rates). We therefore have to consider the astrophysical events that could provide such an enormous amount of energy.

There are three primary candidates that could do this: asteroid impacts, supernovae and gamma-ray bursts. Of these, asteroids are the most familiar. We've been hit by several over the course of Earth's history. But, in our solar system there are just 17 candidate objects (including dwarf planets like Pluto and Eris) large enough to provide this energy—and none with orbits coinciding with that of Earth.

By looking at the rate of asteroid impacts on Earth, we can extrapolate the rate at which doomsday events like this would likely occur. This turns out to be approximately once every 10^{17} years—far longer than the life of the universe. So it's very, very unlikely to ever happen.

Supernovae (massive explosions of stars) release huge amounts of energy–10^{44} joules, which is more than enough to boil our oceans. Fortunately, the energy delivered to a planet rapidly drops off the further away it is from a supernova. So for the Earth, sterilization would require a supernova to occur within around 0.013 light-years. The nearest star apart from the Sun, Proxima Centauri, is 4.25 light years away (and is the wrong type to go supernova).

For Earth-like planets in our galaxy, the distance between stars depends on their distance from the galactic center. The central bulge is more densely populated than our neighborhood. But even closer in, given the rates at which supernovae occur, sterilization is unlikely to happen more than once in 10^{15} years, again far beyond the age of the universe.

Finally, there are gamma-ray bursts, mysterious explosions producing enormous amounts of energy focused into jets of radiation as narrow as a couple of degrees. Analyzing these bursts as we did supernovae, we found that they could only kill off life on an Earth-like planet if their origin was within about 42 light-years and the planet lay within the beam. Again, the rate at which this would occur is sufficiently low that very few planets would ever be sterilized by a gamma-ray burst.

APOCALYPSE NEVER

Given how tiny the chances are of any of these apocalyptic events actually happening, we're left with the conclusion that tardigrades will survive until the Sun expands about 1 billion years from now. One final, incredibly unlikely possibility is that a passing star could kick a planet out of its orbit. But, even then, volcanic vents that host some tardigrades could potentially provide heat for long enough for the planet to be captured by another star.

There are many events, both astrophysical and local, that could lead to the end of the human race. Life as a whole, however, is incredibly hardy. As we begin our search for life away from Earth, we should expect that if life had ever begun on a planet, some survivors might still be there.

Earth Without People

Are we in danger of being erased from the universe? Here we look at the factors tWhat would happen to our planet if the mighty hand of humanity simply disappeared?

BY **ALAN WEISMAN**

MIKADUN/SHUTTERSTOCK

Given the mounting toll of fouled oceans, overheated air, missing topsoil, and mass extinctions, we might sometimes wonder what our planet would be like if humans suddenly disappeared. Would Superfund sites revert to Gardens of Eden? Would the seas again fill with fish? Would our concrete cities crumble to dust from the force of tree roots, water, and weeds? How long would it take for our traces to vanish? And if we could answer such questions, would we be more in awe of the changes we have wrought, or of nature's resilience?

A good place to start searching for answers is in Korea, in the 155-mile-long, 2.5-mile-wide mountainous Demilitarized Zone, or DMZ, set up by the armistice ending the Korean War. Aside from rare military patrols or desperate souls fleeing North Korea, humans have barely set foot in the strip since 1953. Before that, for 5,000 years, the area was populated by rice farmers who carved the land into paddies. Today those paddies have become barely discernible, transformed into pockets of marsh, and the new occupants of these lands arrive as dazzling white squadrons of red-crowned cranes that glide over the bulrushes in perfect formation, touching down so lightly that they detonate no land mines. Next to whooping cranes, they are the rarest such birds on Earth. They winter in the DMZ alongside the endangered white-naped cranes, revered in Asia as sacred portents of peace.

If peace is ever declared, suburban Seoul, which has rolled ever northward in recent decades, is poised to invade such tantalizing real estate. On the other side, the North Koreans are building an industrial megapark. This has spurred an international coalition of scientists called the DMZ Forum to try to consecrate the area for a peace park and nature preserve. Imagine it as "a Korean Gettysburg and Yosemite rolled together," says Harvard University biologist Edward O. Wilson, who believes that tourism revenues could trump those from agriculture or development.

