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# Long-Range Consequences Of Interplanetary Collisions

*The risk is real, but the technology to divert approaching bodies is even more dangerous.*

As Comet Shoemaker-Levy 9 races toward its mid-July collision with the planet Jupiter, considerable public attention is being focused on catastrophic impacts with the Earth—in the past and in the future. In recent years calls have been made to develop technologies that could deflect any asteroid or comet found to be on a collision course with Earth. But before devoting resources to this scheme, careful consideration must be given to the nature and time scale of the risk and to the cost-effectiveness and possible booby traps in the suggested means of mitigation.

Comets have been associated with catastrophes in almost all cultures and since remotest antiquity. The first such argument with a modern scientific flavor was offered by Edmund Halley in 1688. He wondered if the Noachic flood could have been caused by tidal effects from a grazing collision (or an actual impact) of a comet with the Earth and proposed in effect a comet-induced tsunami. Since then the impact danger of small worlds has been a common motif in popular culture. Scientists have, until recently, generally responded with reassurances about the improbability of perilous collisions. This summer's impact with Jupiter reminds us that improbable is not impossible.

We now know that the Earth orbits the Sun amid a swarm of small bodies. Some 200 Earth-orbit-crossing asteroids (ECAs) and a much smaller number of Earth-orbit-crossing comets have been discovered, almost entirely by a handful of observers using small telescopes. These limited searches, in tandem with analyses of the lunar and terrestrial cratering records, have established that the ECA population awaiting detection is enormous. There are thought to be some 2,000 objects as large as 1 kilometer in diameter, 320,000 as large as 100 meters, and 150,000,000 as large as 10 meters.

It is a straightforward consequence of orbital mechanics and probability theory that, through its long history, the Earth will be struck, at typical velocities of 20 kilometers per second, many times by these objects. Collisions with the larger members of this population are catastrophic. The greatest danger is from im-

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pacts energetic enough to inject so much pulverized soil and rock into the stratosphere as to darken and cool most of the Earth, regardless of the impact location.

Unlike most familiar hazards, the impact threat works on many different time scales, all much longer than a human lifetime. On average, every millennium there will be a collision event as energetic as the highest-yield nuclear weapon ever detonated (the result of an impact of an object a few tens of meters in diameter); every 10,000 years, one that may have global climatic effects (the result of an impact of an object 200 meters in diameter); and every million years, an impact event tens of times more energetic than the aggregate yield of the world's current nuclear arsenal (the result of an impact of an object 2.5 kilometers in diameter)—enough to cause a global catastrophe and kill a significant fraction of the human species.

The evolution of life on Earth seems to have been profoundly altered by collisions with such bodies. The best-attested such event, and the single-most important reason that interplanetary collision hazards are being taken seriously today, is the Cretaceous-Tertiary (K-T) catastrophe of about 66 million years ago, in which all the dinosaurs and about 75 percent of the other species of life on Earth were rendered extinct. The events attendant to that impact are thought to include a global immolation of land plant life, widespread tsunamis, chaotic ocean mixing, a decline in light levels toward and below the compensation point of photosynthesis (below which plants burn more chemical energy than they store), short-term average global temperature declines of 10°C or more, global acid rain, significant depletion of the protective ozone layer, and prolonged carbon-dioxide-induced global warming. The relative hazards provided by each of these factors is unknown, but it seems likely that a quick succession of environmental catastrophes is nonlinearly more dangerous, because organisms immune to or only weakened by one assault may be finished off by the next. Even an impact much less severe than the K-T event would pose a serious threat to our global civilization.

A conservative rough threshold for the diameter of a colliding asteroid that would cause a global catastrophe (and not just local devastation) is set at about 1.5 kilometers. Such a collision would release an energy equivalent to 100,000 megatons of TNT, disrupt the ecosphere, terminate agriculture, and likely kill more than a billion people. Refining current assessments of the impact hazard is therefore well worth doing, especially because, compared with many other activities of our civilization, it is so cheap.

## Assessing risks

David Morrison of NASA and an international team of scientists have prepared a report on how to acquire more information about ECAs. They propose a project called "Spaceguard" to identify and track ECAs of at least 1 kilometer diameter. With the use of six 2.5-meter ground-based telescopes spaced around the world, images would be recorded with electronic cameras and then studied with the help of computers to pick out comets and asteroids and roughly calculate their orbits. It would then be possible to identify those on collision trajectories with Earth in, say, the next century and to subject them to more careful observation and analysis. The Spaceguard team estimates that within 30 years more than 95 percent of these potentially threatening objects can be inventoried at a total cost of $300 million.

