



## News &amp; Highlights

## The Nuclear Option—Could It Work for Planetary Defense?

Chris Palmer

Senior Technology Writer



In a *Nature Physics* report published in late September 2024 [1], a team of scientists and engineers at Sandia National Laboratories (Albuquerque, NM, USA) described the results of a laboratory experiment showing that a nuclear blast could create a burst of X-rays powerful enough to change the path of a large asteroid that might one day be on a collision course with Earth. But while the demonstration suggests that this well-trod science fiction idea may not be so fictional, whether it could scale up to a real-world device that would be effective and safe to deploy remains hypothetical. Its use would also challenge a long-standing international ban on launching nuclear weapons into space [2].

The solar system is awash with asteroids and meteoroids (pieces of asteroids, generally < 1 m in diameter) of all sizes, and chance gravitational encounters fling these space rocks into the Earth (Fig. 1). Fortunately, most of these objects are small enough that they burn up in the atmosphere, as meteors (shooting stars); meteoroids that do reach the ground are called meteorites. Much less frequently, fortunately, asteroids can also hit the Earth, and these can pack a punch. One, some 10 to 15 km wide, smashed into the Earth 66 million years ago—it is credited with wiping out three quarters of all animals living at the time, including the dinosaurs [3].

Humankind's survival on Earth might ultimately depend on being able to prevent another such collision with an asteroid. Already tested in space against a real asteroid, kinetic deflection is currently the most realistic option for planetary defense. In 2022, the US National Aeronautics and Space Administration (NASA)'s Double Asteroid Redirection Test (DART) mission demonstrated the feasibility of altering the trajectory of a medium-sized asteroid hurtling through space by crashing into it a non-ordnance, van-sized hunk of metal and electronics [4]. Although scientists found the impact changed the orbit of Dimorphos, an approximately 160 m-wide asteroid, larger objects might require multiple DART-like impacts, each one nudging the asteroid a little more off course. For larger space rocks, however, or if the impact with Earth is projected within 10 years of detection, an energy-based deflector approach, with the power of, say, a nuclear explosion, may be a more successful option.

In theory, nuking an asteroid has advantages over a kinetic mission like DART. The biggest is energy—nuclear explosions produce more energy per mass than any other human technology. “While there are many factors to consider, the size of the asteroid and the amount of warning time are critical—if the object is small or

will not hit Earth for many decades, a kinetic impactor like the DART mission could work acceptably,” said Nathan Moore, a physicist at Sandia and first author of the *Nature Physics* report. “On the other hand, a nuclear explosion is going to be the only option for the largest space rocks, or for ones that surprise us by showing up near Earth with little warning.”

However, unlike actor Bruce Willis and his crew in the 1998 Hollywood movie *Armageddon*, you cannot just nuke an asteroid. Detonating a nuclear explosive directly on (or in) an asteroid runs the risk of fracturing it instead of deflecting it, resulting in many smaller and still deadly meteorites raining down onto Earth. The safer strategy would be a nuclear detonation at some distance away from a threatening asteroid, an approach called a “stand-off nuclear explosion.” Such a blast is theoretically more likely to deflect the asteroid than break it apart. “With a stand-off nuclear deflection, the force is applied over a much larger area, so you can give the asteroid just enough push without breaking it apart,” Moore said. “How well that will work in practice is still an open question.”

And that open question is one that will be difficult to answer since a mission like DART deploying a nuclear explosion in space would violate the 1967 Outer Space Treaty [2]. Such a test would also run the risk of a calamitous launch that could disperse radioactive material into the Earth's atmosphere. There may never



**Fig. 1.** Most of the asteroids on a direct collision course with Earth are small and harmlessly burn up in the atmosphere, as depicted in this artist's illustration. Researchers are exploring using kinetic impactors and nuclear detonations to knock potentially harmful asteroids—ones large enough to reach the Earth's surface and cause tremendous devastation—off their dangerous trajectories. Credit: Alonbrosmann/Ufon.com (public domain).

be a test in space to study the effect of a nuclear explosion on a real asteroid. “Even though one could argue there is a positive justification for doing so, the use of nuclear explosives full stop must quite obviously be carefully controlled,” said Alan Fitzsimmons, professor of astronomy and expert in asteroid and cometary science at Queen’s University Belfast in Northern Ireland, UK.

Because of these limitations, most of the research in this area is done with computer simulations. The Sandia team, however, designed an experiment to simulate a nuclear detonation near an asteroid. Sandia scientists had previously used a similar scheme to simulate the momentum of a nuclear explosion’s shock wave—which results from the expansion of gas in the vicinity—pushing against an asteroid [5]. However, according to the new Sandia results, the massive energy of the X-rays produced by the explosion would do more to change the asteroid’s trajectory than the shock wave itself [1].

