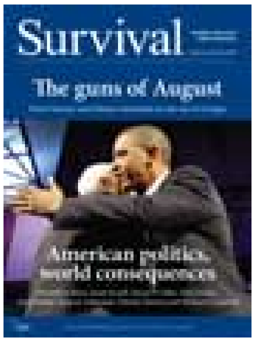

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Asteroid Threat? The Problem of Planetary Defence

Mark Bucknam and Robert Gold

On 13 April 2029, an asteroid the size of 50 US Navy supercarriers and weighing 200 times as much as the USS *Enterprise* will hurtle past the Earth at 45,000 kilometres per hour – missing by a mere 32,000km, closer to Earth than the 300 or so communications satellites in geosynchronous orbit. In astronomical terms it will be a very near miss. The asteroid, called 99942 Apophis, is named after an ancient Egyptian god of destruction: for several months after it was discovered in 2004, scientists were concerned that Apophis might strike the Earth. It still might, though not in 2029. If, on its close approach in 2029, Apophis passes through what is known as a 'gravitational keyhole', its orbit will be perturbed so as to cause it to hit the Earth in 2036 – striking with an energy equivalent to 400 megatonnes of TNT. Although the chances of a 2036 impact are judged to be just one in 45,000, it is unnerving to recall that until just a few years ago, Apophis was completely unknown to mankind, and that similarly sized asteroids have silently shot past Earth in recent years, only to be discovered after the fact.

An asteroid like Apophis would cause considerable damage if it collided with Earth. If it hit on land, it would make a crater about 6km across and the shock wave, ejecta and superheated air would level buildings and trees and

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ignite fires over a wide area.[1] If it hit an ocean, it would cause a devastating cycle of gradually diminishing tsunamis. Scientists cannot yet predict the exact point Apophis might impact in 2036, but their current assessment predicts it would be somewhere along a long, lazy backward 'S' running from northeastern Kazakhstan through Siberia, north of Japan and across the Pacific Ocean before dipping south to converge with the west coast of North America; running eastward across Panama, Columbia and Venezuela, and finally terminating around the west coast of Africa near Senegal. The mid-point of this line lies several hundred kilometres west of Mexico's Baja Peninsula, about midway between Honolulu and Los Angeles. The tsunami from an ocean impact would likely inflict horrific human and economic losses – damage from Apophis could certainly surpass the Indian Ocean tsunami of 26 December 2004, which claimed over 200,000 lives and inflicted damages on the order of $15 billion.

Small probability, huge impact

Apophis is not the only massive and potentially threatening object crossing Earth's orbit. Larger objects that could inflict even greater damage also circulate in Earth's neighbourhood. Fortunately, larger objects are proportionally rarer. There are roughly 100 times as many objects one-tenth the size of Apophis, and only one-hundredth as many objects ten times its size. At one-tenth the size of Apophis – approximately 23m across – an asteroid is big enough to make it through Earth's atmosphere but unlikely to do widespread damage. As a point of comparison, some 50,000 years ago an asteroid roughly 46m in diameter is thought to have created Arizona's impressive 1,200m-wide Meteor Crater. Scientists estimate impacts from asteroids of that size occur, on average, approximately once every 1,000 years.[2] At ten times the size of Apophis – roughly 2.3km across – an asteroid colliding with Earth would cause global effects and could kill tens of millions, if not billions, of people. Finally, the National Aeronautics and Space Administration (NASA) has categorised a strike from a 10km-wide asteroid as 'an extinction-class event'.[3] An asteroid of that size is widely believed to have hit the continental shelf off Mexico's Yucatán Peninsula some 65m years ago, near the present-day town of

Chicxulub, wiping out an estimated 70% of all animal species, including the dinosaurs.[4] Fortunately, such catastrophes are estimated to occur only once every 100m years.[5]

On average, a 1.5km asteroid will strike the Earth approximately every 500,000 years. The devastation from such an impact could kill up to 1.5 billion people. In one sense, that puts the risk of dying from an asteroid strike on a par with dying from a passenger-aircraft accident—around 1 in 20,000 averaged over a 65-year lifetime. But half a million years is so long compared to a human lifespan that it defies believable comparison. Twenty thousand generations will go unscathed for each generation that is decimated by a 1.5km asteroid. Aeroplanes have been around for little more than a century, and fatal aircraft accidents occur every year, so it is not difficult to convince people of the risks associated with flying and the need to spend money to improve flying safety standards.

