6

Planetary Defence

6.1 Introduction

This book was written in two locations in British Columbia, Canada. The first was on Salt Spring Island, against a background of birdsong from the neighbourhood robins, finches, warblers and the occasional pileated woodpecker. The second was on an oceanside bluff in Tsawwassen, south of Vancouver, where the chatter of bald eagles was constantly present. Both woodpeckers and eagles are formidable creatures, and for good reason. Modern birds are in fact dinosaurs, with the avian dinosaurs having survived a cataclysmic collision between the Earth and an asteroid with a diameter of about 10 kilometres some 66 million years ago. All other dinosaurs, the non-avian ones, either perished in the resulting firestorms or starved to death during the ensuing years of 'impact winter'.

Today, the field of 'planetary defence' involves the detection, characterisation, risk assessment and, if necessary, deflection or destruction of asteroids and comets that have the potential to strike Earth. Throughout its history, Earth has frequently been struck by such leftover 'planetesimals'. These remaining planetary building blocks formed from metals, rocks and ice that condensed and coalesced in the solar nebula – the disc of dust and gas that surrounded the nascent Sun. Impacts from asteroids and comets have served as an ongoing geological process, with almost 200 confirmed impact craters on Earth today (see Figure 6.1).

Fortunately, most Earth impactors are meteoroids and interplanetary dust. According to the International Astronomical Union definition, meteoroids range from 30 microns to one metre in diameter. These objects burn up harmlessly at high altitudes in Earth's atmosphere, producing a bright flash of light called a meteor. Interplanetary dust particles are also harmless because of their size – less than 30 microns. Curiously, this small size also enables them to survive atmospheric re-entry, because their large surface-area-to-mass ratio radiates away

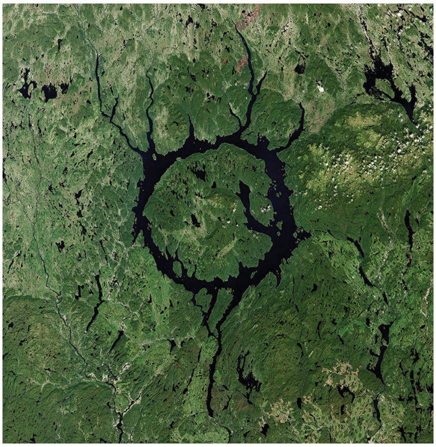

Figure 6.1 Lake Manicouagan was created by a five-kilometre-diameter asteroid approximately 214 million years ago. Located in Quebec, Canada, it is approximately 100 kilometres across, with the reservoir ring being approximately 70 kilometres across. This image was taken by the European Space Agency's Sentinel-2 satellite.

frictional heat. Interplanetary dust particles are found everywhere on Earth, including in our bodies and on the pages of this book. At the other end of the scale, objects larger than one metre in diameter are considered small asteroids, but this is a very imprecise definition. Sometimes, any natural body entering Earth's atmosphere is referred to as a meteoroid.

Each year, dozens of small asteroids with diameters greater than one metre strike Earth, exploding harmlessly in the upper atmosphere with energies of less than a few kilotons of TNT. Figure 6.2 depicts all such 'airbursts' detected by US government sensors over a 34-year period. Additional strikes would have escaped detection, especially if they occurred over the oceans. Only one of the airbursts depicted on the map caused injuries to people.

The larger the impactor, the longer the typical timescale between impact events. However, this is a 'stochastic process': statistically analysable but still random. Although the average time between strikes causing widespread damage is measured in tens of thousands of years, nothing precludes a major strike this century.

In 2013, a meteoroid about 19 metres in diameter exploded at an altitude of about 30 kilometres above the Russian city of Chelyabinsk, which is in the middle of the red dot in Figure 6.2. The resulting airburst

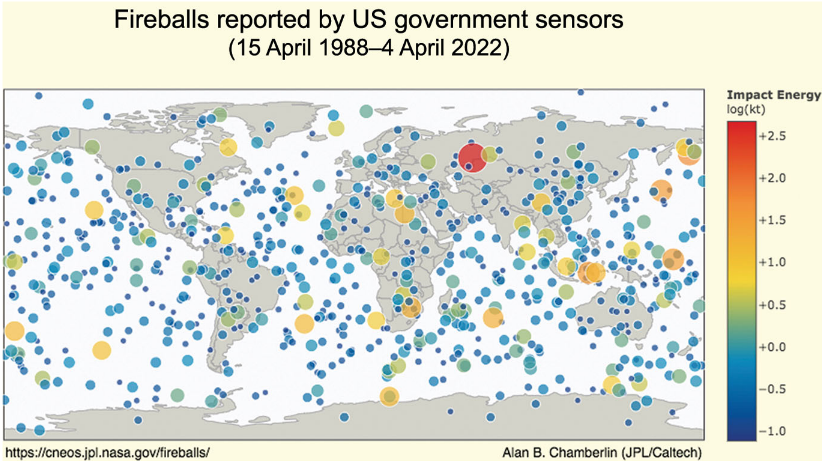

Figure 6.2 Alan B Chamberlin, 'Fireball and bolide data: Fireballs reported by US government sensors (1988-Apr-15 to 2022-Apr-21)', (April 2022), *Center for Near Earth Object Studies*, online: cneos.jpl.nasa.gov/fireballs. A fireball is a very bright meteor, reaching a brightness comparable to that of the planet Venus, while a bolide is a bright fireball that explodes.

had an energy equivalent to about 500 kilotons.[1] It blew out windows, caused minor structural damage to buildings, and sent over 1,000 people to hospital, most of them injured by shattered glass after they rushed to windows to observe the bright flash in the sky.[2] The airburst over Chelyabinsk was the first confirmed Earth impact in recorded history to cause a significant number of injuries. While objects of such size strike our planet on average once every handful of decades, they had – until 2013 – never done so over a populated city.[3] A slightly larger asteroid, just 30 metres or more, could cause serious damage to a large city.

[1] Peter G Brown, Jelle D Assink, Luciana Astiz, Rhiannon Blaauw, Mark B Boslough, Jiří Borovička, N Brachet, D Brown, M Campbell-Brown, L Ceranna and WD Cooke, 'A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors' (2013) 503:7475 *Nature* 238.

[2] Ellen Barry and Andrew E Kramer, 'Shock wave of fireball meteor rattles Siberia, injuring 1,200', *New York Times* (15 February 2013), online: nytimes.com/2013/02/16/world/europe/meteorite-fragments-are-said-to-rain-down-on-siberia.html.

[3] The historical record is persuasive but inconclusive concerning the 'Ch'ing-yang event' of 1490, which occurred over the city of Qingyang in northwest China. According to some

In 1908, the so-called 'Tunguska event' levelled over 2,000 square kilometres of Siberian forest and probably involved an asteroid that was 50 to 70 metres in diameter.[4] More worrying, but less likely, would be an asteroid with a diameter above 140 metres that could devastate an entire region. Events like this can be expected about once every 30,000 years. Strikes from larger asteroids, with diameters above 1,000 metres, only occur about once every 500,000 years.

The perceived threat from asteroids and other 'near-Earth objects' (NEOs) like comets is often overblown. Journalists regularly report about upcoming 'near misses' that in fact pose no impact risk to Earth. They do so, in part, because the vast distances between Space objects can be confusing. In April 2020, the Internet was abuzz with reports of an upcoming near miss by an asteroid with a diameter of between two and four kilometres.[5] There was some excited newspaper reporting also, though most newspapers did at least mention that the asteroid would miss Earth – by 6.3 million kilometres,[6] which is about 16 times the distance between Earth and the Moon, or 1,000 times the distance between New York City and Berlin.

As international lawyer James Green explains, this 'asteroid paranoia' makes it 'easy to dismiss calamitous NEO impact as a concern that should be reserved for science fiction fans and conspiracy theorists'.[7] It probably does not help that astronomers categorise all objects that pass within 1.3 astronomical units of the Sun as NEOs. An 'astronomical unit'

reports, thousands of people were struck dead by a shower of small rocks that may have been fragments from an asteroid or comet.

[4] David Morrison, 'Tunguska workshop: Applying modern tools to understand the 1908 Tunguska impact' (December 2018) NASA Ames Research Center, NASA Technical Memorandum 220174, *NASA*, online: ntrs.nasa.gov/citations/20190002302.

[5] Surabhi Sabat, 'Fact check: Will an asteroid really hit Earth on April 29, 2020?', *Republic World* (31 March 2020), online: www.republicworld.com/fact-check/coronavirus/fact-check-will-asteroid-really-hit-earth-on-april-29.html.

[6] See e.g. Sebastian Kettely, 'Asteroid news: A 4km rock will zip past Earth this month – astronomers can already see it', *Daily Express* (10 April 2020), online: www.express.co.uk/news/science/1267536/Asteroid-news-4km-asteroid-Earth-close-approach-NASA-NEO; Jack Hobbs, 'Huge asteroid 52768 to fly by Earth the morning of April 29', *New York Post* (28 April 2020), online: nypost.com/2020/04/28/huge-asteroid-passing-earth-morning-of-april-29.

[7] James A Green, 'Planetary defense: Near-Earth objects, nuclear weapons, and international law' (2019) 42 *Hastings International and Comparative Law Review* 1 at 6; citing Evan R Seamone, 'When wishing on a star just won't do: The legal basis for international cooperation in the mitigation of asteroid impacts and similar transboundary disasters' (2002) 87 *Iowa Law Review* 1091 at 1108–11.

(au) is the semi-major axis (i.e. one-half of the longest axis) of Earth's elliptical orbit around the Sun.[8] This characteristic distance is 149.6 million kilometres, which is about 389 times the distance between Earth and the Moon (i.e. a 'lunar distance'), or 23,400 times the distance between New York City and Berlin.

But, as the dinosaurs discovered, large asteroids do strike the planet from time to time. With steady population growth and rapid urbanisation, which have resulted today in over 30 'mega-cities' with more than 10 million inhabitants, our vulnerability to large impactors continues to increase.[9] As with other low-probability, high-consequence events such as large earthquakes and global pandemics, preparing for NEO threats is good public policy. NEO threats are more like pandemics than they are like earthquakes, in that an Earth impact is potentially preventable – if the threat is detected early, a deflection capability has been prepared and action is taken quickly.

6.2 Detection

Good public policy begins with detection. Approximately 23,000 NEOs have been identified so far, with the detection of objects one kilometre in diameter or larger likely being nearly complete (i.e. well above 90 per cent) (see Figure 6.3). However, it is estimated that only about 30 per cent of NEOs with diameters between 140 metres and one kilometre have been identified. An even smaller fraction of NEOs of less than 140 metres will have been detected so far.

There are numerous efforts under way to detect and catalogue more NEOs, with the most significant ones being funded by the United States' National Aeronautics and Space Administration (NASA). The Pan-STARRS Project, located on a mountaintop in Hawaii, devotes 90 per cent of its time to NEO detection.[10] NASA also supports the Catalina Sky Survey, which operates from Arizona.[11] Then there is the Asteroid

[8] Perhaps more simply, it is the average of the Earth's closest distance to the Sun (perihelion) and its farthest distance from the Sun (aphelion).

[9] Joseph N Pelton, 'Global space governance and planetary defense mechanisms', in Nikola Schmidt, ed., *Planetary Defense: Global Space Collaboration for Saving Earth from Asteroids and Comets* (Cham: Springer, 2019) 339 at 348.

[10] NASA Science Mission Directorate, 'Pan-STARRS across the sky' (5 April 2019), *NASA*, online: science.nasa.gov/pan-starrs-across-sky.