In their experiment, Moore and colleagues used Sandia’s Z Pulsed Power Facility, the world’s largest pulsed power machine. The device fires electrical pulses 1000 times stronger than a bolt of lightning, delivering up to 22 megajoules of X-ray energy [6]. At one end of their set-up, the team used 13  $\mu\text{m}$ -thick pieces of foil to suspend, in a vacuum, 12 mm-wide pieces of either quartz or fused silica, two forms of a common mineral found in asteroids. At the other end, they blasted a pocket of argon gas with an intense burst of electricity, imploding the gas and transforming it into an electrically charged plasma millions of degrees in temperature. The X-rays released from this plasma, which approximate the bursts of energy from a nuclear explosion, cut through the foil and put the “asteroids” into free fall. Unlike the previous experiments in which the targets remained stationary, the induced free fall allowed the researchers to observe the true impact of the X-rays on the objects’ trajectories in conditions simulating the vacuum of space [1].

Lasting just 20 millionths of a second, the experiment showed that the quartz and silica samples accelerated to 69.5 and 70.3  $\text{m}\cdot\text{s}^{-1}$ , respectively [1]. The X-rays themselves imparted some momentum to the targets, but much of the push came from the X-rays heating the surfaces of the mock asteroids. The heat vaporized only a small amount (~4%) of each sample’s surface, but that was enough to create a propulsive thrust in the opposite direction as gas expanded away from the surface [1]. A similar propulsive effect occurred when the DART mission crashed into Dimorphos, with the flying ejecta produced by the spacecraft’s impact propelling the asteroid further afield than the impact itself [4]. “By releasing the mock asteroids freely into a vacuum to emulate the condition of real asteroids in outer space, not only were we able to directly demonstrate the concept, but we were also able to impart 30% to 50% more momentum than previous studies had suggested would be possible,” Moore said.

The Sandia team is planning future experiments with mixtures of iron and nickel that more closely mimic the composition of asteroids [6]. According to Mary Burkey, a staff scientist at Lawrence Livermore National Laboratory (LLNL) in Livermore, CA, USA, other groups are working on similar physical experiments at LLNL’s National Ignition Facility (NIF) and the Omega laser at the Laboratory for Laser Energetics in Rochester, NY, USA. The latter group, Burkey said, will examine the effects of stand-off nuclear explosions across a range of energies, detonation distances, and sample compositions. “Exploring that parameter space a bit more allows more breadth of understanding the different effects, and makes it easier to benchmark previous simulations,” said Burkey, who participates in the NIF research and first authored a 2023 paper reporting the results of computer simulations exploring numerous initial conditions [7].

The Sandia team’s computer modeling suggests the nuclear detonation strategy should work at scales far larger than they tested in

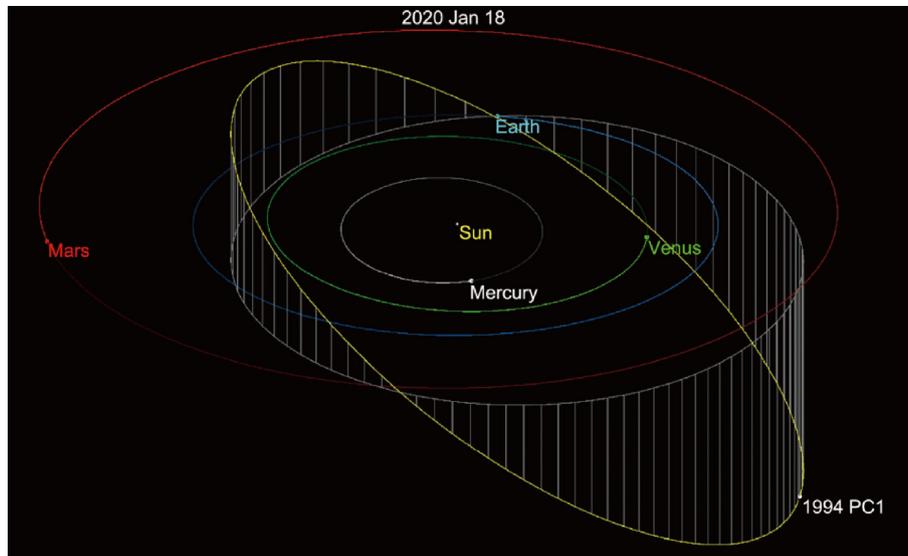
the lab. They calculated that the generated force is powerful enough to successfully deflect an asteroid up to 4.4 km across with a 1-megaton nuclear explosive detonating about 2 km from the space rock’s surface [1]. Burkey, however, was skeptical about this conclusion. “My simulations would not agree with the results of their model,” she said. “As you crank up the energy, the ability of the thin layer of the rock to absorb tons of energy decreases—most of that energy would reradiate back out into space.”