The chances of Earth being hit by a comet are even smaller than for asteroids. This is a very good thing: comets travel faster and would deliver about nine times as much energy as comparably sized asteroids. When Comet Shoemaker–Levy 9 broke up and slammed into Jupiter in 1994, one of its fragments delivered energy equivalent to 6 million megatonnes of TNT, hundreds of times more energy than in all of the world's nuclear arsenals combined. Long-period comets spend most of their existence in the outer regions of the solar system, beyond the orbits of Jupiter, Saturn, Uranus and even Neptune, infrequently visiting the neighbourhood of the inner planets. Unfortunately, such comets, unknown to us, would only become visible when they were within 6–18 months of possibly striking Earth, leaving little time to react.

There is not a single recorded death by meteoroid

There has not been a single recorded incident of a person being killed by a meteoroid, asteroid or comet, so it is understandable that most people, including scientists, have not traditionally worried about the threat posed by space objects. It is to be hoped that Apophis will not pass through the 'gravitational keyhole' that would put it on course to collide with Earth in 2036, and that there are no undetected asteroids or comets on such a course. But hope is not a strategy, and as small as the probabilities might be, the possible consequences of such an impact merit efforts to mitigate the risk.

Despite human inventiveness and rapidly expanding knowledge, the ability to detect threatening asteroids and comets is weak, and there are no proven systems for deflecting them. Scientists have identified the problem and analysed possible approaches for addressing it, but no one has begun to implement any of the proposed techniques. The threat of collision from asteroids and comets calls for a three-step approach to mitigating the risks: first, find and track objects that are potentially hazardous to the Earth; second, study their characteristics so as to understand which mitigation schemes are likely to be effective; and third, test various deflection techniques to ascertain the best way to adjust the orbits of asteroids and comets, and possibly field a planetary-defence system. Each of these steps would benefit from international cooperation or agreement. It takes an asteroid like Apophis, or a comet like Shoemaker–Levy 9, to remind us that the threat from space is real. And while the probabilities of a strike are small, the consequences are potentially cataclysmic, making our current state of near ignorance unacceptable.

Watching the skies

In 1998, NASA began the Spaceguard Survey, an effort to find, catalogue and track Near-Earth Objects (NEOs) larger than 1km in diameter, and to identify any that might be a hazard to Earth. An NEO is defined as an object that passes within 1.3 astronomical units, or 193m kilometres, of the Sun – that is, 1.3 times the average distance between the Earth and the Sun.[6] The programme is funded at $4.1m per year through 2012. In 2005, Congress tasked NASA with analysing alternatives for detecting and deflecting NEOs. NASA responded in March 2007 with a report entitled *Near-Earth Object Survey and Deflection Analysis of Alternatives*.[7] In that report, NASA stated that it had, by December 2006, discovered 701 NEOs larger than 1km, and that NASA's models projected 1,100 such objects might exist. A kilometre-sized asteroid, if it struck the Earth, would deliver well over 25,000 megatonnes of energy, the equivalent of more than a million Hiroshima bombs.[8]