[11] University of Arizona Lunar and Planetary Laboratory, 'Catalina sky survey' (2022), online: catalina.lpl.arizona.edu.

Terrestrial-Impact Last Alert System (ATLAS), a robotic early-warning system designed to detect smaller NEOs in the weeks or days before they impact Earth. Using two 0.5-metre telescopes located on Hawaiian mountaintops 160 kilometres apart, ATLAS provides repeat coverage of the observable sky on an almost nightly basis.[12]

Outside the United States, the Instituto de Astrofísica de Canarias hosts dozens of international telescopes on two mountaintops in the Canary Islands, several of which contribute to NEO detection as part of the International Asteroid Warning Network – as will be discussed below. Numerous other observatories also contribute globally, while additional capability will soon be provided by the Vera C. Rubin Observatory (previously known as the Large Synoptic Survey Telescope) under construction in Chile. It will be able to detect about 60 per cent of NEOs larger than 140 metres in diameter.[13] The Vera C. Rubin Observatory will also greatly help to address the shortage of NEO surveys providing coverage of the southern hemisphere sky. The same shortage explains why NASA is funding two additional telescopes for ATLAS, which will likewise be located in the southern hemisphere.[14]

Asteroids approaching Earth from the direction of the Sun can be difficult to spot, though this challenge can be addressed with Space-based sensors. In 2009, NASA's Wide-Field Infrared Survey Explorer (WISE) was launched to detect 'minor planets' – another term for asteroids and comets. But just two years later, the spacecraft was placed in hibernation after the frozen hydrogen used to cool the telescope was depleted. Then, in 2013, WISE was reactivated and renamed NEOWISE to reflect a new approach to its mission. Using its two shortest-wavelength detectors, it has since made more than 993,000 infrared measurements of 37,161 different Solar System objects, including 1,145 NEOs and 198 comets.[15] In July 2020, a long-period comet became visible to the naked eye from Earth, delighting sky watchers. The comet was named after NEOWISE,

[12] University of Hawaii Institute for Astronomy, 'Asteroid Terrestrial-Impact Last Alert System (ATLAS): How it works' (2020), *ATLAS*, online: atlas.fallingstar.com/how_atlas_works.php.

[13] NASA Planetary Defense Coordination Office, 'Planetary defense frequently asked questions' (22 April 2019), *NASA*, online: www.nasa.gov/planetarydefense/faq.

[14] Traci Watson, 'Project that spots city-killing asteroid expands to southern hemisphere', *Nature* (14 August 2018), online: www.nature.com/articles/d41586-018-05969-2.

[15] Infrared Processing and Analysis Center, 'The NEOWISE project: Finding, tracking and characterizing asteroids' (23 March 2022), *California Institute of Technology*, online: neowise.ipac.caltech.edu.

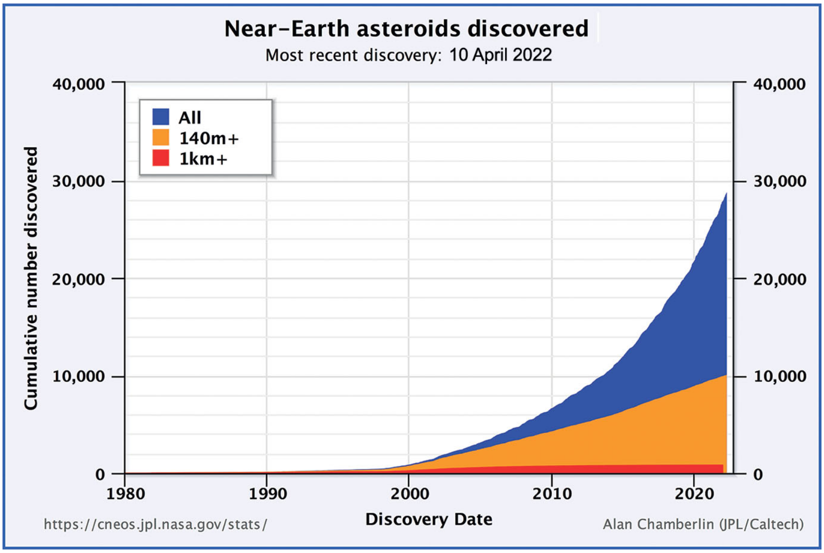

Figure 6.3 Near-Earth asteroid discovery plot, cumulative over time. The upward slope is due to the completeness of catalogued objects still being low for smaller bodies.

which had detected it just four months earlier. Around 2025, NEOWISE will be replaced with the Near-Earth Object Surveillance Mission (NEOSM), a 0.5-metre Space-based telescope that will operate in the infrared spectrum and be able to detect 'dark asteroids' – asteroids with low albedo (reflectivity) that are almost impossible to detect with optical telescopes but may be quite common.[16]

Another challenge concerns NEOs approaching from the opposite direction to the Sun, because they often do not show large sky motion relative to the stars. Such NEOs are often detected late, providing little time for a response. On 24 July 2019, the asteroid 2019 OK was detected when it was just 1.5 million kilometres away from Earth. One day later, it passed within 65,000 kilometres, which is just 0.17 of the distance between Earth and the Moon.[17] Travelling at around 24 kilometres per

[16] Paul Voosen, 'NASA to build telescope for detecting asteroids that threaten Earth', *Science* (23 September 2019), online: www.sciencemag.org/news/2019/09/nasa-build-telescope-detecting-asteroids-threaten-earth.

[17] NASA Center for Near Earth Object Studies, 'Largest asteroid to pass this close to Earth in a century' (6 August 2019), *NASA*, online: cneos.jpl.nasa.gov/news/news203.html.

second, and with a diameter of between 57 and 130 metres, an asteroid this size could kill millions of people if it struck a large city.

Satellites also pose challenges to NEO detection, particularly mega-constellations such as Starlink – as discussed in Chapters 2 and 3. Sunlight reflecting off satellites creates light pollution for optical telescopes, while the heat signature of the satellites could create a similar problem for infrared telescopes. In both instances, the possible misidentification of satellites is not the primary concern. Rather, satellite streaks across images can render some of the data unusable, with multiple streaks having greater effects. Particularly bright satellites can cause 'artefacts' (disruptions of the astronomical data) across the entire detector. All these effects will frustrate NEO detection searches.

Refining the orbital uncertainties of known NEOs is also a primary concern, particularly if the object in question has a small 'minimum orbital intersection distance' (MOID) with Earth. To visualise a MOID, imagine two elliptical orbits as curves in Space, one representing Earth's orbit and the other an NEO's orbit. The smallest distance between the curves is the MOID (Figure 6.4). This does not represent, in general, the closest that Earth and the NEO will ever get, as their orbital phases matter (i.e. they will not necessarily arrive at the MOID at the same time). But it does highlight the potential for a close encounter. An NEO is classified as 'potentially hazardous' if it has a size larger than 140 metres and a MOID of less than 0.05 au (7.5 million kilometres, or about 20 times the distance between Earth and the Moon).[18] Many large asteroids pass harmlessly by Earth at distances much closer than this threshold. Such close encounters can, however, alter the MOID and thus the risk of a future impact.

Determining the MOID for Earth and a given NEO is one factor in calculating collision risks. But even if the MOID is essentially zero, i.e. the orbits do directly cross, this does not mean that there will be a collision in the foreseeable future. As noted above, a collision may only occur if Earth and the asteroid arrive at a sufficiently small MOID at the same time. Thus the detailed positions and movements of Earth and the asteroid are critical to evaluating the actual collision risk, which must be measured.

[18] NASA Center for Near Earth Object Studies, 'NEO basics' (2022), *NASA*, online: cneos.jpl.nasa.gov/about/neo_groups.html.

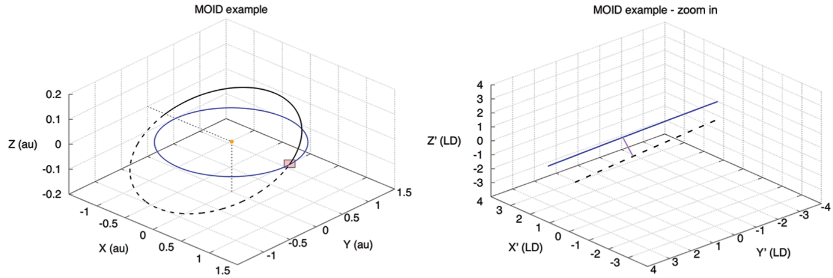

Figure 6.4 Visualisation of the minimum orbital intersection distance (MOID) between a Bennu-like asteroid orbit and Earth. The left panel shows the full view of the orbits, with Earth (blue curve) lying in the X–Y plane and the Sun at the centre, indicated by the orange dot. The co-ordinates are in astronomical units (au). The asteroid is shown with the black curve. The solid portion depicts the orbit section that is above Earth's orbital plane, and the dashed section shows the section below. The projection alone gives the impression that the orbits intersect twice, even though they do not. The pink box highlights where the MOID occurs. The right panel shows a zoomed-in region of the MOID. The units are now in lunar distances (LD) and are arbitrarily centred. The primes are used to denote that the co-ordinate centre is different from the left panel. The short purple line segment is the MOID itself, i.e. the closest the two orbits ever come to each other. In this example, the MOID is about 0.003 au (just slightly larger than one LD). They appear closer at negative Y' due to projection effects, with the black dashed curve crossing under the blue curve.

However, observations and measurements of an asteroid always come with uncertainties,[19] which means that there will always be uncertainty in our knowledge of the actual orbit of the asteroid. As a consequence, the impact risk is given as a probability, which might be low enough to suggest that an impact is essentially ruled out, or high enough to cause concern. An impact can only be predicted with certainty if the orbit of the potential impactor is very well known, which often is only the case just weeks or months before the actual impact. Dedicated observation campaigns could add years to this warning time. In addition, the evolution of orbits also needs to be considered. Although most asteroids identified as potential threats are eventually proven to be harmless once their trajectories have been precisely determined, constant vigilance is required. Gravitational effects from the planets can cause changes in

[19] Uncertainties in a measurement can result from a variety of factors, including physical constraints and limitations of the calibrations and detector performance.

asteroid trajectories over time, with Earth and Mars playing a major role for NEOs. Even the gravitational effects of some of the major asteroids could make the subtle difference between a collision and a close call.[20] Orbital changes can even be caused by micrometeoroid collisions,[21] asteroid surface activity, and the minute amounts of force transmitted by photons.[22] The last of these is possible because light carries momentum, with shorter wavelengths carrying more momentum than longer ones. For example, a rotating asteroid has a morning side that is cooler, and an afternoon side that is hotter due to the 'day'-long effects of solar heating. The hotter side will give off more short-wavelength radiation, and thus more momentum, than the cooler side. In this way, light behaves like a rocket impulse, and this so-called 'Yarkovsky effect' can move an asteroid away from or towards the Sun, i.e. grow or shrink the asteroid's orbital semi-major axis, depending on the direction of its rotation. Because of these perturbing forces, an accurate prediction of the impact risk of an object is usually only attempted for 100 years into the future.

For all these reasons, radar is used whenever asteroids pass close to Earth to provide more accurate assessments of their orbit, size and composition.[23] This information helps to determine whether subsequent flybys pose risks and, if so, what deflection method might work best. Information from radar proved to be critical in the determination that the 340-metre-diameter asteroid Apophis will not pose an impact risk for at least the next century.[24] In the future, potentially dangerous asteroids could be tagged with radio beacons, or have small spacecraft orbiting them or conducting frequent flybys. This would enable more precise studies of the asteroids' orbits and the various factors that influence them.