We have the time to conduct such a survey. The average time interval between civilization-disrupting impacts is a few hundred thousand years, so the risk of such an impact during the next century is one in a few thousand.

A major impact would surely devastate the global civilization, but it must be understood in the context of its likelihood and the likelihood of other risks—catastrophic and otherwise. In the actuarial calculus of risk assessment, one combines the roughly 500,000-year interval between global impact catastrophes with the (highly uncertain) estimate that 1.5 billion people would be killed (mostly by starvation or disease) to compute an equivalent annual mortality rate of 3,000 deaths per year. This estimate is very approximate, but serves for comparisons with other risks.

The annual global death rate from smoking tobacco is currently about 3 million persons (projected to rise to 10 million by 2025), and the number of infants and small children who die each year worldwide from easily preventable diarrhea and dehydration is of the same magnitude. With effects amortized, cosmic impacts are far from being our most pressing problem. A critic might contend that with limited global resources, the human species would benefit much more from global antismoking and oral-rehydration campaigns.

But the counterargument can be offered that interplanetary collision hazards are in a very different category from tobacco smoking and infant dehydration. The destruction of our civilization or the extinction of our species, no matter how improbable, are disasters of a different kind. If we take this counterargument seriously, though, then we must consider other hazards of the same class. Is there, for instance, a higher probability of the short-term destruction of our civilization from pulmonary AIDS—a hypothetical mutation or transgenic exchange in the HIV virus that permits it to be transmitted through the air like many respiratory diseases and the common cold? What about other possible pandemic diseases, perhaps caused by natural selection of microbes for resistance to antibiotics or the release of agents developed for biological warfare? What about unexpected positive feedbacks in global warming? What about destruction of the primary photosynthetic producers from increased ozone depletion, or the destruction of key ecosystems from the extinction of a few unobtrusive species? What about the world population crisis? What systematic effort is being made to identify all members of this class of improbable but extremely perilous disasters, and to demonstrate that the impact of a large asteroid or comet with the Earth is, over the next few centuries, the most dangerous of these contingencies?

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## Countering the threat

It is of course sensible to seek cost-effective reduction of risks for all hazards to our civilization. Spaceguard arguably constitutes a reasonable and cost-effective precaution, permitting us to refine our understanding of how serious and how imminent this threat may be.

However, arranging in advance to destroy or deflect a hazardous ECA in anticipation that such an object might, against 5,000-to-1 odds, be discovered during the 21st century is quite another matter—because of the time scales involved, the cost, and the possible dangers of developing the relevant technology. Since the interval between such impacts is comparable to the age of the human species and since ECAs are likely to be identified in a Spaceguard-like survey many decades, or even centuries, before impact, there can be no urgency about taking measures to prevent or mitigate collisions. We lose almost nothing in terms of the safety of humanity during the next few decades (or centuries) if we delay the costly development of means of prevention until a threatening object is found. Indeed, it seems likely that technological progress in the next few decades (or centuries) will provide much cheaper, as well as much safer, means of prevention than any we can conceive of today.

Proposals have been circulating since 1967 that recommend developing rocket and nuclear-weapon technologies to destroy or deflect near-Earth objects (NEOs) on impact trajectories with the Earth. (Nuclear weapons in space are explicitly forbidden by both the Limited Test Ban Treaty of 1963 and the Outer Space Treaty of 1967, but these strictures would presumably be relaxed if it were necessary to save the global civilization.)

In the most widely discussed scenario, the orbit of the NEO is altered by exploding nuclear devices above the asteroid's surface near the closest point its orbit takes it to the Sun. (This gives the greatest leverage.) Although underground explosions will provide the maximum impulse, the escape velocity on NEOs is so low that any single-impulse change in velocity greater than about 1 meter per second would disrupt the body. In practice, for the most readily moved NEOs, deflection requires several to many stand-off nuclear explosions, each with a yield of 20 megatons or less. Even if a single nuclear weapon had adequate yield for such deflection, this is an unwise approach because of the irreducible errors in knowledge of yield and of how strongly held together the asteroid is, both of which influence the effect of the explosion. The only prudent approach is to "herd" an NEO with a series of smaller explosions, carefully monitoring (perhaps with emplaced transponders) the orbital dy-

namics after each explosion. Some have also proposed employing this technique to insert selected asteroids into orbit around the Earth to facilitate mining their platinum-group metals.