Congress also called on NASA to lead efforts to find, by the end of 2020, 90% of all NEOs larger than 140m – objects smaller than the 1km NEOs initially surveyed, but still large enough to cause catastrophic regional effects. NASA's March 2007 report analysed various approaches to finding and deflecting these, but recommended the focus of the survey be shifted from NEOs – the vast majority of which pose no threat to Earth – to the subset of potentially hazardous objects (PHOs), objects passing within 0.05 astronomical units (7.4m kilometres) of Earth's orbit, thereby posing a greater risk of collision. Scientific estimates predict the existence of 20,000 PHOs larger than 140m.[9]

NASA analysed options for better detecting PHOs, ranging from continuing the current terrestrial-based Spaceguard Survey to putting visual or infrared sensors on satellites in space. The existing Spaceguard techniques have little to contribute to the expanded goal of detecting objects on the scale of 140m, and NASA estimates Spaceguard could only detect approximately 14% of the 140m-or-larger PHOs by 2020,[10] well short of Congress' goal of 90%. The addition of a ground-based telescope, such as the University of Hawaii's planned Panoramic Survey Telescope and Rapid Response System (PanSTARRS 4)[11] or the proposed Large Synoptic Survey Telescope (LSST),[12] would boost the results to 75–85%, depending on whether NASA shared the telescope with another agency or supported building an additional copy of its own. The most efficient means of finding PHOs would be to place an infrared sensor in a Venus-like orbit – that is, 0.7 astronomical units from the sun. By itself such a sensor system could find 90% of PHOs larger than 140m by 2020. Furthermore, a space-based infrared telescope would allow scientists to reduce the uncertainties in determining the size of PHOs to 20% from over 200% for optical telescopes.[13] A factor-of-two uncertainty – the limit of accuracy with optical telescopes – equates to a factor-of-eight uncertainty in mass. Because the size and mass of a PHO are important characteristics for assessing the danger it could pose, the added performance of a space-based infrared telescope warrants serious consideration. Moreover, an infrared telescope in a Venus-like orbit could efficiently detect PHOs that primarily orbit between the Earth and the Sun; these are difficult to detect from Earth and, according to NASA, have a chance of being perturbed by gravity and becoming a threat. The cost of such a system is on the order of $1bn, and the harsh space environment would likely limit its useful life to around seven to ten years.[14]

Though radar telescopes, such as the giant 305m dish at Arecibo, Puerto Rico, enable rapid and accurate assessments of PHO size and orbit, they are only useful when the objects pass within a few million kilometres of Earth. NASA recommended against developing a radar specifically for finding and tracking PHOs, stating that 'orbits determined from optical data alone will nearly match the accuracy of radar-improved orbits after one to two decades of observation'.[15] Existing radar telescopes should be used as far as possible to refine predictions of Apophis's trajectory – either confirming or ruling out the potential for an impact in 2036. In addition to fielding new Earth- and space-based sensors as suggested by NASA, former astronaut Rusty Schweickert called for placing a transponder on Apophis during a close approach in 2013 to help determine whether a 2036 collision is likely.[16] This could save years of worrying, or give us extra years to prepare and act. Such a mission would cost on the order of a few hundred million dollars.

In addition to new sensors, NASA will need new data-processing capabilities for the expanded effort to find, track, characterise, catalogue and then store and distribute the data for the estimated 18,000 PHOs larger than 140m that the space agency will be expected to monitor. Today, NASA's Jet Propulsion Laboratory uses a system called *Sentry* to turn known PHO data into predictions of PHO orbits projected 100 years into the future. Though NASA's March 2007 report briefly described four possible alternatives for managing data, it left out details on the costs of going from tracking nearly 800 PHOs today to a system that could handle 18,000 PHOs.

Characterising the objects

NASA's *Near-Earth Object Survey* also outlined various options for studying and characterising NEOs. The purpose of characterising NEOs would be to 'assess the threat' and to 'inform mitigation'. Despite their relative proximity to Earth, little is known about the NEOs or PHOs scientists are currently tracking, let alone the 18,000 smaller but potentially dangerous objects NASA expects to find over the next 15 years. They are typically glimpsed as pinpoints of faint light gliding across the comparatively static background of stars. Once an object is discovered, follow-up observations must be compiled just to gain estimates of its size and orbit. While dozens of man-made satellites have probed and analysed the planets and moons in our solar system over the past four and a half decades, scientists have only recently sent the first fledgling unmanned missions to rendezvous with and study asteroids and comets.