[20] Steven R Chesley, Davide Farnocchia, Michael C Nolan, David Vokrouhlický, Paul W Chodas, Andrea Milani, Federica Spoto, B Rozitis, LA Benner, WF Bottke and MW Busch, 'Orbit and bulk density of the OSIRIS-REx target Asteroid (101955) Bennu' (2014) 235 *Icarus* 5.

[21] Paul A Wiegert, 'Meteoroid impacts onto asteroids: A competitor for Yarkovsky and YORP' (2015) 252 *Icarus* 22.

[22] William F Bottke Jr, David Vokrouhlický, David P Rubincam and David Nesvorný, 'The Yarkovsky and YORP effects: Implications for asteroid dynamics' (2006) 34 *Annual Review of Earth and Planetary Sciences* 157.

[23] NASA Center for Near Earth Object Studies, 'NASA scientists use radar to detect asteroid force' (5 December 2003), *NASA*, online: cneos.jpl.nasa.gov/news/news141.html.

[24] NASA Center for Near Earth Object Studies, 'Earth is safe from asteroid Apophis for 100-plus years' (25 March 2021), *NASA*, online: www.jpl.nasa.gov/news/nasa-analysis-earth-is-safe-from-asteroid-apophis-for-100-plus-years.

In the next decade, we can expect over 50 asteroids with diameters greater than 100 metres to pass within ten lunar distances of Earth, a handful of which are in the 1,000-metre range.[25] Fortunately, the positions and orbits of these asteroids are fairly well established – and none of them poses any risk to us in this century. At some future time, however, we will likely discover a large asteroid on an Earth impact trajectory, at which point the mission will change from detection to deflection.

6.3 Deflection

If an impending Earth impact is discovered early enough, a deflection might be possible. Deflecting an asteroid involves slightly altering its orbit by perturbing its velocity, with astrodynamicists referring to a change in velocity as Δv, pronounced 'delta-v'. The most effective way to perturb an asteroid (or indeed any orbiting object) is to apply the Δv along or against its orbital track, as opposed to perpendicular to it. For small perturbations, this can be thought of as a matter of timing, so that the asteroid's close approach is advanced or delayed, thus allowing Earth to be out of the way. To understand why this is the case, we need to briefly consider one of the fundamental concepts of planetary dynamics: Kepler's third law. By painstakingly going through Tycho Brahe's records of meticulous naked-eye planet observations, Johannes Kepler discovered that planets orbit in ellipses about the Sun and that the period, P, of the orbit is proportional to the semi-major axis, a, of the planet's orbital ellipse raised to the 3/2 power:

$$P \propto a^{\frac{3}{2}}.$$

Because the absolute distances between planets were not known at the time, Kepler scaled everything relative to Earth's orbit. An object that has a semi-major axis of four aus orbits the Sun in eight years, regardless of how eccentric the orbit might be. Kepler did not know why planets behaved in this way – it took Newton's law of gravitation and laws of physics to explain why – but his discoveries were a major feat of astronomy and data science.

[25] NASA Center for Near Earth Object Studies, 'NEO Earth close approaches' (2022), *NASA*, online: cneos.jpl.nasa.gov/ca.

It turns out that nudging an asteroid with a Δv will also change the semi-major axis of that asteroid by a small amount. If the semi-major axis is increased, then the period is also increased. If it is decreased, the period is decreased. It is important to emphasise that the overall orbit remains essentially the same. For the purposes of planetary defence, the goal of deflection is to change the rate at which the asteroid goes around the Sun, so that after years, the small timing difference between the old and new periods amounts to spatial differences on a planetary scale, and a miss.

It is instructive to have a sense of the magnitude of Δv needed for any given deflection. To do this, we need to introduce another concept called the B-plane, or body plane. Consider an asteroid's close approach as seen from Earth. If, for the moment, we ignore Earth's gravity, we can imagine that, during the flyby, the asteroid's trajectory is approximately a line passing by Earth. We can next imagine a plane that passes through the centre of the Earth and is oriented such that the line (asteroid trajectory) intersects the plane at 90° (in other words, the trajectory is normal to the plane).

The degree to which a potential impactor threatens Earth can be assessed by the object's passage through the B-plane, as well as whether the uncertainty of the orbit (down to some threshold) overlaps Earth. For example, the nominal (best-fit) orbit might clearly miss Earth, but for a very uncertain orbit there might be a 1 per cent chance that the asteroid hits Earth – based on the current knowledge of the dynamics. As we refine our knowledge of the orbit through additional observations, we hope to see the probability of an impact event drop to a level where it can be ruled out. However, it might also be the case that, as the orbit is refined, the possibility of an impact collapses to 100 per cent and motivates action.

If we want to move the location of the asteroid's closest approach on the B-plane by one Earth radius, the necessary Δv perturbation along or against track can be estimated by considering the change in orbital rates due to the perturbation, yielding[26]

$$\Delta v = \frac{3.5\ \frac{\text{cm}}{s}}{T_{yr}}$$

where T_{yr} is the 'lead time' in years, i.e. the time between the closest approach and when the Δv is applied. For comparison, the orbital speed for something going around the Sun at one au (again, an astronomical

[26] Steven R Chesley and Timothy B Spahr, 'Earth impactors: Orbital characteristics and warning time', in Michael JS Belton et al., eds., *Mitigation of Hazardous Comets and Asteroids* (Cambridge: Cambridge University Press, 2004) 22.

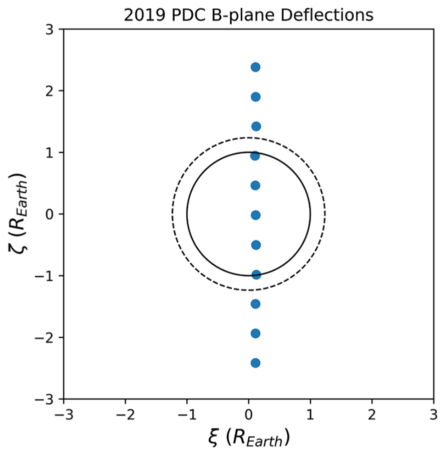

Figure 6.5 B-plane showing simulation results of different deflection scenarios for the hypothetical impactor 2019 PDC. The B-plane co-ordinates are in units of Earth radii. The solid circle represents the cross section of Earth, and the dashed line is Earth's effective cross section when including gravitational focusing. Each point represents where the hypothetical 2019 PDC passed through the B-plane – if the point is within the dashed circle, then the impactor would have hit Earth. The central point represents no deflection attempt. Starting from the uppermost point moving downward, the deflections used are $\Delta v = -10, -8, -6, -4, -2, 0, 2, 4, 6, 8, 10$ millimetres per second. Each Δv was applied 7.7 years before the potential impact, with the results roughly consistent with the approximate relation in the text. Figure produced in collaboration with Edmond Ng.

unit is the semi-major axis of Earth's orbit) is about 30 kilometres per second. The longer the lead time, the greater the effect the small perturbation will have. And the shorter the lead time, the greater the perturbation needed to avoid an Earth impact.[27]

The Center for NEO Studies at NASA's Jet Propulsion Laboratory periodically releases impact scenarios for tabletop exercises.[28] The hypothetical impactor in the 2019 scenario discussed at the 2019 Planetary Defense Conference was called asteroid 2019 PDC. Figure 6.5 shows the results of

[27] The Center for NEO Studies has released a 'deflection app' to demonstrate some of these features. See Center for Near Earth Object Studies, 'NASA/JPL NEO deflection app' (2017), *NASA*, online: cneos.jpl.nasa.gov/nda.

[28] NASA Center for Near Earth Object Studies, 'Hypothetical impact scenarios' (2022), *NASA*, online: cneos.jpl.nasa.gov/pd/cs.

executing different Δv's (each case only uses one Δv) along or against the orbital track 7.7 years before the hypothetical impact by 2019 PDC.

Presently, the two most feasible methods for perturbing an asteroid's velocity are kinetic impactors and nuclear explosive devices (NEDs). However, other methods exist and might be possible, such as ion beams, lasers, mass drivers (essentially, asteroid-mining machines) and 'gravity tractors'.[29]

6.3.1 Kinetic Impactors

A kinetic impactor works by transferring momentum from the spacecraft's motion to the target asteroid through a collision, which also causes secondary momentum 'kicks' through debris ejection during crater formation. Momentum is a conserved property in physics that depends on an object's mass and velocity. Like velocity, momentum is a vector quantity, meaning it has a magnitude ('how much') and a direction.[30] The overall effect of the kinetic impactor will depend on the total amount of momentum change imparted onto the asteroid and the direction in which the momentum change is applied relative to the asteroid's current motion.

To develop this idea further, first consider the effect of the spacecraft's collision alone. For simplicity, we only consider the case of a spacecraft hitting the asteroid directly along or against the asteroid's instantaneous direction of motion (i.e. its track).

Modelling the collision such that the spacecraft's momentum is perfectly absorbed by the asteroid, we can write the change in the asteroid's velocity immediately after the impact as

$$\Delta v = v_r \frac{m_{sc}}{m_{astr}}$$

[29] Edward T Lu and Stanley G Love, 'Gravitational tractor for towing asteroids' (2005) 438:7065 *Nature* 177.

[30] If you are not used to thinking about vectors, then consider velocity as a conceptual reference. Your velocity is your speed and direction of motion. Changing either your speed or your direction of motion requires an acceleration applied through a force. Note that you can move at a constant speed, but have your velocity continuously change, such as being in a turn. Extending this to momentum for most situations is straightforward. But because momentum is mass times velocity, a momentum change can be due to a change in mass or a change in velocity or both. Forces cause changes in momentum, and forces can be applied instantaneously, drawn out, or somewhere in between.

for asteroid mass m_{astr}, spacecraft mass m_{sc}, and spacecraft velocity relative to the asteroid v_r. The direction of the change is governed by the direction of v_r, with the against motion being represented by a negative value for the spacecraft's relative velocity.

The spacecraft's mass will be much smaller than the asteroid's mass, making very high-velocity impacts necessary for even modest deflections. Fortunately, as we saw above, even small changes can have a large effect when given enough time. Moreover, the momentum imparted onto the asteroid is larger than that given by the spacecraft alone. This is because the high speeds of the collision will result in a cratering event, causing the ejection of asteroid material during crater formation. The mass loss due to cratering provides a rocket-reaction-like 'kick' on the asteroid itself. Assuming the ejecta is released predominantly in the direction opposite to that taken by the incoming spacecraft, the crater ejecta enhances the overall Δv. However, it is also possible that waves will propagate through the asteroid and cause mass to be lost on the side opposite the impact, which would work against the desired momentum change and reduce the overall Δv.

Cratering effects in the kinetic impact method are taken into account using a parameterised approach, modifying the equation above by including an additional factor:

$$\Delta v = \beta v_r \frac{m_{sc}}{m_{astr}},$$

where β (pronounced 'beta') is greater than unity if cratering enhances the kinetic impact method and less than unity if it works against it. Simulations show that $\beta > 1$ are very feasible,[31] but this depends on the type of asteroid and exactly how the shock waves propagate through the asteroid. To truly know, we need to perform tests.

NASA recently sent a spacecraft to an asteroid to do just that. The Double Asteroid Redirection Test (DART) mission targetted Didymos, a binary asteroid system consisting of a large asteroid accompanied by a 'moonlet': a smaller asteroid that orbits the larger one.[32] This moonlet,

[31] AM Stickle, ESG Rainey, M Bruck Syal, JM Owen, P Miller, OS Barnouin and CM Ernst, 'Modeling impact outcomes for the Double Asteroids Redirection Test (DART) mission' (2017) 204 *Procedia Engineering* 116.