As serenely natural as the DMZ now is, it would be far different if people throughout Korea suddenly disappeared. The habitat would not revert to a truly natural state until the dams that now divert rivers to slake the needs of Seoul's more than 20 million inhabitants failed—a century or two after the humans had gone. But in the meantime, says Wilson, many creatures would flourish. Otters, Asiatic black bears, musk deer, and the nearly vanquished Amur leopard would spread into slopes reforested with young daimyo oak and bird cherry. The few Siberian tigers that still prowl the North Korean–Chinese borderlands would multiply and fan across Asia's temperate zones. "The wild carnivores would make short work of livestock," he says. "Few domestic animals would remain after a couple of hundred years. Dogs would go feral, but they wouldn't last long: They'd never be able to compete."

If people were no longer present anywhere on Earth, a worldwide shakeout would follow. From zebra mussels to fire ants to crops to kudzu, exotics would battle with natives. In time, says Wilson, all human attempts to improve on nature, such as our painstakingly bred horses, would revert to their origins. If horses survived at all, they would devolve back to Przewalski's horse, the only true wild horse, still found in the Mongolian steppes. "The plants, crops, and animal species man has wrought by his own hand would be wiped out in a century or two," Wilson says. In a few thousand years, "the world would mostly look as it did before humanity came along—like a wilderness."

The new wilderness would consume cities, much as the jungle of northern Guatemala consumed the Mayan pyramids and megalopolises of overlapping city-states. From A.D. 800 to 900, a combination of drought and internecine warfare over dwindling farmland brought 2,000 years of civilization crashing down. Within 10 centuries, the jungle swallowed all.

Mayan communities alternated urban living with fields sheltered by forests, in contrast with today's paved cities, which are more like man-made deserts. However, it wouldn't take long for nature to undo even the likes of a New York City. Jameel Ahmad, civil engineering department chair at Cooper Union College in New York City, says repeated freezing and thawing common in months like March and November would split cement within a decade, allowing water to seep in. As it, too, froze and expanded, cracks would widen. Soon, weeds such as mustard and goosegrass would invade. With nobody to trample seedlings, New York's prolific exotic, the Chinese ailanthus tree, would take over. Within five years, says Dennis Stevenson, senior curator at the New York Botanical Garden, ailanthus roots would heave up sidewalks and split sewers.

That would exacerbate a problem that already plagues New York—rising groundwater. There's little soil to absorb it or vegetation to transpire it, and buildings block the sunlight that could evaporate it. With the power off, pumps that keep subways from flooding would be stilled. As water sluiced away soil beneath pavement, streets would crater.

Eric Sanderson of the Bronx Zoo Wildlife Conservation Society heads the Mannahatta Project, a virtual re-creation of pre-1609 Manhattan. He says there were 30 to 40 streams in Manhattan when the Dutch first arrived. If New Yorkers disappeared, sewers would clog, some natural watercourses would reappear, and others would form. Within 20 years, the water-soaked steel columns that support the street above the East Side's subway tunnels would corrode and buckle, turning Lexington Avenue into a river.

New York's architecture isn't as flammable as San Francisco's clapboard Victorians, but within 200 years, says Steven Clemants, vice president of the Brooklyn Botanic Garden, tons of leaf litter would overflow gutters as pioneer weeds gave way to colonizing native oaks and maples in city parks. A dry lightning strike, igniting decades of uncut, knee-high Central Park grass, would spread flames through town.

As lightning rods rusted away, roof fires would leap among buildings into paneled offices filled with paper. Meanwhile, native Virginia creeper and poison ivy would claw at walls covered with lichens, which thrive in the absence of air pollution. Wherever foundations failed and buildings tumbled, lime from crushed concrete would raise soil pH, inviting buckthorn and birch. Black locust and autumn olive trees would fix nitrogen, allowing more goldenrods, sunflowers, and white snakeroot to move in along with apple trees, their seeds expelled by proliferating birds. Sweet carrots would quickly devolve to their wild form, unpalatable Queen Anne's lace, while broccoli, cabbage, brussels sprouts, and cauliflower would regress to the same unrecognizable broccoli ancestor.

Unless an earthquake strikes New York first, bridges spared yearly applications of road salt would last a few hundred years before their stays and bolts gave way (last to fall would be Hell Gate Arch, built for railroads and easily good for another thousand years). Coyotes would invade Central Park, and deer, bears, and finally wolves would follow. Ruins would echo the love song of frogs breeding in streams stocked with alewives, herring, and mussels dropped by seagulls. Missing, however, would be all fauna that have adapted to humans. The invincible cockroach, an insect that originated in the hot climes of Africa, would succumb in unheated buildings. Without garbage, rats would starve or serve as lunch for peregrine falcons and red-tailed hawks. Pigeons would genetically revert back to the rock doves from which they sprang.