Some PHOs are solid, made of rock or metal; others seem to be composed, at least in part, of material resembling gravel and sand held loosely together by the weak attraction of gravity. Still other PHOs are thought to be extinct comets, made up of a mixture of dust, rock and frozen water, ammonia, methane or other volatile materials. To use most of the theoretically feasible means of mitigating the threat of a PHO, scientists would first need to know the object's size, mass, internal structure, rotation rate and even colour or reflectivity (albedo).

Dedicated missions to visit and study the PHOs actually threatening Earth would be needed before attempts were made to deflect them, unless one were to rely solely on stand-off nuclear explosions, in which case little information beyond orbit and approximate mass would be needed.[17] Funding several PHO rendezvous missions would probably cost between $1–5bn. For the sake of comparison, the *Near Earth Asteroid Rendezvous* mission launched by NASA in 1996 cost a little over $100m. Several years later, NASA's *Deep Impact* mission, which slammed into Comet Temple-1 on 4 July 2005, cost approximately $300m; and NASA's *Dawn* mission, launched last September to explore two asteroids in the main asteroid belt, cost nearly $500m. Finally, in April 2006, *SpaceDaily.com* reported that a QinetiQ-led consortium had won a €450,000 'contract to design a satellite mission that could one day be used to deflect an asteroid threatening the Earth'.[18] A separate report says the QinetiQ team 'won a £315,000 grant for its preliminary designs', and that the overall mission – named *Don Quijote* – would cost an estimated £200m.[19]

Deflecting the threats

If two objects are on a collision course, it is necessary only to speed up, or slow down, one of them early enough to prevent the collision. Changing Earth's orbital velocity would likely be impossible; it is, however, theoretically possible to change the orbital velocity of a smaller PHO. The smaller the PHO, the easier it would be to affect its velocity, and the earlier attempts were made, the smaller the required change would be to avert a collision.

NASA's March 2007 report stated plainly that using stand-off nuclear explosions to deliver an impulsive force to a PHO would be 10–100 times more effective than other means of deflecting PHOs. Nonetheless, other tools and techniques, including kinetic impactors, gravity tractors, focused solar and laser energy, and rockets to change a PHO's orbital velocity were identified and analysed.

An asteroid resembling a massive pile of sand and gravel might be impossible to push with a rocket or to affect by slamming into it with a kinetic impactor. However, a gravity tractor could, theoretically, hover nearby and – using the gravitational pull between itself and the rubble pile – fire rockets to gradually pull the pile faster or slower in its orbit. The gravity-tractor scheme is the least efficient and least technologically mature option. Indeed, NASA concluded that a gravity tractor would likely prove useful only for the smallest PHOs, and even then decades would be needed for the tractor to effect the desired change in velocity. However, for cases where only a very small deflection is required – keeping Apophis from hitting the gravitational keyhole in 2029, for example – the gravity tractor may be the simplest solution.

An asteroid of sand and gravel might be impossible to push with a rocket

An asteroid tug could be used to deflect a solid PHO. First, rockets would be attached firmly to the PHO in order to push it. Because PHOs rotate or tumble in various ways, the rocket system would have to fire precisely at particular times to impart pushes in the desired direction only. Effecting such a rendezvous, anchoring and initiating a series of precisely controlled rocket-firings would require a great deal of knowledge about the particular PHO, and would pose serious engineering challenges once the requisite characteristics of the PHO were known.