[32] Andrew F Cheng, Andrew S Rivkin, Patrick Michel, Justin Atchison, Olivier Barnouin, Lance Benner, Nancy L Chabot, C Ernst, EG Fahnestock, M Kueppers and P Pravec, 'AIDA DART asteroid deflection test: Planetary defense and science objectives' (2018) 157 *Planetary and Space Science* 104.

now officially designated Dimorphos (but sometimes called 'Didymoon') is about 170 metres in diameter, a size scale that would pose a considerable threat if a comparable object were to hit Earth. (There is, it is important to note, no current threat to Earth from either Didymos or Dimorphos).

We can assume that Dimorphos has a mass of about 5 billion kilograms.[33] The DART spacecraft mass was 500 kilograms and was planned to collide with Dimorphos at about 6.6 kilometres per second. To get a feel for the numbers, if we assume that $\beta = 2$, then the expected Δv would be approximately one millimetre per second. Why use a double asteroid for the test? Didymos has a very well-characterised light curve (variation of brightness over time) with easily discernible variation due to the passage of Dimorphos across and behind Didymos, as seen from Earth. A change in the period of Dimorphos due to DART was, indeed, quite noticeable using observations from the ground. In contrast, measuring the velocity change for a single asteroid orbiting the Sun would have been extremely difficult, at least without precise ranging equipment or years of meticulous observations.[34]

The kinetic impactor method for asteroid redirection has some clear advantages: the technology is relatively simple and the legal issues surrounding its implementation are (as we will see) largely uncontroversial. The downside is that the way the kinetic impactor strikes the asteroid matters significantly. As discussed in the previous section, the impact is most likely to be designed to be along or against the track of the asteroid. However, due to constraints set by the details of orbital dynamics, one of the directions will be much easier to accommodate than the other. This means that the kinetic impactor method has a preferred direction for deflection, a direction that might not be the same as what is needed on the B-plane. Consider Figure 6.5 again. Suppose we know that an asteroid will strike Earth at the first dot below the centre position. The best deflection strategy would accordingly be to perturb the asteroid such

[33] Andrew F Cheng, J Atchison, Brian Kantsiper, Andrew S Rivkin, A Stickle, Cheryl Reed Andres Galvez, Ian Carnelli, Patrick Michel, and S Ulamec, 'Asteroid Impact and Deflection Assessment mission: Kinetic impactor' (2016) 121 *Planetary and Space Science* 27.

[34] Andrew F Cheng et al., 'The Double Asteroid Redirection Test (DART): Planetary Defense Investigations and Requirements', (2021) 2 *Planetary Science Journal*, id. 173, online: https://ui.adsabs.harvard.edu/abs/2021PSJ.....2..173R/abstract. Confirmation of the success was announced during the proof stages of this book. NASA, 'NASA Confirms DART Mission Impact Changed Asteroid's Motion in Space', NASA, online: https://www.nasa.gov/press-release/nasa-confirms-dart-mission-impact-changed-asteroid-s-motion-in-space

that it moves downward on the B-plane, only needing to go a bit more than half of an Earth radius. But say such a deflection is not practical due to the details of the orbits, and instead the asteroid needs to be moved up on the diagram. This would mean that a larger perturbation is required (over 1.5 Earth radii), which in turn requires a more massive spacecraft, a higher impact speed, multiple impactors or a combination of two or more of these. In fact, multiple impactors might be the safest approach in this situation, since using a large Δv all at once risks fragmenting the asteroid, which would in turn increase the collisional cross section of the material and could, potentially, cause multiple destructive airbursts when the fragments reach Earth.[35] Then there is uncertainty in the effective β, which can have a significant effect on the strength and number of impacts required. When looking at a larger motion on the B-plane, all these uncertainties could amount to an unsuccessful deflection. For these reasons – more flexibility and control over the perturbations – we should now consider the use of a nuclear explosive device.

6.3.2 Nuclear Explosive Devices

Nuclear explosive devices (NEDs) deflect an asteroid by vaporising a region of its 'regolith' – a layer of unconsolidated rock and dust found on the surface of most asteroids (as well as other celestial bodies such as the Moon). The newly formed vapour, bounded by the asteroid on one side and Space on the other, expands rapidly away from the asteroid's surface. The result is that the vapour acts just like the exhaust from a rocket, imparting a Δv onto the asteroid, with the direction set by the location of the NED (and hence the location of regolith that becomes vaporised).

An NED spacecraft only needs to rendezvous with the asteroid, removing the directional bias inherent in the kinetic impactor method; the NED can be detonated along or against track. In addition, the spacecraft carrying the NED can first study the asteroid to best determine how far away the NED should be detonated, which will control the amount of regolith that is vaporised and thus the resulting Δv. In 2007, a NASA report prepared for the US Congress concluded, 'Nuclear

[35] Brent W Barbee, Megan Bruck Syal, David Dearborn, Galen Gisler, Kevin Greenaugh, Kirsten M Howley, Ron Leung, J Lyzhoft, PL Miller, JA Nuth and C Plesko, 'Options and uncertainties in planetary defense: Mission planning and vehicle design for flexible response' (2008) 143 *Acta Astronautica* 37 at 38.

standoff explosions are assessed to be 10–100 times more effective than the non-nuclear alternatives analyzed in this study.'[36]

Despite the clear advantages, NEDs have their own challenges. Just as in the kinetic impactor method, too large a single Δv could fragment the asteroid; to reduce this risk, multiple, sequential NEDs may be necessary. Moreover, the perturbation will depend on the actual yield of regolith vaporisation, which may not behave as expected. A nuclear explosion close to Earth, such as an attempt to break up a small but still destructive asteroid, could also have unintended consequences, for instance delivering radioactive debris to Earth's atmosphere and possibly even to the surface.[37] Perhaps most pressing from an implementation standpoint, NEDs have legal and security implications, as will be discussed below.

Still, there are several reasons why NEDs are widely considered to be an attractive option for asteroid deflection: the necessary technology already exists in the form of nuclear warheads and large Space rockets, they can deliver far more energy than other conceivable methods, and they offer more flexibility in timing. The latter is significant, as perturbations have a maximum effectiveness if applied during certain parts of an asteroid's orbit; specifically, you get more orbital change for your Δv if the 'kick' is applied at perihelion (the closest approach of the asteroid to the Sun), where the asteroid is moving the fastest in its orbit. This well-known 'Oberth effect' can thus cause larger changes to the asteroid location on the B-plane than an otherwise equivalent mission that perturbs the asteroid away from perihelion.

6.3.3 *The Long Game: Mass Drivers and Gravity Tractors*

The previous two sections explored 'impulsive' asteroid redirection methods, in which the desired Δv is achieved more or less instantaneously. With enough lead time, however, a gentler approach could be taken, with a continuous application of small nudges accumulating over time into the desired movement of the asteroid on the B-plane. Although

36 US National Aeronautics and Space Administration (NASA), 'Near-Earth object survey and deflection analysis of alternatives: Report to Congress' (Washington DC, NASA, March 2007) at 2, online: cneos.jpl.nasa.gov/doc/neo_report2007.html.

37 Bohumil Doboš, Jakub Pražák and Marie Němečková, 'Atomic salvation: A case for nuclear planetary defense' (2020) 18:1 *Astropolitics* 73 at 84.

there are several such methods, we focus on two very different approaches to highlight the range of possibilities.

A mass driver is potentially the crudest approach. It involves landing one or more spacecraft on an asteroid and throwing mass in the opposite direction of the desired deflection.[38] With every throw, the 'recoil' due to Newton's third law (equivalent momentum conservation) imparts a small δv ('little delta v') to the asteroid. This by itself is insufficient to redirect the asteroid, but after time all the little δv's deliver a cumulative Δv that is large enough to produce the desired effect.

The asteroid itself is the source of the mass. In the most basic form, you might imagine a mining-like apparatus that is continuously scooping up material and jettisoning it into Space. In a more sophisticated form, the material might be sorted, processed and used in a high-velocity ion engine.

Essentially, a mass driver turns the asteroid into a rocket. Under the assumption of rocket motion only, the change in speed of a rocket after throwing out some mass ΔM is

$$\Delta v = -v_e \; ln\left(\frac{M_0 - \Delta M}{M_0}\right),$$

where M_0 is the initial mass and v_e is the exhaust speed of the propellant. And here we run into the harsh reality of rocketry: the velocity change is proportional to the logarithm of the mass change. This means we need to either throw out a lot of mass, or have high exhaust speeds, or both. Flipping the equation around, we see that

$$\Delta M = M_0(1 - \; exp\,(-\Delta v/v_e)).$$

If we want to achieve a Δv of approximately one millimetre per second (comparable to the kinetic impactor scenario discussed above), then for $v_e =$ 10 metres per second, two kilometres per second, and 40 kilometres per second, we need to respectively use $\frac{\Delta M}{M_0} = 10^{-4}$, 5×10^{-7}, and 2.5×10^{-8} of the asteroid's mass as fuel (note this is *useful* mass – the amount that

[38] George Friedman, John Lewis, Leslie Snively, Lee Valentine, Richard Gertsch and Dennis Wingo, 'Mass drivers for planetary defense' (paper delivered at the Planetary Defense Conference: Protecting Earth from Asteroids, Orange County, California, 23–26 February 2004); GK O'Neill and HH Kolm, 'High-acceleration mass drivers' (1980) 7 *Acta Astronautica* 1229.

needs to be processed may be much higher). The different speeds are chosen to highlight those that (1) might be comparable to what will be used to expel waste during mining, (2) reflect conventional rocketry nozzle speeds and (3) are comparable to ion drive exhaust speeds. Although these mass fractions are small, they might be challenging to mine. For an asteroid such as Dimorphos, even the ion drive scenario requires consuming 125 kilograms of useful mass from the asteroid. The conventional rocket scenario requires 2.5 tonnes (again this is useful mass), and the low-speed mining ejection scenario requires 500 tonnes. The last approach literally involves throwing rocks, so while large amounts are needed, no processing is required.

The difficulty of the mass driver method rises quickly both with the size of the asteroid and with the size of the desired Δv. It should also be kept in mind that Dimorphos is fairly small. All other things being equal, an asteroid twice as large would require eight times as much mass as fuel to achieve comparable Δv's. Achieving a higher Δv would also require considerably more mass: ten times more mass as fuel in the case of a Dimorphos-like asteroid that we wanted to give a Δv of about one centimetre per second.

The benefit of a mass driver is that the spacecraft turns the asteroid into a fuel source. Since each δv is quite small, there is also no risk of fragmenting the asteroid from the impulses themselves. Moreover, should Space resource utilisation of asteroids become commonplace, mining spacecraft could be repurposed for planetary defence, in a fortuitous application of dual-use technology. There are, nonetheless, numerous and potentially quite serious challenges. Physically touching the asteroid is required, which could disturb the surface layers and potentially cause instabilities, including an unwanted outburst of material. Moreover, throwing any material off the asteroid will naturally cause a debris stream, which in turn could have long-term unintended consequences – as we explain in Chapter 5 on Space mining. The asteroid will also be spinning and may need to be de-spun before mass drivers can be landed or operated effectively.