It's unclear how long animals would suffer from the urban legacy of concentrated heavy metals. Over many centuries, plants would take these up, recycle, redeposit, and gradually dilute them. The time bombs left in petroleum tanks, chemical plants, power plants, and dry-cleaning plants might poison the earth beneath them for eons. One intriguing example is the former Rocky Mountain Arsenal next to Denver International Airport. There a chemical weapons plant produced mustard and nerve gas, incendiary bombs, napalm, and after World War II, pesticides. In 1984 it was considered by the arsenal commander to be the most contaminated spot in the United States. Today it is a national wildlife

PAVEL CHAGOCHKIN/SHUTTERSTOCK

refuge, home to bald eagles that feast on its prodigious prairie dog population.

However, it took more than $130 million and a lot of man-hours to drain and seal the arsenal's lake, in which ducks once died minutes after landing and the aluminum bottoms of boats sent to fetch their carcasses rotted within a month. In a world with no one left to bury the bad stuff, decaying chemical containers would slowly expose their lethal contents. Places like the Indian Point nuclear power plant, 35 miles north of Times Square, would dump radioactivity into the Hudson long after the lights went out.

Old stone buildings in Manhattan, such as Grand Central Station or the Metropolitan Museum of Art, would outlast every modern glass box, especially with no more acid rain to pock their marble. Still, at some point thousands of years hence, the last stone walls—perhaps chunks of St. Paul's Chapel on Wall Street, built in 1766 from Manhattan's own hard schist—would fall. Three times in the past 100,000 years, glaciers have scraped New York clean, and they'll do so again. The mature hardwood forest would be mowed down. On Staten Island, Fresh Kills's four giant mounds of trash would be flattened, their vast accumulation of stubborn PVC plastic and glass ground to powder. After the ice receded, an unnatural concentration of reddish metal—remnants of wiring and plumbing—would remain buried in layers. The next toolmaker to arrive or evolve might discover it and use it, but there would be nothing to indicate who had put it there.

Before humans appeared, an oriole could fly from the Mississippi to the Atlantic and never alight on anything other than a treetop. Unbroken forest blanketed Europe from the Urals to the English Channel. The last remaining fragment of that primeval European wilderness—half a million acres of woods straddling the border between Poland and Belarus, called the Bialowieza Forest—provides another glimpse of how the world would look if we were gone. There, relic groves of huge ash and linden trees rise 138 feet above an understory of hornbeams, ferns, swamp alders, massive birches, and crockery-size fungi. Norway spruces, shaggy as Methuselah, stand even taller. Five-century-old oaks grow so immense that great spotted woodpeckers stuff whole spruce cones in their three-inch-deep bark furrows. The woods carry pygmy owl whistles, nutcracker croaks, and wolf howls. Fragrance wafts from eons of mulch.

High privilege accounts for such unbroken antiquity. During the 14th century, a Lithuanian duke declared it a royal hunting preserve. For centuries it stayed that way. Eventually, the forest was subsumed by Russia and in 1888 became the private domain of the czars. Occupying Germans took lumber and slaughtered game during World War I, but a pristine core was left intact, which in 1921 became a Polish national park. Timber pillaging resumed briefly under the Soviets, but when the Nazis invaded, nature fanatic Hermann Göring decreed the entire preserve off limits. Then, following World War II, a reportedly drunken Josef Stalin agreed one evening in Warsaw to let Poland retain two-fifths of the forest.

To realize that all of Europe once looked like this is startling. Most unexpected of all is the sight of native bison. Just 600 remain in the wild, on both sides of an impassable iron curtain erected by the Soviets in 1980 along the border to thwart escapees to Poland's renegade Solidarity movement. Although wolves dig under it, and roe deer are believed to leap over it, the herd of the largest of Europe's mammals remains divided, and thus its gene pool. Belarus, which has not removed its statues of Lenin, has no specific plans to dismantle the fence. Unless it does, the bison may suffer genetic degradation, leaving them vulnerable to a disease that would wipe them out.