A non-nuclear kinetic impactor would probably work against mostly solid PHOs and would obviate the need to know details of their rotation or kinematics. Technology for hitting PHOs is relatively mature and was demonstrated on the *Deep Impact* mission. A single kinetic impact could be effective for deflecting small PHOs – which pose the most probable threat – if the impact were accomplished early enough before the predicted collision with Earth. Unfortunately, kinetic impacts would be unlikely to achieve the desired results against larger asteroids. At best, kinetic impactors would be capable of delivering one-hundredth to one-tenth the impulse of a nuclear explosion for a given payload size.[20]

For objects larger than 1km, only nuclear explosions could deliver enough of a push to achieve the necessary change in velocity, especially if little time were available to effect the needed change. However, nuclear explosions and kinetic impactors risk breaking up a PHO, potentially making it more difficult to deal with. Because stand-off nuclear explosions would reduce the chances of fragmenting the object, they would be, generally speaking, preferable to nuclear blasts on or below the surface of a PHO. This benefit of using stand-off explosions would be purchased at the cost of a 10- to 100-fold reduction in the energy imparted to the object by a given explosion. Thus, multiple stand-off explosions might be needed to achieve the necessary change in PHO velocity. *In extremis*, attempting to fragment a PHO with a nuclear explosion might be the best available option – perhaps mitigating the inevitable catastrophe without preventing it.

The most powerful current rockets cannot deliver spacecraft directly to PHOs in a timely fashion. Travel time to intercept a PHO might be several years and might also require a close fly-by of Earth, or other celestial object, to modify the orbit of the interceptor to help it reach the PHO. Therefore, responsible authorities would have to preposition planetary-defence systems in space, so that when needed, an interceptor's rockets could be fired for a swing past a nearby planet, giving the interceptor a boost in speed and shaping its trajectory toward the threatening object. Placing a PHO interceptor in a high-energy orbit around Venus would make for a fairly responsive arrangement. Interceptors could be stored in Venus orbit, leaving them poised for missions toward a threatening PHO each Venus year – or once every 225 days.

Developing missile-defence systems has famously been likened to attempting to hit a bullet with a bullet – a metaphor intended to portray the inherent difficulty of the task. Yet today such systems exist and are sufficiently successful to remove doubt about their technical feasibility. Sending spacecraft to conduct fly-by shootings of asteroids or comets will require even higher standards of scientific and engineering excellence than missile defence. Responsible officials would want to be confident an attempt to deflect an inbound asteroid or comet would work, given the potentially catastrophic consequences of failure. They would therefore want to experiment with mitigation systems and to field some redundant capacity as a hedge against system failure.

Costs and consequences

If one or more PHOs are destined to impact Earth in the foreseeable future, the sooner the discovery, the sooner steps can be taken to prepare for and possibly prevent a cataclysm. In addition to a dedicated ground-based telescope such as PanSTARRs or LSST, the advantages of a space-based, dual-band infrared telescope argue persuasively for funding at least one. For approximately $1bn – the amount needed to fund an infrared telescope in a Venus-like orbit – we could greatly improve our knowledge of the scope and details of the threat from asteroids, as well as increase the chances of detecting any particular asteroid before it collides with the Earth.

The overall costs of programmes to find and track asteroids, and to rendezvous with and study them, would amount to between $2–6bn, depending on how many rendezvous missions would be launched. The effort could be carried out over a ten-year time frame at a cost of no more than $500m per year, or less than 4% of NASA's annual budget (approximately $17bn in 2007). By comparison, in fiscal year 2006 alone, the US Congress provided approximately $4bn for avian-flu initiatives[21] – a thousand times more than it budgeted for NASA's Spaceguard Survey programme. In 2006, the World Bank estimated that a severe pandemic with a 1% mortality rate could kill about 70m people and cost upwards of US$1.25 trillion (3.1% of global GDP).[22] An asteroid the size of Apophis, which is not particularly large as asteroids go, could cause comparable levels of death and destruction.