Gravity tractors, by contrast, employ Newton's third law and momentum conservation in a manner that avoids having to physically touch the asteroid. In this approach, gravity is a finicky tether that connects the asteroid and a nearby spacecraft. Just as the mutual gravity between the spacecraft and the asteroid accelerates the spacecraft towards the asteroid, it also accelerates the much more massive asteroid towards the spacecraft. The gravity tractor's job is to fly in formation with the asteroid, using thrusters to maintain a steady distance and direction. Gravity then provides a continuous supply of δv's to the asteroid.

The benefits of a gravity tractor are clear. There is no need to physically touch the asteroid and therefore no risk of generating debris or inducing surface activity. Details such as the asteroid's spin rate or surface composition do not matter. But there are also at least two major challenges: a large spacecraft is needed, and it needs to carry enough fuel for a lengthy period of formation flying with the asteroid.

Since there is essentially no difference between the mass driver and the gravity tractor in terms of satisfying the rocketry equations, well over 100 kilograms of fuel would be needed for an effective Δv of approximately one millimetre per second using an ion thruster (or something similar) on an asteroid like Dimorphos. Note that this is for the gravity 'tug' only. For further context, if there were a need to give a bigger asteroid like Apophis a larger Δv of approximately one centimetre per second, then about ten or more tonnes of fuel would be required. In all likelihood, however, even more fuel would be needed – because the rockets cannot be fired in the optimal direction, since this would place the asteroid in the path of the exhaust. Moreover, we have again used the term 'effective' Δv to signify that the impulse is not instantaneously applied, which can lead to some important differences in the detailed orbital evolution.

There is one further point to mention. With an impulsive technique such as a kinetic impactor or an NED, the full Δv can be applied at an optimal orbital configuration, providing the maximal movement on the B-plane for the given momentum change. In contrast, low-impulse, long-duration techniques apply δv's throughout the orbit. For this reason, the total Δv for a mass driver or a gravity tractor could be larger than that needed for an impulsive technique, all other things being equal. Still, the low-impulse methods have many advantages – if there is sufficient lead time to implement them! A practical scientific demonstration of such a method, similar to the demonstration of a kinetic impactor being provided by DART, would be a major contribution to planetary defence.

6.4 Comets

Asteroids tend to be the focus of planetary defence discussions because of the high number that pass close to Earth. Yet comets also pose a risk, and should not be dismissed. Comets, which are composed of ice, rock and dust, are the leftover planetesimals that formed in the colder regions of the solar nebula during planet building.[39] There are two primary comet reservoirs in the solar system. One is the Edgeworth–Kuiper Belt (often simply referred to as the Kuiper Belt) that comprises icy bodies located just beyond Neptune's orbit.[40] These comets orbit in roughly the same plane and direction as the planets. The other reservoir, which is presumed to exist based on an analysis of certain types of cometary orbits, as well as planet formation calculations, is the Oort Cloud.[41] This can be thought of as a spherical shell of cometary material that formed when bodies were almost ejected from the solar system during planet building. They then had their closest approach to the Sun (perihelion) increased through gravitational perturbations by the Milky Way galaxy, decoupling the Oort Cloud from the rest of the solar system's dynamics. The main Oort Cloud is thought to have an inner edge around 20,000 au from the Sun, making it the most distant material that is still part of the solar system. According to Kepler's laws, an orbit about the Sun with a semi-major axis of 20,000 au will have a period of about 3 million years. In other words, it will take that long, or longer, for a comet in the Oort Cloud to make a single orbit around the Sun.

But just as the varying gravitational perturbations from stars and galactic clouds of gas and dust helped to form the Oort Cloud, similar types of perturbation can decrease the perihelia of Oort comet orbits, making them very elliptical, and bringing these distant bodies well into the inner solar system.[42] This is possible because the Sun's gravitational influence is weak at such large distances, and small perturbations can have significant orbital consequences. The result is 'long-period' comets, that is to say comets with periods of more than (and in many cases much more than) 200 years. If these bodies also have a strong interaction with a giant planet, such as Jupiter, a Halley-type comet could be produced: one that, despite having a highly inclined orbit, has a period of less than 200 years. In all these cases, the orbits can have a wide range of orientations. They can even be 'retrograde', meaning that the comet orbits in the opposite direction of the planets.

39 Michael F A'Hearn, 'Comets as building blocks' (2011) 49 *Annual Review of Astronomy and Astrophysics* 281.

40 Brett Gladman and Kathryn Volk, 'Transneptunian Space' (2021) 59 *Annual Review of Astronomy and Astrophysics* 203.

41 Ibid.

42 Luke Dones, Paul R Weissman, Harold F Levison and Martin J Duncan, 'Oort Cloud formation and dynamics', in Doug Johnstone, FC Adams, DNC Lin, DA Neufeeld and EC Ostriker, eds., *Star Formation in the Interstellar Medium: In Honor of David Hollenbach, Chris McKee and Frank Shu* (San Francisco: Astronomical Society of the Pacific, 2004) 371.

In contrast, many of the short-period comets (less than 200 years) are thought to originate from the Kuiper Belt. Over time, orbital evolutions of some of the icy bodies in the Kuiper Belt can lead to strong, multiple interactions with one or more of the giant planets. When this happens, an icy body can eventually be placed on an orbit that extends into the inner solar system. This mechanism is thought to produce comets with orbits that are roughly in the same orbital plane as the planets.

Regardless of their origin, when cometary bodies get close enough to the Sun, they 'turn on' due to the sublimation of frozen gas. The resulting 'outgassing',[43] which includes 'jetting' of material, releases gas and dust and produces a visible atmosphere ('coma') that surrounds the icy body (the core or 'nucleus'). It also produces a gas ion tail, which points away from the Sun along the solar wind, as well as a dust tail, which tends from the Sun but is curved due to orbital dynamics. While we think of comets as being bright objects, this is only true when they are active, and even then the cometary nucleus tends to be very dark and difficult to detect. This is especially true for comets that are making their first close approach to the Sun.

This discussion leads to a sobering point: we know little, if anything, about the existence and trajectories of most comets, even ones that will, one day, pass close to Earth.[44]

Efforts to detect and better understand comets are under way. In 2004, the European Space Agency (ESA) launched a robotic spacecraft (*Rosetta*) and a smaller lander (*Philae*) to study the comet 67P/Churyumov–Gerasimenko (see Figure 6.6), with *Philae* reaching the surface in November 2014. Importantly, *Rosetta* monitored the comet as it began outgassing and jetting as it approached the Sun.[45] In 2005, NASA sent the robotic spacecraft *Deep Impact* to the comet Tempel 1, where it deployed a small impactor to excavate material. The resulting crater revealed that the comet's interior was dustier and less icy than expected,[46] a fact which ultimately has planetary defence implications, at least for comets similar to Tempel 1.

[43] Jake Parks, 'Organic molecules make up half of Comet 67P', *Astronomy* (1 December 2017), online: astronomy.com/news/2017/12/comet-67p.

[44] NASA Science Mission Directorate, 'Comets' (19 December 2019), *NASA*, online: solarsystem.nasa.gov/asteroids-comets-and-meteors/comets/in-depth.

[45] Emily Baldwin, 'Comet jet in 3D' (9 October 2015), *ESA*, online: blogs.esa.int/rosetta/2015/10/09/comet-jet-in-3d.

[46] NASA Deep Impact Mission, 'Deep Impact Team reports first evidence of cometary ice' (3 February 2006), *NASA* , online: www.nasa.gov/mission_pages/deepimpact/media/deepimpact_water_ice.html.

Figure 6.6 Comet 67P/Churyumov–Gerasimenko, in a mosaic of four photographs from ESA's *Rosetta* spacecraft. The comet, which appears to be two icy bodies weakly held together, is about 4.3 by 4.1 kilometres at its longest and widest dimensions. One of *Rosetta*'s many discoveries was that the isotopic signature of the water on the comet is quite different from that on Earth, which suggests that Earth's oceans did not come from comets like 67P.[47]

Part of the interest in comets is driven by collisions that were observed on the surface of Jupiter in 1994. The event derived from the short-period comet Shoemaker–Levy 9, which was likely captured by Jupiter's immense gravity around 1970 while passing close to the gas giant during its aphelion (the point of the comet's orbit furthest from the Sun). There it stayed in an evolving, highly elliptical Jovian-centric orbit. Then, in

[47] Ian Sample, 'Rosetta discovers water on Comet 67p like nothing on Earth', *The Guardian* (11 December 2014), online: www.theguardian.com/science/2014/dec/10/water-comet-67p-earth-rosetta.

https://doi.org/10.1017/9781108597135.007 Published online by Cambridge University Press

1992, the planet's tidal forces overwhelmed the comet, breaking it into fragments, several of which were about two kilometres in diameter. Two years later, these fragments collided with Jupiter at 60 kilometres per second, leaving scars on its gaseous surface that remained visible for months.[48] The event is often cited as one of the main drivers for early planetary defence initiatives.[49]

An Earth impact scenario involving a comet was prepared by NASA scientists and shared with the attendees at the International Academy of Astronautics' (IAA) 2019 Planetary Defense Conference.[50] Although the scenario was not as developed as the exercise involving asteroid 2019 PDC, it illuminated the greater uncertainties and potentially greater risks of comets as compared to asteroids. Again, many comets have very long orbits, meaning that we have no prior knowledge of their existence, trajectories or composition. Comets also tend to be larger than asteroids, travel much faster, and be composed of a combination of solid and gaseous materials that lends itself to fragmentation events.[51] All of these factors make it difficult to predict whether a comet passing close to Earth will fly by harmlessly or collide destructively, and equally difficult to predict where on Earth any such impact would occur.

For all these reasons, a comet would be much more difficult to deflect or destroy than an asteroid. The only good news is that comets pass by Earth much less frequently than asteroids. Still, it is good public policy to develop mechanisms for the early detection of comets, for determining their orbits with as much precision as possible, and for deflecting or destroying them should such a need ever arise.

48 NASA Science Mission Directorate, 'P/Shoemaker-Levy 9' (19 December 2019), *NASA*, online: solarsystem.nasa.gov/asteroids-comets-and-meteors/comets/p-shoemaker-levy-9/in-depth.

49 Lindley N Johnson, 'Preparing for planetary defense: Detection and interception of asteroids on collision course with Earth' (paper delivered at the 32nd Space Congress, Cocoa Beach, Florida, 25 April 1995), online: commons.erau.edu/space-congress-proceedings/proceedings-1995-32nd/april-25-1995/18.

50 NASA Center for Near Earth Object Studies, 'Hypothetical comet impact scenario – PDC 2019' (2019), *NASA*, online: cneos.jpl.nasa.gov/pd/cs/pdc19c.

51 Claire Andreoli, Ray Villard, David Jewitt and Quanzhi Ye, 'Hubble watches comet ATLAS disintegrate into more than two dozen pieces' (28 April 2020), *NASA*, online: www.nasa.gov/feature/goddard/2020/hubble-watches-comet-atlas-disintegrate-into-more-than-two-dozen-pieces.

6.5 International Co-operation

The challenges of detecting and characterising dangerous asteroids and comets, assessing risks and, if necessary, deflecting or destroying them are likely to exceed the capabilities of any single state and therefore call for international co-operation. Should mitigation turn to disaster management, even a city-wide or regional impact from a near-Earth object (NEO) could have worldwide economic and social effects.[52] Yet there has been a lack of high-level diplomacy on this issue, with the low-probability character of Earth impact making planetary defence a low priority for political leaders whose timelines seldom extend beyond the next four to five years. Such international co-operation on planetary defence as is currently taking place is occurring among national Space agencies, observatories and even amateur astronomers rather than among foreign ministries.