While Burkey, Moore, and others continue to explore the nuances of nuclear-powered deflections, astronomers are working on more thoroughly identifying and tracking the asteroids that pose a danger to the planet. In a study published in 2023 [8], a research team from the University of Colorado (Boulder, CA, USA) and the Jet Propulsion Laboratory at the California Institute of Technology (Pasadena, CA, USA) pored over NASA’s catalogue of asteroids that are both near Earth and larger than 1 km wide. This size is large enough to cause global devastation and possible disruption of civilization, according to NASA’s Planetary Defense Strategy and Action Plan [9]. The researchers modeled when each of those asteroids was expected to come near Earth in their orbits and extrapolated the estimates up to 1000 years into the future [8]. They found that the asteroid with the highest impact risk was one called 1994 PC1 (Fig. 2). That object, a rocky asteroid about 1 km wide, was found to have a 0.0015% chance of passing within the orbit of the Moon in the next millennium. While miniscule, this risk was 10 times higher than that posed by any other large asteroid in the catalogue.

But many rocks hurtling through our solar system have not yet been identified, and a few have passed by the Earth with shocking near misses. An asteroid the length of a football field passed less than 72 000 km from Earth in 2019 [10]. A 1 km-wide asteroid came close in 2012 [11], as did a 70 m-wide asteroid in 2021 [12] and a 290 m-wide asteroid in 2024 [13]. Each of these space rocks was discovered only days before they passed by Earth, thankfully without incident. It has been suggested that some large asteroids escape notice on Earth because the planet’s rotation creates a blind spot whereby some asteroids remain undetected or appear stationary [14].

For asteroids larger than 140 m across, NASA’s size threshold for objects that could cause grave damage upon impact (e.g., capable of wiping out an entire city and potentially killing more than 2 million people), the space agency’s catalogue is estimated to be about 40% complete [15]. The Vera Rubin Observatory in Chile, set to begin surveying the solar system in 2025 [16], and Near Earth Objects (NEO) Surveyor—an infrared, space-based telescope slated to launch in 2027 and dedicated to searching for potentially dangerous asteroids [17]—have been designed to make significant progress toward meeting the US Congress’s mandate for NASA to find more than 90% of all NEO larger than 140 m [17]. “Between the Rubin and the NEO observations, we will be in a situation within 10 years or so where possibly all of the risk of large impacts over the next century or two has been retired,” Fitzsimmons said.

Regardless, the risk of annihilation by asteroid, though small, remains a credible threat, making planetary defense a priority for space research. While the United States is working with the European Union on the Hera Mission that will conduct a post-mortem analysis of the DART test in October 2026 [18], China plans to launch its own kinetic impactor mission in 2026. The mission, which will target the Earth-crossing, near-Earth asteroid 2020 PN1, will resemble a mashup of DART and Hera, with one module smashing into the 40 m-wide space rock and another module hanging back to complete a thorough post-impact inspection [19]. China is also planning another asteroid-redirect mission to crash 23 Long March 5 rockets into the asteroid Bennu to divert it from its current trajectory of winding within  $7.4 \times 10^6$  km of Earth’s orbit between 2175 and 2199 [20].



**Fig. 2.** The orbit of 1994 PC1, a large (1 km), stony asteroid currently thought to be the most potentially hazardous asteroid to Earth over the next 1000 years. Credit: Tomrueh/Wikimedia Commons (CC BY-SA 4.0).

However, not all potential impacts can be predicted 15 decades ahead of time, or even a decade ahead of time, which means having a nuclear deflection option could be critical. “We have shown, using actual experiments, that nuclear deflection could work on km-scale asteroids, or for smaller asteroids that surprise us and need a harder push,” Moore said. “Nuclear deflection fills that gap in planetary defense that kinetic impact cannot address. Having both options assures we can be ready to deflect any impending impact.”