The spectre of pandemic influenza pales in comparison to mounting concerns over the damages expected from climate change – at least in economic terms. While the estimated costs for dealing with climate change vary enormously, they still provide a useful foil for considering how much to spend to fund defences against asteroids and comets. In late 2007, 'sceptical environmentalist' Bjorn Lomborg told *Scientific American* the impact of global warming would likely cost about 1% of world GDP ($658bn) and should be addressed by spending one-twentieth of 1% of world GDP ($33bn) on new non-carbon-producing energy technology.[23] At the higher end of such cost projections, Nicholas Stern, former chief economist of the World Bank, estimated that damages from climate change would amount to 5% or more of world GDP (over $3.29tr).[24] Stern claimed that to effectively deal with the problem, global annual expenditures of 1% of GDP ($658bn) would be necessary.[25] The upper limit for damage caused by an asteroid or comet could exceed the worst projections likely to be wrought by climate change, while the low-end estimate for climate-change mitigation costs – $33bn – would be sufficient to purchase not only the equipment needed to find, track and study threatening asteroids and comets, but also field an operational system to deflect them. The key is to do something before the next devastating impact – in contrast to the Indian Ocean tsunami of 2004, which saw tens of millions of dollars in improvements to the tsunami-warning system come only after disaster struck.

Damage from an asteroid or comet could be worse than climate change

International cooperation

Some aspects of testing and implementing planetary-defence systems should be relatively uncontroversial. For example, practice fly-by missions, or rendezvous to implant homing transponders, could also be used as occasions to study PHOs, thereby serving the interests of scientists and planetary defenders alike.[26] But there are legal impediments and thorny policy choices associated with certain proposals. Although nuclear detonations offer the only feasible hope of imparting enough energy to deflect the largest PHOs, several treaties prohibit placing nuclear weapons in space. Indeed, the mere prospect of testing or deploying nuclear explosives in space would draw opposition from many quarters.

The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (the Outer Space Treaty) came into force in October 1967. It banned the placement of weapons of mass destruction in outer space, in orbit around the Earth, or on celestial bodies. It also established principles of responsibility and liability for a state's actions in space and has served as the basis for other space-specific treaties. If nuclear explosives offered the most promising means of deflecting an incoming asteroid or comet, the threat of annihilation would presumably convince parties to the treaty to make an exception to it. But absent a palpable threat – a named asteroid and a known collision date – signatories to the treaty might resist placing nuclear bombs in space. Such reluctance could undermine defences against long-period comets, where the probability of success could very well hinge on having a system in place before the threatening object was detected. Before world leaders agree to amend Article IV of the Outer Space Treaty to allow nuclear weapons in space, they will need to be convinced that the threat posed by asteroids and comets is not only real, but that it exceeds the dangers that led to Article IV in the first place.

Assuming the Outer Space Treaty could be modified for planetary defence, several difficult policy issues would remain. Treaty signatories would have to decide how many nuclear devices to place in space, and where and for how long they should be left there. There would need to be a policy for disposing of them once they exceeded their shelf life. There would need to be agreement about who would put them in place, monitor them and maintain their orbits. Finally, there would need to be agreement over who could decide upon and control their use.

Given the complexities of conducting rendezvouses and precisely timed stand-off nuclear explosions to deflect inbound asteroids or comets, responsible authorities would certainly want to conduct tests before having to rely on a deflection system to avert a catastrophe. However, the Limited Test-Ban Treaty of 1963 prohibits the testing of nuclear weapons in outer space. Ideally, a PHO should be deflected well before the anticipated collision, meaning that if nuclear explosives were used for planetary defence, they would detonate so far from Earth they would be harmless and utterly inconsequential for anything but their targets. The treaty could be modified to allow tests for planetary defence, so long as they were conducted sufficiently far from Earth. But if an existing nuclear weapon were to be used in a planetary-defence test, the country that designed it might use the test in a way that would contribute to its military weapons programme. Monitoring of the test for military purposes would be indistinguishable from monitoring for the ostensible purpose of evaluating asteroid-deflection results.