In 1999, the Third UN Conference on the Exploration and Peaceful Uses of Outer Space recommended improvements to international co-ordination on planetary defence.[53] As a response, 'Action Team 14' – a co-ordinated effort by 19 countries to study potentially hazardous NEOs – was formed by the UN Committee on the Peaceful Uses of Outer Space (COPUOS) in 2001.[54] After the airburst over Chelyabinsk, Russia, in February 2013, which injured more than 1,000 people, the work done by Action Team 14 enabled a prompt response from higher levels of the United Nations. In December 2013, the UN General Assembly adopted Resolution 68/75 in which it welcomed recommendations from COPUOS to establish the International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG).[55]

[52] R Albrecht and MHJ Dore, 'Toward plans for mitigating possible socio-economic effects due to a physical impact of an asteroid on Earth' (paper delivered at the 7th IAA Planetary Defense Conference, virtual, 26–30 April 2021), online: ui.adsabs.harvard.edu/abs/2021plde.confE..74A/abstract.

[53] United Nations Office for Outer Space Affairs, *Report of the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (Vienna, 19–30 July 1999)*, UN Doc A/CONF.184/6 (18 October 1999) at res 1(I) para. 1(c)(i)–(iii), online: digitallibrary.un.org/record/287788.

[54] *Report of the Committee on the Peaceful Uses of Outer Space*, UN GAOR, 56th sess, Supp No 20, UN Doc A/56/20 (2001) at paras. 44–61, online: www.unoosa.org/pdf/gadocs/A_56_20E.pdf; Pelton, op. cit. at 348.

[55] *International Cooperation in the Peaceful Uses of Outer Space*, GA Res 68/75, 68th sess, UN Doc A/RES/68/75 (16 December 2013) at para. 8, online: www.unoosa.org/oosa/oosadoc/data/resolutions/2013/general_assembly_68th_session/ares6875.html.

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6.5.1 International Asteroid Warning Network

The International Asteroid Warning Network (IAWN) connects astronomers, observatories and other institutions that were already engaged in identifying and studying potentially hazardous NEOs. By pooling existing capabilities, IAWN aims to 'discover, monitor, and physically characterize' the entire population of potentially hazardous NEOs using 'optical and radar facilities and other assets based in both the northern and southern hemispheres and in space'.[56] It also serves as an international clearing house for NEO observations,[57] co-ordinates campaigns for the observation of NEOs of particular concern, and recommends criteria and thresholds for when emerging impact threats should be communicated to national governments and general publics. Finally, IAWN aims to develop a database of potential 'impact consequences', to assess 'hazard analysis results', to communicate them to governments and to assist in the planning of 'mitigation responses'.[58] These latter activities, it should be noted, are directed at dealing with the effects of an impact after it occurs.

Participation in IAWN is open to all governmental and non-governmental entities with relevant capabilities, including survey telescopes, follow-up observations, orbit computations, hazard analysis, data distribution, processing and archiving. However, participants must accept a policy of free and open communication. If someone identifies an NEO threat, they must tell everyone else about it! The network's 'Statement of Intent' currently has more than 40 signatories, ranging from highly skilled 'amateur' astronomers to NASA, ESA, the China National Space Administration and the Special Astrophysical Observatory of the Russian Academy of Sciences.[59] In terms of participation in IAWN, a shared interest in knowing about cataclysmic threats has superseded national rivalries.

[56] Elizabeth Warner, 'History' (31 March 2022), *IAWN*, online: iawn.net/about.shtml.

[57] IAWN works closely with the International Astronomical Union's Minor Planet Center, which is hosted by the Harvard and Smithsonian Center for Astrophysics, located at the Smithsonian Astrophysical Observatory and funded primarily by NASA. See 'International Astronomical Union Minor Planet Center' (18 April 2022), *Center for Astrophysics*, online: minorplanetcenter.net.

[58] Warner, 'History', op. cit.

[59] Elizabeth Warner, 'Membership' (31 March 2022), *IAWN*, online: iawn.net/about/members.shtml.

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6.5.2 *Space Mission Planning Advisory Group*

The Space Mission Planning Advisory Group (SMPAG, generally pronounced 'same page') was created to 'prepare for an international response to an NEO impact threat through the exchange of information, development of options for collaborative research and mission opportunities, and NEO threat mitigation planning activities'.[60] Currently composed of representatives from 18 Space agencies, including NASA, ESA, Roscosmos and the China National Space Administration, SMPAG addresses issues such as the feasibility of and options for mitigating an impact threat through a Space mission, and the length of time that it would take to build and launch a spacecraft to deflect an NEO. SMPAG is grounded on a shared conviction that the 'threat of an asteroid or comet impact is a real and global issue demanding an international response'. Recognising that states 'already share a number of common interests in NEO threat identification and mitigation', SMPAG aims 'to develop cooperative activities among its members and to build consensus on recommendations for planetary defense measures'.[61] In other words, unlike IAWN, which focuses on international co-operation in the detection of potentially hazardous NEOs, SMPAG focuses on co-ordinating the capabilities that might be needed to deflect or destroy them.

That said, SMPAG is not working to marshal a fleet of asteroid deflection spacecraft and rockets in preparation for a planetary emergency. Nor would it fulfil any decision-making role should such an emergency arise. Rather, SMPAG would respond to a credible impact threat by proposing 'mitigation options and implementation plans for consideration by the international community'.[62] This means that the decision makers would be national governments, whether acting unilaterally, in some ad hoc coalition, or through an existing international mechanism such as the United Nations Security Council. No predeterminations have been made as to who would contribute, and what they would contribute, in the event of an Earth impact emergency. These issues, of who decides and who acts, will be discussed below. First, however, we should consider the kinds of decisions that would have to be taken.

60 Space Mission Planning Advisory Group (SMPAG), 'Terms of reference for the Near-Earth Object Threat Mitigation Space Mission Planning Advisory Group – Version 2.0' (13 September 2019), *ESA*, online: www.cosmos.esa.int/web/smpag/terms_of_reference_v2.

61 Ibid.

62 Ibid.

6.6 Tabletop Exercises

The fictional asteroid 2021 PDC was developed for the 2021 Planetary Defense Conference,[63] in a scenario that quite deliberately provided a very short timeline for reacting to an impact emergency, in order to highlight several new issues of concern. The exercise played out as follows.

- IAWN announced the discovery of 2021 PDC, which posed an impact risk to Earth within approximately six months. At the time, the estimated impact risk was 5 per cent and the size of the asteroid was very uncertain – somewhere between 35 and 700 metres, which corresponds to very localised to widespread (a few kilometres to hundreds of kilometres) severe damage potential.
- One week later, ground-based follow-up observations confirmed that an impact would take place. However, the impact corridor remained uncertain and stretched from Scandinavia to North Africa. Nor was there any more information on the size of the asteroid. SMPAG began to explore Space mission options.
- Four months before the impact, Space-based observations by NEOWISE narrowed the impact corridor to a swath across Central Europe. They also constrained the size of the asteroid to between 35 and 500 metres, with a likely size of 160 metres in diameter. At the same time, SMPAG determined that 'no space mission can be launched in time to deflect or disrupt the asteroid'. Nor could any reconnaissance mission be launched.
- With the lack of deflection options, mitigation became disaster management, with a focus on refining the impact location and size of the asteroid, as well as implementing civil responses. The estimated size of the asteroid meant that a '[l]arge airburst or impact is likely to cause extensive blast damage over areas extending from tens to hundreds of kilometers in radius', affecting 'hundreds of thousands of people, potentially up to several million in rare worst-cases'.[64]

[63] NASA Center for Near Earth Object Studies, 'Planetary Defense Conference Exercise – 2021' (2021), *NASA*, online: cneos.jpl.nasa.gov/pd/cs/pdc21.

[64] Lorien Wheeler, Jessie Dotson, Michael Aftosmis, Eric Stern, Donovan Mathias and Paul Chodas, '2021 PDC Hypothetical Impact Exercise: probabilistic asteroid impact risk, scenario day 3' (paper delivered at the 7th IAA Planetary Defense Conference, virtual, 26–30 April 2021), *NASA*, online: cneos.jpl.nasa.gov/pd/cs/pdc21/pdc21_day3_briefing2.pdf.

- The Goldstone Solar System Radar in California was able to observe the asteroid for the last six days before the impact and narrow the impact location to the tri-border region of Germany, Austria and the Czech Republic. Fortunately, the asteroid was smaller than previously thought, though still sizeable at 100 metres in diameter. Within the remaining uncertainty, the object could cause serious damage to a region 300 kilometres across for the highest plausible impact energies and 150 kilometres across for the average estimated impact energy. Serious damage refers to window breakage, some structural damage and possible second-degree burns. The 'unsurvivable' region, closest to the impact centroid, would be about 10 per cent of the serious-damage extent.

Several important things were learned as a result of this exercise. First, reliable and ready-to-launch spacecraft for planetary defence reconnaissance are needed and currently lacking. Second, had sensitive all-sky surveys been operational a decade before the hypothetical discovery, the asteroid could have been discovered with sufficient lead time to launch one or more deflection missions. Third, access to reliable archival data is fundamental to planetary defence, allowing for the possibility of 'pre-recoveries', i.e. finding the asteroid in older data, in the form of observational information about a previous pass by Earth. But a pre-recovery of archival data could be precluded for many reasons, and might only become possible when new real-time information about the asteroid's location comes in.

Although the 2021 PDC exercise was important for exploring disaster response, it was not designed to raise or address issues of mitigation. For this, we need to turn to the fictional asteroid 2019 PDC,[65] as developed for the 2019 Planetary Defense Conference.[66] That tabletop exercise, which provided an optimistic eight-year timeline between detection and impact, identified a series of questions that would have to be addressed in any such situation:

- What type of space missions should be used to rapidly improve our understanding of the asteroid's orbit, to determine whether and where it will impact Earth?

[65] Note that this is the same hypothetical asteroid used in Figure 6.5 for introducing the B-plane.

[66] NASA Center for Near Earth Object Studies, 'Planetary Defense Conference Exercise – 2019' (2019), *NASA*, online: cneos.jpl.nasa.gov/pd/cs/pdc19.

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- Are flyby missions sufficient or do we need a rendezvous with the asteroid?
- Who will build the spacecraft? Who will launch?
- Should a nuclear explosive device be part of the reconnaissance spacecraft, to provide an immediate deflection option, or should the deflection options be restricted to non-nuclear methods?
- Who decides whether a deflection is needed?
- Who decides what method will be used?
- What if there is substantial disagreement on the need for a deflection or the method used?
- Who will be responsible for any negative consequences of a failed or only partial deflection?
- If the asteroid is on course to impact a non-spacefaring state, do spacefaring states have an obligation to mount a deflection mission?

To this list we might add: what is the most reliable way to characterise the asteroid, in terms of its composition and therefore the suitability and safety of different deflection methods?

In the 2019 exercise, flyby and rendezvous reconnaissance spacecraft were considered, as well as immediate-deflection scenarios. The immediate-deflection options involved significant uncertainties due to incomplete knowledge about the asteroid. Indeed, at the time SMPAG began looking at mission possibilities, the impact probability was still only 10 per cent. Yet the optimal orbital characteristics for the use of kinetic impactors were only present for an early launch. During the exercise, it was also noted that an NED-capable rendezvous spacecraft would have the greatest flexibility – combining asteroid characterisation with the option of deflection – but that it would also introduce a number of legal and policy issues, as discussed below. Regardless of the method chosen, the scenario anticipated that more than a year would be required to build the necessary spacecraft. Ultimately, the shortest-timeline reconnaissance mission was performed, which was a flyby. This still left uncertainty about the asteroid's mass but removed any doubt that an impact would occur: a 140- to 220-metre asteroid striking the Greater Denver, Colorado area.

