The Nuclear Option is No Option At All

We wish to respond to Michael J. Dunn's opinion piece, "Earth's best defense" in the February 2018 issue, which makes the case for trying to destroy a dangerous near Earth object, with a nuclear detonation. The community of researchers who worry about this issue on a daily basis long ago considered and wisely discarded the nuclear option. The reasons had nothing to do with political correctness and everything to do with analysis, physics, and information shared through a series of Planetary Defense Conferences held every two years. Allow us to explain.

Suppose an asteroid, 10 to 50 meters in diameter, is discovered on a collision course with Earth. This is the size of the object that created the 1.2 km wide Barringer Crater near Winslow, Arizona, and one large enough to cause extensive damage, ballistically throwing ejecta out to 3 km from the crater.

Such a body could not be discovered *in situ* at its ultimate source region, the asteroid belt, $\sim$3 astronomical units (AU) from the Sun and $\sim$2 AU from Earth. At those distances, and assuming a realistic albedo of 15%, the impactor would have a V magnitude of +31.6 to +28.1. This is beyond our detection threshold of $V \sim 23$ by over two orders of magnitude. (Note: 5 magnitudes = a factor of 100 in brightness.) Such a body would not be discovered unless detected during a previous, much closer encounter with Earth.

The Barringer impactor had an iron/nickel composition. While 10 Megatons (MT) is the most commonly adopted impact energy for the crater, realistic estimates vary anywhere from 1–60 MT. Contrary to Dunn's statement, the impactor was not completely vaporized by the collision. Many chunks were strewn about the surrounding countryside; some are now in collections. Just because the body was *not* imbedded intact below the impact site does not imply total vaporization. In fact, the presence of spherules found in the vicinity indicate the majority of the bolide was melted, not vaporized.

Dunn suggests interception of the threat at 1 AU from Earth and that detonation of a 10 MT nuclear device at a range of 0.1 to 1 km from the surface would vaporize the object, or at least deflect it enough so that it would miss impacting Earth.

Laboratory studies and numerical modeling show that one needs a pressure of $\sim$500 GPa to vaporize iron (more for a Fe/Ni mix). If we take the upper limit of force (3.229×10^{12} N) the device would deliver and divide by the meteoroid's surface area (1.96×10^{3} m^2) that only gives a mean pressure of 1.65 GPa. There is no way the nuclear blast would vaporize an iron-rich asteroid. Rather, we would be left with a disrupted body.

Fragmentation of the body compounds the problem. Instead of having to deflect one bullet, we have a hailstorm of particles, large and small, to dodge. Perturbation of each particle from its original orbit cannot be predicted, and we would have to ensure the entire ensemble misses Earth so as not to compound the damage inflicted. Note that a 10-cm wide iron fragment (the size of your fist) can survive atmospheric entry to hit the ground, heating and producing shock waves in the atmosphere on its way down. The 2013 Chelyabinsk bolide (estimated to be initially 20 m in diameter) attests to how seriously damaging these shock waves can be.

What is an appropriate amount of deflection to ensure a miss of the Earth? Taking the geometrical radius of the Earth is a severely unrealistic underestimate, for several reasons.

First, a body whizzing by the Earth in a near miss will have its trajectory deflected inward to the Earth's center of mass due to our planet's gravitational attraction. One can calculate the perigee distance as a function of the body's velocity at infinity (v_∞). Setting this distance to one Earth radius allows us to derive an "effective gravitational cross section" for a given flyby speed, an effect called "gravitational focusing."[1] For v_∞ of zero, the effective gravitational radius of Earth is $\sqrt{2}$ times the physical radius of 6,378 km. A typical relative impact velocity of an asteroid with the Earth at 1 AU is between 15–20 km/s, corresponding to gravitational radii of 7,960 and 7,310 km (or 1.25 and 1.15 Earth radii), respectively. With Dunn's (approximately 50%) safety margin, a single impactor would need to be deflected roughly 16,000 km, not 10,000 km.

Second, we now consider a body disrupted by our nuclear blast. The gravity of a 50 m wide body is negligible ($v_{\rm escape}$ $\sim$0.5 m/sec for an iron sphere). Fragments of this body would be imparted with a range of kinetic energies, and would drift apart. If detonation occurs at 1 AU and 100 days before Earth encounter, there would be 8.63×10^6 sec available for fragment dispersal. For example, at 1 m/sec (a clearly conservative number) the cloud would have

[1]Specifically, $r_{\rm grav} = r_{\rm geom}\sqrt{1 + \left(\frac{v_{\rm escape}}{v}\right)^2}$.

expanded to 17,000 km, or 1.35 Earth diameters. We would have to ensure a deflection of at least 2.6 Earth radii, plus a 50% safety margin, or nearly 4 Earth radii.

Dispersal also would occur along the trajectory, not just normal to it. After the same 100 days, what would have been a single impact event would have spread out to last over an hour, an additional time zone equivalent in longitude.

The threat avoidance problem is much more complicated than a simplistic, one-time diversion, whatever its size. If the mutual orbits of Earth and asteroid intersect at one time, they will intersect at other times in the future. A "near miss" is not an acceptable solution. Future encounters must also be considered using the perturbed orbits of the impactor fragments. The fragments will continue to disperse even after Earth encounter, becoming an ever-widening debris cloud. Tidal forces, the Yarkovsky effect (the slight thrust caused by solar heating and re-radiation of thermal IR by the evening hemisphere), radiation pressure, and perturbations by other bodies of the inner solar system will constrain what constitutes a "successful" change in trajectory. Each of these stochastically adds to what comprises an acceptable "miss."