Moreover, nuclear-weapons states would need to decide whether to limit tests to existing nuclear devices, or to allow new nuclear-explosive designs to be evaluated. Stand-off nuclear explosions would impart energy to PHOs when X-rays or neutrons were absorbed on the face of the object nearest the blast. The resulting heating and spallation of material from the target would give it a push away from the blast. Thus, nuclear explosives designed to focus X-rays or neutrons in a particular direction would presumably be more effective for planetary defence than existing bombs. International cooperation would be highly desirable to determine whether such new devices should be designed, developed and tested. Energy-focusing nuclear explosives would almost certainly have military applications, and countries currently adhering to self-imposed moratoria on nuclear testing would have to decide whether to allow underground tests of devices designed for planetary defence, knowing that such tests could very well have far-reaching effects on non-proliferation regimes. In all likelihood, it would seem more acceptable to test and place weapons in space if they were drawn from existing stockpiles, rather than developed anew.

The 1991 Strategic Arms Limitation Treaty (START I) bans placing weapons of mass destruction in orbit or using intercontinental ballistic missiles to deliver ‘objects into outer space for purposes inconsistent with a party’s other international obligations’. This treaty between the US and Russia, as the successor to the Soviet Union, might need modification to enable the testing or fielding of a planetary-defence system – assuming, that is, START I survives beyond its expiration date in 2009.

Legal claims that might arise in the aftermath of an attempt to deflect a PHO would be governed by the Outer Space Treaty and by the 1972 Convention on International Liability for Damage Caused by Space Objects. Perhaps governments of countries that are believed to be most at risk of bearing the brunt of an asteroid strike could be persuaded to waive claims of liability against governments attempting to deflect the asteroid. But problems would arise if attempts to deflect an inbound asteroid were only partially successful, greatly reducing the scale of death and damage, but shifting it to areas presumed safe before the deflection. Governments possessing an ability to deflect a PHO might therefore choose to refrain from doing so to avoid the consequences that might accompany less-than-complete success. There are no universal governing bodies capable of producing the equivalent of a 'good Samaritan' law to protect would-be planetary defenders. Therefore, it would seem the Outer Space Treaty and the Liability Convention would have to be amended to absolve from blame governments acting in good faith to deflect threatening PHOs.

* * *

For most people, pandemic influenza and climate change pose more palpable and immediate threats than asteroid or comet impacts. Human deaths from avian influenza are tracked methodically and occur regularly, and there is mounting, visible evidence of damage from climate change. By contrast, it is difficult to quantify the risks posed by comets and asteroids. Recall that 20,000 generations will go unscathed for each generation decimated by a 1.5km asteroid.

It is not a question of if Earth will be walloped again by a sizeable asteroid or comet, but when. Learning whether it will happen in the next 100 years ought to be a top global priority. An international consortium could pool resources and enhance the capacity to locate and track PHOs, while simultaneously creating a forum to foster the sort of transparency and removal of legal barriers desirable for developing and fielding a mitigation system. Major spacefaring states – the United States, Russia, China, Japan, India and member states of the European Space Agency – should be enlisted in the effort. The consortium would have to decide whether to collaborate on all areas of the challenge or create a division of labour among its members. That decision would involve weighing concerns over technology transfer against a desire for transparency.

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Notes

1 In general, a large asteroid impacting the Earth creates a crater about 25 times its own diameter.

2 National Aeronautics and Space Administration (NASA), *Near-Earth Object Survey and Deflection Analysis of Alternatives: Report to Congress*, March 2007, p. 6, Figure 2, http://www.nasa.gov/pdf/171331main_NEO_report_march07.pdf. See also C.R. Chapman and D. Morrison, 'Impacts on the Earth by Asteroids and Comets: Assessing the Hazard', *Nature*, vol. 367, no. 6458, 6 January 1994, pp. 33–40.