Although an NED could have been launched, a sub-optimal but still-feasible kinetic impactor mission was chosen instead. Between them, NASA, ESA, Roscosmos and the Chinese and Japanese Space agencies built and launched six spacecraft – a number designed to provide redundancy and prevent the need for a single, large Δv. Three of the six

EXERCISE

Day 5 Ground Zero; Central Park NYC, NY*

*Boslough & Chodas

DAMAGE ZONES		
CATEGORY	SQ. MILES	EXPECTED DAMAGE BY PSI
Serious	275	Serious: Overpressures >1 psi (window breakage, minor structural damage); Thermal Exposure > 2nd degree burns
Severe	174	Overpressures >2 psi (doors/windows blown out, widespread structural damage); Thermal Exposure >3rd degree burns
Critical	35	Overpressures > 4 psi (most residential structures collapse); Thermal Exposure > clothing ignition
Unsurvivable	32	Overpressures > 10 psi (complete devastation); Thermal Exposure > roll roofing ignition / sand explodes

EXERCISE

Figure 6.7 The area of expected damage due to an airburst from a 60-metre asteroid, arranged by increasing severity. The region of 'severe' damage is enclosed by the region of 'serious' damage, and so forth. Regions need not be circular, and they depend on several factors. The term 'overpressure' refers to the pressure, in pounds per square inch (psi), in excess of the ambient pressure prior to the arrival of the blast wave. From Barbara Jennings, 'Day 5 at Risk Critical Infrastructure Effects' (paper delivered at the 6th Planetary Defense Conference, College Park, Maryland, 29 April–3 May 2019), *NASA*, online: cneos.jpl.nasa.gov/pd/cs/pdc19/pdc19_briefing5c.pdf.

spacecraft reached the asteroid, but despite using multiple impactors, one of the collisions caused the asteroid to fragment. And so, while the deflection effort prevented the entire asteroid from striking Boulder, a 60-metre fragment remained on course to strike Earth and, more precisely, New York City. With the decision makers having failed to agree on sending an NED, even as a back-up option ('due to widespread controversy that was not resolved in time'[67]), they were unable to save New York City and the surrounding area. Figure 6.7, prepared for the exercise, gives a sense of the destruction that could be caused by a 60-metre asteroid.

[67] Brent Barbee, Paul Chodas, Joshua Lyzhoft, Anastassios E. Petropoulos, Javier Roa and Bruno Sarli, '2019 PDC mitigation mission options' (paper delivered at the 6th IAA Planetary Defense Conference, College Park, Maryland, 29 April–3 May 2019), *NASA*, online cneos.jpl.nasa.gov/pd/cs/pdc19/pdc19_briefing4c.pdf.

Quite a few tabletop exercises similar to this have taken place,[68] as well as one *ex post facto* legal analysis conducted by an Ad-Hoc Working Group on Legal Issues established by SMPAG. In its 2020 'Legal Overview and Assessment', the Ad-Hoc Working Group took a tabletop exercise from the 2017 Planetary Defense Conference, where the legal issues were not addressed, and conducted its own analysis of the legal issues that would have arisen – had the scenario played out in real life.[69] Some of this analysis will be discussed below.

6.7 Legal Issues

Some difficult legal issues can be expected to arise in the context of planetary defence. Most of these are discussed in an excellent 2020 report from the Ad-Hoc Working Group on Legal Issues established by SMPAG.[70] This section follows the structure of that report and reproduces some of its content, while adding commentary and raising a few additional issues.

6.7.1 Information sharing

If an NEO with a potentially dangerous orbit is discovered, it is almost inconceivable that the astronomers involved would not promptly inform the global astronomical community of their find. There are strong ethical obligations to share information that could potentially save millions of lives. Moreover, science relies on the international circulation of discoveries and data, and careers are made through peer-reviewed publications leading to global reputations. The astronomers who discovered a significant NEO threat would thus have powerful incentives to share that information; indeed, if the NEO were a comet, it would be named after them. But even in the absence of strong ethical and professional motivations, keeping secret the existence of a possible Earth-impacting asteroid or comet is not a real possibility. After observations of an NEO

[68] NASA Center for Near Earth Object Studies, 'Hypothetical comet impact scenario – PDC 2019' (29 April 2019), *NASA*, online: cneos.jpl.nasa.gov/pd/cs/pdc19c.

[69] Space Mission Planning Advisory Group (SMPAG), 'Planetary defence legal overview and assessment: Report by the Ad-Hoc Working Group on Legal Issues to the Space Mission Planning Advisory Group' (8 April 2020), *ESA*, online: www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-004_1_0_SMPAG_legal_report_2020-04-08.pdf.

[70] Ibid.

are taken, the data are almost universally submitted to the International Astronomical Union's Minor Planet Center and made publicly available, and for good reason. Initial observations are typically unable to yield reliable orbit solutions. Publicly accessible announcements of new objects are circulated so that astronomers worldwide, including highly skilled 'amateurs', can acquire more observations of the object. Several independent groups also focus on computing orbital solutions with known data. Even independently of formal collaborations, the detection and characterisation of NEOs is a team effort and thus involves many people with open information.

National governments are unlikely to interfere because they, too, would have powerful incentives to share the information. Even if the data are sufficient to determine whether an impact will happen, the resulting orbit solutions are unlikely, at first, to be accurate enough to determine an impact location with actionable certainty. With everyone (or at least many) at equal risk, all states would have an equal interest in seeing the full deployment of the international astronomical community's capabilities to determine whether an impact were forthcoming, and where exactly it would take place.

International law augments these reasons for information sharing with a binding legal obligation that can be inferred from two articles of the 1967 Outer Space Treaty. Article IX reads,

> In the exploration and use of outer space, including the Moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty.[71]

As we explained in Chapter 3, observatories are engaged in the 'exploration' of Space. It is also clearly in the interests of all parties to the treaty to be promptly informed of any new NEO threat.

Further to this, Article XI sets out a general obligation to share information:

> In order to promote international cooperation in the peaceful exploration and use of outer space, States Parties to the Treaty conducting activities in

[71] *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*, 27 January 1967, 610 UNTS 205 (entered into force 10 October 1967) (Outer Space Treaty).

> outer space, including the Moon and other celestial bodies, agree to inform the Secretary-General of the United Nations as well as the public and the international scientific community, to the greatest extent feasible and practicable, of the nature, conduct, locations and results of such activities. On receiving the said information, the Secretary-General of the United Nations should be prepared to disseminate it immediately and effectively.[72]

This treaty obligation is uncontroversial and may well have contributed to the development of a parallel rule of customary international law that binds all states and not just the parties to the Outer Space Treaty. This process, of treaties contributing to parallel customary obligations, is well established in the international legal system – and will be discussed at greater length below.

Treaties and customary international law are the first two 'sources of international law', as identified by the Statute of the International Court of Justice. The third source of international law – 'the general principles of law recognized by civilized nations' – is also relevant here.[73] This is because the International Court of Justice (ICJ) has held that the obligation to share information in life-and-death situations is supported by 'elementary considerations of humanity' that constitute 'general and well-recognized principles' of law. As the Ad-Hoc Working Group on Legal Issues explains, in the 1949 *Corfu Channel Case*,

> The ICJ found that Albania was under the obligation to inform foreign vessels about the existence of a minefield in its territorial waters. This obligation was, according to the Court, based on '*general and well-recognized principles, namely: elementary considerations of humanity*'.[74] In this case, the failure to notify foreign ships led to the death or injury of over 80 persons. Since '*nothing was attempted by the Albanian authorities to prevent the disaster*'[75], the Court found that Albania was responsible

[72] Ibid. Art. IX.

[73] Art. 38(1) of the Statute of the International Court of Justice identified three primary sources of international law, with the third being 'the general principles of law recognized by civilized nations'. See Statue of the International Court of Justice, 26 June 1945, Can TS 1945 No 7 Art. 38(1) (entered into force 24 October 1945); The phrase 'civilized nations' is, of course, colonial terminology. In 2019, the United Nations International Law Commission noted that the term is generally agreed to be inappropriate and outdated, and suggested it should be read as 'community of nations'. See *Report of the International Law Commission: Seventy-First Session 29 April–7 June and 8 July–9 August 2019*, UNGAOR, 74th Sess, Supp No 10, UN Doc A/74/10 (2019) at 336, para. 243, online: digitallibrary.un.org/record/3827355?ln=en.

[74] *Corfu Channel Case* (*UK* v. *Albania*), [1949] ICJ Reports 4 at 22, SMPAG's emphasis.

[75] Ibid. at 23, SMPAG's emphasis.

> under international law for the damage and loss of human life which resulted from the explosion of the minefield and that there was a duty upon Albania to pay compensation.[76]

This led the Ad-Hoc Working Group to conclude, 'While the case does not address the specific situation of an NEO impact threat, it can nevertheless support the argument that elementary considerations of humanity can form the basis of a duty to share information in order to avoid the loss of human lives.'[77]

The obligation to share information promptly and publicly about NEO threats is thus strongly supported on ethical, professional, practical and legal grounds.

6.7.2 Assisting Other States

If an asteroid on an Earth impact trajectory is identified, and if the asteroid is small enough that the damage will be limited to one state or a small number of states, those states clearly have the right to attempt a deflection mission. They might then be responsible for any damage caused to third states, for instance if the mission altered the trajectory of the asteroid only slightly, causing it to strike a state or states which had not initially been threatened. This issue of 'state responsibility' will be addressed below, along with the question whether this damage could be excused by either a United Nations Security Council resolution or 'circumstances precluding wrongfulness'.

The Ad-Hoc Working Group raises another issue, namely whether states having the capability to mount a deflection mission are legally obligated to come to the assistance of states that lack this capability but discover that they will be the location of an NEO impact. We will turn to this issue of a possible legal obligation in a moment, but first there are compelling reasons to believe that the issue is unlikely ever to arise. Indeed, there are at least three reasons to believe that spacefaring states would always seek to prevent an NEO impact even if their own territories and populations were not directly threatened. First, an asteroid large enough to cause significant damage in one state will have indirect effects in other states. These effects could include alterations to the climate, if large amounts of material are lofted into the atmosphere, leading to a

[76] SMPAG, 'Planetary defence', op. cit. at 20.
[77] Ibid.

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consequential diminishment of global food supplies. They could impact the broader economy, if international trade, investment and travel are disrupted. They could also lead to migration, if an asteroid strike in one country forced large numbers of people to flee to other countries, either before or after the impact. Such sudden and dramatic changes could, in turn, affect the political stability or national security of multiple states. Second, the random nature of NEO threats means that an impeding strike on a non-spacefaring state or states would provide an excellent opportunity for spacefaring states to test their deflection capabilities, knowing that another NEO will, sooner or later, eventually threaten them. Third, governments everywhere are responsive to public opinion. It is difficult to imagine that the public in the United States, Europe, Russia or China, would – if accurately informed about the situation – abide their leaders abandoning millions of fellow human beings to a preventable NEO threat.