Other methods of deflection have been discussed, including high-velocity kinetic energy interception, implanting a rocket engine using indigenous material as reaction mass, or attaching large lightweight panels to the NEO to constitute a solar-powered mass driver. Although the following analysis applies equally to such methods, we do not discuss them further here—either because they cannot provide enough deflection or because the technology is unlikely to be available in the near future. We do wish to call attention to the possibility that such schemes, in the real world and in light of well-established human frailty and fallibility, might be very dangerous.

The possibility of utilizing nuclear weapons to save the Earth has—unsurprisingly—proved attractive to some elements of the defense establishment at a time of declining budgets and changing missions. They tend not to stress the dangers of deflection technology. Los Alamos National Laboratory held a three-day Near-Earth Object Interception Workshop without a single clear statement, even in passing, of the possibility that this technology might have serious ancillary dangers. But the whole subject is, by its very nature, inextricably bound up with policy judgments about risk. We contend that in any discussion of the deflection proposal it is necessary to address explicitly whether it creates a problem more worrisome than the one it aims to solve.

## Deliberate misuse

Any method that can be devised to destroy or deflect an approaching large near-Earth object can be used, on a much shorter time scale, to do great damage to the global environment. If we can perturb one object on impact trajectory so it does not collide with the Earth, we can transform many near-Earth objects on benign trajectories into impactors. The latter is more difficult, but it does not constitute an orders-of-magnitude difference in technical effort.

Given the current pool of about 100 known ECAs with diameters as large as 1 kilometer, statistics suggest that only about one a century will pass close enough to be deflectable into the Earth. One of the best present candidates is 1991 OA, which in 2070 can be deflected into Earth impact trajectory with an aggregate yield of only about 60 megatons, according to calculations by Alan Harris of the Jet Propulsion Laboratory, Greg Canavan of Los Alamos National Laboratory, and ourselves. However, the total, still largely undiscovered, population of such objects probably numbers about 2,000; were nearly all of them inventoried—as is proposed in the Spaceguard survey—it might take no more than a few years to identify a suitable object, alter its orbit, and send it crashing into the Earth. There is no other way known in which a small number of nuclear weapons can destroy the global civilization.

The technology for ground-based and space-borne detection of NEOs, orbit determination, and automated spacecraft control and rendezvous can be expected to improve and diffuse rapidly in the coming decades. Rocket boosters capable of lifting 10 tons to low-Earth orbit are likely also to be widely available, and nuclear weapons are in rapid proliferation. It is possible that in a few decades many nations will be able to detect kilometer and subkilometer NEOs, determine their orbits with high precision, and rendezvous with them unobtrusively.

We sometimes hear that this or that technology would certainly not be misused, or that only a madman would misuse it. We note that madmen exist and sometimes achieve the highest levels of political power in modern industrial states. This is the century of Hitler and Stalin, tyrants who posed great dangers not just to the rest of humanity, but to their own people. In the winter and spring of 1945, Hitler ordered Germany to be destroyed—even "what the people will need for elementary survival"—because the surviving Germans were "inferior" to those who had already died. If Hitler had nuclear weapons, the threat of a counterstrike by Allied nuclear weapons is unlikely to have dissuaded him.

If the technology to deflect NEOs away from the Earth can with equal facility be used to turn inoffensive NEOs to Earth-impact trajectories, is it wise to develop such a technology? Might it be used not as a weapon of war between nations but as a means for the indiscriminate murder of multitudes? How sure can we be that it will not get into the wrong hands—a Hitler or a Stalin, some misanthropic sociopath, a religious fanatic hastening the Day of Judgment, some victim of ethnic violence bent on revenge, or tech-

nicians incompetent or insufficiently vigilant in handling the controls and safeguards?

These examples from 20th-century history could be multiplied manyfold. They urge on us great caution in the development of potentially apocalyptic technologies. No matter what reassurances are given, the acquisition of such a package of technologies by any nation is bound to raise serious anxieties worldwide. A vision of a launch-ready armada standing by to deal with impact threats is not reassuring. The technologies in question are on a wholly unique scale, implying dangers never before faced by the human species. Surely those who argue the prudence of preventing catastrophic impacts with a probability per century of one in a few thousand will recognize the prudence of preventing comparable catastrophes from the misuse of this technology—with unknown but probably much higher annual probabilities.