## References

- [1] Moore NW, Mesh M, Sanchez JJ, Schaeuble MA, McCoy CA, Aragon CR, et al. Simulation of asteroid deflection with a megajoule-class X-ray pulse. *Nat Phys* 2024;20:1833–9.
- [2] United Nations Office for Outer Space Affairs. Treaty on principles governing the activities of states in the exploration and use of outer space, including the Moon and other celestial bodies [Internet]. New York City: United Nations; 1977 Dec 19 [cited 2024 Nov 10]. Available from: <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html>.
- [3] Osterloff E. How an asteroid ended the age of the dinosaurs [Internet]. London: Natural History Museum; [cited 2025 Feb 6]. Available from: <https://www.nhm.ac.uk/discover/how-an-asteroid-caused-extinction-of-dinosaurs.html>.
- [4] Palmer C. DART mission shows potential for planetary defense by smashing asteroid into new orbit. *Engineering* 2023;24:7–9.
- [5] Remo JL, Furnish MD, Lawrence RJ. Plasma-driven Z-pinch X-ray loading and momentum coupling in meteorite and planetary materials. *J Plasma Phys* 2013;79:121–41.
- [6] Haynes K. Nuclear bombs really could deflect asteroids, lab tests suggest [Internet]. Chattanooga: Astronomy; 2024 Sep 23 [cited 2024 Nov 10]. Available from: <https://www.astronomy.com/science/nuclear-bombs-really-could-deflect-asteroids-lab-tests-suggest/>.
- [7] Burkey MT, Managan RA, Gentile NA, Bruck Syal M, Howley KM, Wasem JV. X-ray energy deposition model for simulating asteroid response to a nuclear planetary defense mitigation mission. *Planet Sci J* 2023;4(12):243.
- [8] Fuentes-Munoz O, Scheeres DJ, Farnocchia D, Park RS. The hazardous km-sized NEOs of the next thousands of years. *Astron J* 2023;166(1):10.
- [9] National Aeronautics and Space Administration (NASA). NASA planetary defense strategy and action plan. Report. Washington, DC: NASA; 2023.
- [10] Chiu A. ‘It snuck up on us’: scientists stunned by ‘city-killer’ asteroid that just missed Earth [Internet]. Washington, DC: Washington Post; 2019 Jul 26 [cited 2024 Nov 10]. Available from: <https://www.washingtonpost.com/nation/2019/07/26/it-snuck-up-us-city-killer-asteroid-just-missed-earth-scientists-almost-didnt-detect-it-time/>.
- [11] Space.com Staff. Surprise! Big asteroid that flew by Earth larger than thought [Internet]. New York City: Space.com; 2012 Jun 23 [cited 2024 Nov 10]. Available from: <https://www.space.com/16263-asteroid-2012lz1-size-earth-flyby.html>.
- [12] Reich A. 747-sized asteroid skimmed by Earth, and scientists didn’t see it coming [Internet]. Jerusalem: The Jerusalem Report; 2021 Sep 23 [cited 2024 Nov 10]. Available from: <https://www.jpost.com/science/747-sized-asteroid-skimmed-by-earth-and-scientists-didnt-see-it-coming-680052>.
- [13] Cuthbertson A. NASA issues alert for stadium-sized asteroid approaching Earth [Internet]. London: The Independent; 2024 Sep 17 [cited 2024 Nov 10]. Available from: <https://www.independent.co.uk/space/asteroid-alert-nasa-2024-on-b2610177.html>.
- [14] Wainscoat R, Weryk R, Chesley S, Veres P, Micheli M. Regions of slow apparent motion of close approaching asteroids: the case of 2019 OK. *Icarus* 2022;373:114735.
- [15] Grav T, Mainzer AK, Masiero JR, Dahlen DW, Spahr T, et al. The NEO surveyor near Earth asteroid known object model. 2023. arXiv:2310.20149.
- [16] Mann A. The Vera C. Rubin Observatory is ready to transform our understanding of the cosmos [Internet]. Cambridge: MIT Technology Review; 2024 Jan 1 [cited 2025 Jan 19]. Available from: <https://www.technologyreview.com/2025/01/01/1108643/vera-c-rubin-observatory-telescope-cosmos-universe-space-digital-camera/>.
- [17] NASA Jet Propulsion Laboratory. Near-Earth Object Surveyor [Internet]. Pasadena: NASA Jet Propulsion Laboratory; [cited 2024 Nov 10]. Available from: <https://www.jpl.nasa.gov/missions/near-earth-object-surveyor/>.
- [18] Strickland A. European spacecraft launches for ‘crash scene investigation’ of first planetary defense test [Internet]. Atlanta: CNN; 2024 Oct 7 [cited 2025 Feb 7]. Available from: <https://www.cnn.com/2024/10/07/science/hera-mission-launch-dart/index.html>.
- [19] Jones A. China to target near-Earth object 2020 PN1 for asteroid deflection mission [Internet]. Alexandria: Space News; 2022 Jul 12 [cited 2025 Feb 7]. Available from: <https://spacenews.com/china-to-target-near-earth-object-2020-pn1-for-asteroid-deflection-mission/>.
- [20] Turner B. China wants to launch asteroid-deflecting rockets to save Earth from Armageddon [Internet]. New York City: Live Science; 2021 Jul 10 [cited 2024 Nov 10]. Available from: <https://www.livescience.com/china-rocket-fleet-divert-asteroid-bennu.html>.