Up until now we have assumed a mechanically-competent Barringer-sized threat. However, metallic (Fe/Ni) bodies are actually only a small minority (∼4.5%) of the population of interplanetary bodies, as shown by the distribution of meteorites recovered from Antarctica. Much more probable is the threatening body would have a stony composition. From the sample of asteroids and comets visited by spacecraft, representative porosities of these bodies are a few tens of percent. These bodies are most likely agglomerations of chunks, large and small. As Dunn correctly notes, any impulsive change in momentum is likely to fragment the body than deflect its trajectory. There is overwhelming evidence that the average asteroid is mechanically weak. Consider Comet Shoemaker-Levy 9's impact with Jupiter in 1992. The comet was torn into 21 fragments merely by tidal forces in a previous encounter with Jupiter. There are many known binary asteroids in the main belt. While some can be produced by impact or 3-body interaction, the majority likely formed by spin-up and mass shedding as a result of the YORP effect. While beyond the scope of this article, YORP (in particular the Yarkovsky effect) is what perturbs main-belt asteroids into nearby resonances, which then scatters them into Earth-crossing orbits.

So far as scientists know, the "rubble pile" model for stony asteroids is a much closer approximation to physical reality for these bodies: both their gravity and mechanical strength are close to zero. If you push a bucket of sand, it moves as a whole. Not the case of a sand castle. Should a stony object be headed our way, it is likely a wash between the kinetic impactor and a nuclear detonation: either would simply fragment the body.

A failed first attempt at deflection by a nuclear device in all probability eliminates any chance of success on subsequent tries, even should sufficient time exist. Say we try to deliver a second vehicle to the requisite ∼1 km detonation distance, arriving 100 days after the first. Many kilometers before arrival it would encounter substantial debris produced by the initial explosion. The free-fall time from 1 km above a 50 m body is on the order of hours. However, the time to reaccrete slow-moving particles can exceed three orders of magnitude longer, if the meteoroid is fragmented, or aspherical and rotating, or less dense than Fe/Ni, and/or if slow-moving ejecta reach altitude >1 km (all likely). These results stem from modeling the distribution of boulder fields observed on the asteroid 951 Gaspra from the reaccretion of slow-moving ejecta. The action of the first, failed attempt has produced a field of kinetic energy weapons around the original meteoroid. At an approach velocity of 11 km/sec, impact by a rice-sized particle would be catastrophic to delivery vehicle and probability of mission success.

Conclusion: The Nuclear Option is No Option At All.

So what can be done to deflect a potentially hazardous asteroid on course for an Earth encounter? The upshot is that true remediation is more likely if the target is not disrupted, but given a gentle, long-lasting nudge in a controlled manner. The longer lead-time we have to Earth encounter, the more options we have. The best path to success depends on 1) early detection and cataloging of potentially hazardous bodies, and 2) knowledge of the physical properties of such a body, both keys to designing a reasonable course of action.

The majority of potentially hazardous bodies are already in Earth-crossing orbits, not pristine first-time visitors from the asteroid belt. The best method is to place a dedicated wide-field telescope in solar orbit just interior to Earth. By looking back at our neighborhood with a CCD imager in an automated survey mode, most potentially hazardous bodies could be cataloged down to less than 100 m diameter in a decade or two. Followup observations on the ones deemed most dangerous will refine our assessment of their threat. Active radar observation from Earth allows an orbit to be refined to high precision (mm/sec). Multicolor observation of this subset gives us information regarding their (at least surface) composition.

The first step, detection, is an amazingly cheap path to follow. And even if zero threatening objects are located, there is a derived scientific benefit.

Many methods of “gentle” diversion have been proposed over the last couple of decades. For example:

1) Gravity tractor: a massive satellite is sent close to the body, where it maintains constant altitude via high specific impulse ion thrusters to “pull” the threat in a calculated and controllable direction. With decades of lead time, substantial diversion is possible without physically contacting the body.

2) Landing a similar satellite on the surface of the body and using similar thrusters to “push” the threat in the desired direction.

3) Physically “painting” parts of the body’s surface with reflective and/or absorptive coloring. By controlling the re-radiation of incident sunlight to space, the YORP effect can be emphasized above and beyond what Nature is already doing to evolve the orbit of the body in a controlled manner.

4) Orbiting a satellite equipped with lasers, which would vaporize select regions on the surface of the body, producing an in situ thrust.

These are just a few of the ways we can intervene. They all leverage a gentle interaction applied over a long time to move the meteoroid. With enough lead time (decades or more) we can move these free-flying mountains and do what no other species in the history of our planet has done: have a say in whether we survive.

Postscript: We have not considered the threat from comets. A “new” comet, falling towards the Sun from the Oort Cloud at 50,000 to 200,000 AU would reach Earth’s orbit at a velocity $\geq$60 km/sec. This clearly represents a distinct class of threat from above. While much less likely, the higher encounter speed, coupled with trajectory uncertainty induced by outgassing, presents both problems and solutions for which there no good answers at this time.

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