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It is difficult in the light of present global politics to imagine sufficiently ironclad guarantees against misuse. It is true that there are some natural mitigating factors. A readily deflectable object such as 1991 OA would presumably be under continuous observation by many nations during its 2070 close approach to Earth's orbit. But will all dynamical data on such objects be shared with all nations? The need for multiple nuclear weapons explosions to herd an asteroid suggests that efforts to deflect asteroids may be detectable before impact trajectory is achieved. But will anyone be investing in the technology to monitor nuclear explosions 300 million kilometers from the Earth? Is it possible to explode nuclear weapons in such a way (shielded by the asteroid itself, for example) as to minimize detection from Earth? Distributing deflection technology among many nations in the hope that one would counterbalance misuse by another, or limiting access to these technologies to the United Nations, seems wildly unrealistic at present. It is hard to be confident that international controls on the misuse of this technology could have a reliability commensurate with the threat.

The countervailing concern is that if we never develop deflection technology, eventually we will be defenseless against a devastating impact. But "eventually" most likely means within the next few hundred thousand years. If we postpone developing such technology until a threatening asteroid is identified, given the likely warning times of many decades or more, our ability to prevent the collision remains uncompromised. But if we develop the technology prematurely, then the opportunity for such an impact becomes much more frequent, through human intention or inadvertence.

## What about comets?

Active comets cross the Earth's orbit only a few percent as often as asteroids do, but because of their higher velocities they can release as much as 10 times more energy than comparably sized asteroids. Accordingly, comets may constitute as much as a quarter of the serious impact hazard. Long-period comets (LPCs) approach on high-speed, nearly straight trajectories from far beyond the outermost planet. Trajectory refinement, threat identification, and mitigation are extraordinarily more difficult for LPCs, because of short warning times (a few months) and obscuration of the solid cometary nuclei by their gas and dust comae.

The harsh reality is that mitigation systems adequate to protect against the LPC hazard probably are well beyond the current economic capability of our civilization and would introduce new risks that seem still more unacceptable. Of course, the odds are that we will have to contend with many collision-threatening, subkilometer NEOs before encountering a large LPC on collision trajectory. Over a shorter time scale, but still in the relatively distant future, it may become possible to deploy detectors, perhaps at large distances from the Sun, that provide comfortable advance notice of incoming comets.

Our greatest concern may be a poorly informed public. If we embark on an ambitious surveillance effort, we could in a generation characterize the orbital elements of more than 30,000 objects at least 100 meters in diameter that cross the Earth's orbit. Thousands of near misses (at less than one lunar distance)

will be experienced before one object on an imminent collision course is discovered. Maps will be published showing near-Earth space black with the orbits of 30,000 asteroids and comets—10 times the number of stars one can see on a clear night. Public anxiety might be much greater in such a time of knowledge of NEOs than in our current age of ignorance. There might then be enormous public pressure for means to mitigate even nonexistent threats, feeding the dangers to which we have alluded. The only foreseeable solution is a combination of accurate orbit estimation, realistic threat assessment, and effective public education—so that in a democracy the citizens can make their own, informed decisions. This is a natural task for NASA.

In an indirect way the threat of interplanetary collisions may have a political silver lining. They represent a common enemy to all nations and ethnic groups. By posing two different classes of danger to the human species, one natural and the other of our own making, Earth-approaching objects may provide a new and potent motivation for maturing international relations, ultimately helping to unify the human species.

*Recommended reading*


T. J. Ahrens and A. W. Harris, *Nature* 360 (1992): 429-433.

G. H. Canavan, J. C. Solem, and J. D. G. Rather, eds., *Proceedings of the Near-Earth-Object Interception Workshop.* Los Alamos National Laboratory Conference. Publication LA-12476-C. Los Alamos, New Mexico: Los Alamos National Laboratory, February 1993.

C. R. Chapman and D. Morrison, *Nature* 367 (1994): 33-40.

T. Gehrels, ed., *Hazards Due to Comets and Asteroids.* Tucson: University of Arizona Press (in press).

D. Morrison et al., *The Spaceguard Survey: Report of the NASA International Near-Earth Orbit Detection Workshop.* Pasadena, Calif.: Jet Propulsion Laboratory, 1992.

C. Sagan, *Bulletin of the Atomic Scientists* 48 (1992): 24-26.

C. Sagan and A. Druyan, *Comet.* New York: Random House, 1985.

V. L. Sharpton and P. D. Ward, eds., *Global Catastrophes in Earth History*, Geological Society of America Special Paper 247 (1990).