If the bison herd withers, they would join all the other extinct megafauna that even our total disappearance could never bring back. In a glass case in his laboratory, paleoecologist Paul S. Martin at the University of Arizona keeps a lump of dried dung he found in a Grand Canyon cave, left by a sloth weighing 200 pounds. That would have made it the smallest of several North American ground sloth species present when humans first appeared on this continent. The largest was as big as an elephant and lumbered around by the thousands in the woodlands and deserts of today's United States. What we call pristine today, Martin says, is a poor reflection of what would be here if Homo sapiens had never evolved.

"America would have three times as many species of animals over 1,000 pounds as Africa does today," he says. An amazing megafaunal menagerie roamed the region: Giant armadillos resembling armor-plated autos; bears twice the size of grizzlies; the hoofed, herbivorous toxodon, big as a rhinoceros; and saber-toothed tigers. A dozen species of horses were here, as well as the camel-like litoptern, giant beavers, giant peccaries, woolly rhinos, mammoths, and mastodons. Climate change and imported disease may have killed them, but most paleontologists accept the theory Martin advocates: "When people got out of Africa and Asia and reached other parts of the world, all hell broke loose." He is convinced that people were responsible for the mass extinctions because they commenced with human arrival everywhere: first, in Australia 60,000 years ago, then mainland America 13,000 years ago, followed by the Caribbean islands 6,000 years ago, and Madagascar 2,000 years ago.

Yet one place on Earth did manage to elude the intercontinental holocaust: the oceans. Dolphins and whales escaped for the simple reason that prehistoric people could not hunt enough giant marine mammals to have a major impact on the population. "At least a dozen species in the ocean Columbus sailed were bigger than his biggest ship," says marine paleoecologist Jeremy Jackson of the Smithsonian Tropical Research Institute in Panama. "Not only mammals—the sea off Cuba was so thick with 1,000-pound green turtles that his boats practically ran aground on them." This was a world where ships collided with schools of whales and where sharks were so abundant they would swim up rivers to prey on cattle. Reefs swarmed with 800-pound goliath grouper, not just today's puny aquarium species. Cod could be fished from the sea in baskets. Oysters filtered all the water in Chesapeake Bay every five days. The planet's shores teemed with millions of manatees, seals, and walrus.

Within the past century, however, humans have flattened the coral reefs on the continental shelves and scraped the sea grass beds bare; a dead zone bigger than New Jersey grows at the mouth of the Mississippi; all the world's cod fisheries have collapsed. What Pleistocene humans did in 1,500 years to terrestrial life, modern man has done in mere decades to the oceans—"almost," Jackson says. Despite mechanized overharvesting, satellite fish tracking, and prolonged butchery of sea mammals, the ocean is still bigger than we are. "It's not like the land," he says. "The great majority of sea species are badly depleted, but they still exist. If people actually went away, most could recover."

Even if global warming or ultraviolet radiation bleaches the Great Barrier Reef to death, Jackson says, "it's only 7,000 years old. New reefs have had to form before. It's not like the world is a constant place." Without people, most excess industrial carbon dioxide would dissipate within 200 years, cooling the atmosphere. With no further chlorine and bromine leaking skyward, within decades the ozone layer would replenish, and ultraviolet damage would subside. Eventually, heavy metals and toxins would flush through the system; a few intractable PCBs might take a millennium.

During that same span, every dam on Earth would silt up and spill over. Rivers would again carry nutrients seaward, where most life would be, as it was long before vertebrates crawled onto the shore. Eventually, that would happen again. The world would start over.

The wilds of New York

If humans were to vanish from New York, how soon would nature take over? Scientists predict that within . . .

10 YEARS: Sidewalks crack and weeds invade. Hawks and falcons flourish, as do feral cats and dogs. The rat population, deprived of human garbage, crashes. Cockroaches, which thrive in warm buildings, disappear. Cultivated carrots, cabbages, broccoli, and brussels sprouts revert to their wild ancestors.

20 YEARS: Water-soaked steel columns supporting subway tunnels corrode and buckle. Bears and wolves invade Central Park.

50 YEARS: Concrete chunks tumble from buildings, whose steel foundations beginto crumble. Indian Point nuclear reactors leak radioactivity into the Hudson River.

100 YEARS: Oaks and maples re-cover the land.

300 years: Most bridges collapse.

1,000 years: Hell Gate Bridge, built to bring the railroad across the East River, finally falls.

10,000 years: Indian Point nuclear reactors continue to leak radioactivity into the Hudson River.

20,000 years: Glaciers move relentlessly across the island of Manhattan and its environs, scraping the landscape clean.