3 NASA, *Near-Earth Object Survey*, p. 7. See also C.R. Chapman and D. Morrison, 'Impacts on the Earth by Asteroids and Comets: Assessing the Hazard'.

4 Jet Propulsion Laboratory, 'K-T Event', http://www2.jpl.nasa.gov/sl9/back3.html. See also L.W. Alvarez, W. Alvarez, F. Asaro and H.V. Michel, 'Extraterrestrial Cause for the Cretaceous–Tertiary Extinction', *Science*, vol. 208, no. 4448, 1980, pp. 1095–1108, http://www.sciencemag.org/cgi/content/abstract/208/4448/1095.

5 NASA, *Near-Earth Object Survey*, p. 7.

6 *Ibid.*, p. 1.

7 *Ibid*.

8 *Ibid*., p. 6.

9 *Ibid*., p. 8.

10 *Ibid*., p. 14, Table 8.

11 See http://pan-starrs.ifa.hawaii.edu/public/home.html.

12 See http://www.lsst.org/lsst_home.shtml.

13 NASA, *Near-Earth Object Survey*, p. 9.

14 *Ibid*.

15 *Ibid*., p. 16.

16 David Noland, 'The Threats Out There', *Popular Mechanics*, December 2006, pp. 84–5.

17 NASA, *Near-Earth Object Survey*, p. 10.

18 'QinetiQ Wins Don Quijote Mission Study Contract', SpaceDaily.com, 10 April 2006, http://www.spacedaily.com/reports/QinetiQ_Wins_Don_Quijote_Mission_Study_Contract.html.

19 Will Iredale, 'Asteroid Buster to Save Planet', *Sunday Times*, 16 April 2006, http://www.timesonline.co.uk/tol/news/uk/article706126.ece.

20 NASA, *Near-Earth Object Survey*, pp. 2, 23.

21 Sarah A. Lister, 'Pandemic Influenza: Appropriations for Public Health Preparedness and Response', CRS Report for Congress, Order Code RS22576, 23 January 2007, p. CRS-4.

This figure is conservative in that it represents a supplemental appropriation on top of billions more dollars spent that year on avian flu: Table 2 on p. CRS-6 of the report seems to indicate that up to $13bn may have been appropriated just in FY2006 for 'Avian and Pandemic Flu'. See also Summary and p. CRS-4 of Tiaji Salaam-Blyther, 'US and International Responses to the Global Spread of Avian Flu: Issues for Congress', CRS Report for Congress, Order Code RL33219, 1 May 2006.

[22] World Bank, 'Avian Flu: The Economic Costs', 29 June 2006, http://web.worldbank.org/WBSITE/EXTERNAL/NEWS/0,,contentMDK:20979352~pagePK:64257043~piPK:437376~theSitePK:4607,00.html.

[23] David Biello, 'Clash: Bjorn Lomborg', *Scientific American*, 26 November 2007, http://www.sciam.com/article.cfm?id=clash-bjorn-lomborg.

[24] David Biello, 'Clash: Sir Nicholas Stern', *Scientific American*, 26 November 2007, http://www.sciam.com/article.cfm?id=clash-sir-nicholas-stern.

[25] All figures for global GDP taken from Central Intelligence Agency, *The World Factbook*, https://www.cia.gov/library/publications/the-world-factbook/.

[26] While scientists will certainly want to learn more about asteroids and comets, launching missions to study the characteristics of PHOs is less urgent than finding ones that pose a threat. If PHOs other than Apophis are judged hazardous to Earth's inhabitants, they will likely become the focus of attention, perhaps prompting missions to explore them. But as long as nuclear explosions remain the most effective means of imparting the requisite push to deflect larger PHOs, efforts to study the traits of such objects should not inhibit the more important work of perfecting means to intercept and deflect them. Fortunately for scientists interested in studying asteroids and comets, the testing of mitigation systems could provide opportunities to gather information about them.