Now we turn to the Ad-Hoc Working Group's analysis of the issue, which concluded that, 'in the absence of specific and clear obligations under international law, States are free to decide whether they provide assistance to other States that are threatened by a possible NEO impact'.[78] Unfortunately, by limiting its analysis to the search for 'specific and clear obligations under international law',[79] the Ad-Hoc Working Group did not consider the third source of international law, i.e. 'the general principles of law recognized by civilized nations'.[80] Interestingly, this is the same Ad-Hoc Working Group that, on the issue of information sharing, referred approvingly to the International Court of Justice's finding in the *Corfu Channel Case* that 'elementary considerations of humanity' constitute 'general and well-recognized principles' of law.[81] Had the Ad-Hoc Working Group conducted a similar and necessary analysis with regard to a duty to rescue human beings in distress, they might have reached a very different conclusion, which we will expand on now.

The duty to rescue exists in many national legal systems. For example, section 323c(1) of the German Civil Code states,

> Whoever does not render assistance in the case of an accident or a common danger or emergency although it is necessary and can

[78] Ibid. at 24.
[79] Ibid.
[80] Statute of the International Court of Justice, op. cit., Art. 38(1).
[81] *Corfu Channel Case*, op. cit. at 23.

> reasonably be expected under the circumstances, in particular if it is possible without substantial danger to that person and without breaching other important duties, incurs a penalty of imprisonment for a term not exceeding one year or a fine.[82]

Similarly, in the Canadian province of Quebec, its provincial Charter of Human Rights and Freedoms states,

> Every human being whose life is in peril has a right to assistance. Every person must come to the aid of anyone whose life is in peril, either personally or calling for aid, by giving him the necessary and immediate physical assistance, unless it involves danger to himself or a third person, or he has another valid reason.[83]

Many other Civil Law systems, from France to Argentina to Egypt, contain the same duty to rescue.

Common Law systems do not have a general duty to rescue, although such a duty has been found in the context of pre-existing relationships, for instance teachers vis-à-vis their students, or parents vis-à-vis their children.[84] In the United States, numerous states have 'Good Samaritan' statutes, and some of these contain a duty to rescue.[85] In Vermont, for instance,

> A person who knows that another is exposed to grave physical harm shall, to the extent that the same can be rendered without danger or peril to himself or without interference with important duties owed to others, give reasonable assistance to the exposed person unless that assistance or care is being provided by others.[86]

Other US states, however, only go so far as to provide immunity from civil liability to a person who acts to rescue another and, in doing so, inadvertently causes harm.

Internationally, the duty to rescue is included in numerous treaties. The International Convention for the Safety of Life at Sea (SOLAS Convention) was adopted in 1914, with the negotiations having been prompted by the sinking of the *Titanic* two years earlier. Although it has

[82] German Criminal Code, 13 November 1998 (Federal Law Gazette I, p 3322), s 323c(1).

[83] Charter of Human Rights and Freedoms, CQLR c C-12, s 2.

[84] Martin Vraken, 'Duty to rescue in civil law and common law: Les extrêmes se touchent' (1998) 47:4 *International & Comparative Law Quarterly* 934.

[85] Patricia Grande Montana, 'Watch or report? Livestream or help? Good Samaritan laws revisited: The need to create a duty to report' (2017) 66:3 *Cleveland State Law Review* 533.

[86] *Vermont Statues Annotated*, Title 12 § 519(a) (2017).

been updated many times since then, the SOLAS Convention has always required each party 'to ensure that any necessary arrangements are made for coast watching and for the rescue of persons in distress at sea round its coasts'.[87] The 1944 Convention on International Civil Aviation (Chicago Convention) has an entire annex devoted to search and rescue. Parties to the Chicago Convention are required to assist survivors of accidents regardless of nationality.[88] The 1979 International Convention on Maritime Search and Rescue (SAR Convention) requires states parties, individually or co-operatively, to 'participate in the development of search and rescue services to ensure that assistance is rendered to any person in distress at sea'.[89]

The 1982 United Nations Convention on the Law of the Sea reinforces these earlier treaties, with Article 98(1) reading,

> Every State shall require the master of a ship flying its flag, in so far as he can do so without serious danger to the ship, the crew or the passengers:
>
> (a) to render assistance to any person found at sea in danger of being lost;
> (b) to proceed with all possible speed to the rescue of persons in distress, if informed of their need of assistance, in so far as such action may reasonably be expected of him;
> (c) after a collision, to render assistance to the other ship, its crew and its passengers and, where possible, to inform the other ship of the name of his own ship, its port of registry and the nearest port at which it will call.[90]

The duty to rescue is also found in numerous regional and bilateral treaties, and not just between allies. For instance, in 1988 the United States and the Soviet Union concluded a bilateral treaty on maritime

87 International Convention for the Safety of Life at Sea, 1 November 1974, 1184 UNTS 278 (entered into force 25 May 1980) (SOLAS Convention) ch V, reg 15. For a brief history of the SOLAS Convention and its many updates, see 'SOLAS' (2019), *International Maritime Organization*, online: www.imo.org/en/KnowledgeCentre/ConferencesMeetings/Pages/SOLAS.aspx.

88 Convention on International Civil Aviation, 7 December 1944, 15 UNTS 295 Annex 12 (7th ed., 2001), Art. 2.1.2 (entered into force 4 April 1947) (Chicago Convention), Annex 12 (7th ed., 2001).

89 International Convention on Maritime Search and Rescue, 27 April 1979, 1405 UNTS 119 Annex, ch 2, Art. 2.1.1 (entered into force 22 June 1985, including amendments adopted in 1998 and 2004).

90 United Nations Convention on the Law of the Sea, 10 December 1982, 1833 UNTS 397, Art. 98 (1) (entered into force 16 November 1994).

search and rescue.[91] Then, after the loss of the Russian nuclear attack submarine *Kursk* in the year 2000, Russia and NATO signed an agreement on submarine rescues in 2003.[92] Two years later, a British submersible was used to free seven Russian sailors whose mini submarine had become tangled in a fishing net 190 metres below the surface of the Pacific Ocean off the Kamchatka peninsula.[93] There is also the 2011 Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic, which reiterates the obligations of the Chicago Convention and the SAR Convention in a regional context among the eight Arctic states, and includes five NATO states as well as Russia.[94]

The duty to rescue is found in the 1967 Outer Space Treaty, with the first sentence of Article V reading, 'States Parties to the Treaty shall regard astronauts as envoys of mankind in outer space and shall render to them all possible assistance in the event of accident, distress, or emergency landing on the territory of another State Party or on the high seas'.[95] Indeed, the duty to rescue was considered so fundamental that, the very next year, the same states concluded the 1968 Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (Rescue Agreement).[96] The Rescue Agreement elaborates on Article V of the Outer Space Treaty. It explains that, in any given situation, the duty to rescue requires that 'those Contracting Parties which are in a position to do so shall, if necessary, extend assistance in search and rescue operations for such personnel to assure their speedy rescue'.[97] As we explain in Chapter 1, this duty applies everywhere: within the jurisdiction of each respective state party as well as in areas beyond national jurisdiction, such as the high seas and Space.

[91] Agreement between the Government of the United States of America and the Government of the Union of Soviet Socialist Republics on Maritime Search and Rescue, 12 December 1986, 2191 UNTS 115 (entered into force 1 January 1989).

[92] NATO Update, 'NATO and Russia sign submarine rescue agreement' (8 February 2003), *North Atlantic Treaty Organization*, online: www.nato.int/docu/update/2003/02-february/e0208a.htm.

[93] 'Russians saved in deep-sea rescue', *BBC News* (7 August 2005), online: news.bbc.co.uk/1/hi/world/europe/4128614.stm.

[94] Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic, 12 May 2011, 50 ILM 1119 (entered into force 19 January 2013).

[95] Outer Space Treaty, op. cit., Art. V.

[96] Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, 22 April 1968, 672 UNTS 119 (entered into force 3 December 1968) (Rescue Agreement).

[97] Ibid. Art. 3.

For all these reasons, the Ad-Hoc Working Group was wrong to conclude that 'States are free to decide whether they provide assistance to other States that are threatened by a possible NEO impact'.[98] States have a general duty to rescue people in distress that would most certainly be engaged by an impending asteroid or comet strike. Of course, the duty is not absolute: no state would be required to develop a deflection capability in order to come to the assistance of another state. However, what if a state already had a deflection capability, including both spacecraft and rockets, on standby? Balancing the duty to rescue against any risks and expenses associated with acting is a fact-specific determination, one that does not detract from the existence of this duty as a general principle of law among the community of nations.

6.7.3 Nuclear Explosive Devices

The potential use of NEDs for deflecting or destroying asteroids is debated among international lawyers, with this debate connecting to a larger one about the legality of using or even possessing nuclear weapons.[99] In this section, we will demonstrate that most of the legal discussion about using NEDs for planetary defence is of limited relevance. This is because a nuclear explosion in Space would constitute a clear violation of the 1963 Limited Test Ban Treaty,[100] which binds the two states most likely to attempt such an action, namely the United States and Russia. It is also possible that the prohibition on nuclear explosions in Space has become a rule of customary international law, in which case it would bind non-parties to the Limited Test Ban Treaty, most notably China – which tested its first atomic bomb in 1964 but has never conducted a nuclear test in Space.[101] China has signed but not ratified the 1996 Comprehensive Test Ban Treaty, which, if it ever comes into force, will ban all nuclear tests including in Space.[102]

98 SMPAG, 'Planetary defence', op. cit. at 24.

99 See Bryce G Poole, 'Against the nuclear option: Planetary defence under international Space law' (2020) 45:1 *Air and Space Law* 55.

100 Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water, 5 August 1963, 480 UNTS 43 (entered into force 10 October 1963) (Limited Test Ban Treaty).

101 James Martin Center for Nonproliferation Studies, 'China nuclear overview fact sheet' (29 April 2015), *Nuclear Threat Initiative*, online: www.nti.org/analysis/articles/china-nuclear.

102 Comprehensive Test Ban Treaty, 24 September 1996, 35 ILM 1439 (not yet entered into force).

This is not the end of the discussion, however, since the United Nations Security Council could still authorise the use of an NED, with resolutions adopted under Chapter VII of the UN Charter prevailing over conflicting rules of international law. Moreover, if the Security Council failed to adopt a resolution – for instance because of a veto cast by one of its five permanent members – a state could still use an NED and claim 'necessity'.[103] Necessity, as we will explain below, is a 'circumstance precluding wrongfulness' within the international law of state responsibility. The relevant questions, at that point, would concern whether the criteria for necessity had been fulfilled.

6.7.4 Nuclear Explosive Devices and the Outer Space Treaty

Most legal discussions concerning the use of NEDs in planetary defence start with the first paragraph of Article IV of the Outer Space Treaty, which reads,

> States Parties to the Treaty undertake not to place in orbit around the earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.[104]

It is important to note that this paragraph does not prohibit the launch of nuclear weapons into Space if they do not make an orbit around the Earth. Nor does it say anything about whether NEDs used for planetary defence should be distinguished from nuclear weapons. However, the absence of any such provisions has not stopped international lawyers from debating whether an NED should be considered a weapon. The Ad-Hoc Working Group looks to dictionaries, writing, 'Generally, the term "weapon" can be defined as "*any object used in fighting or war, such as a gun, bomb, knife*" (Cambridge English Dictionary) or as "*an instrument*

[103] It is also conceivable that, in the event of a veto being cast in the Security Council, the UN General Assembly could adopt a resolution supporting the use of a NED. There are precedents here, most notably Resolution 377A(V), the so-called 'Uniting for Peace' resolution, which was adopted in 1950 in support of 'collective measures . . . to maintain or restore international peace and security' on the Korean peninsula. See *Uniting for Peace*, GA Res 377(V), UNGAOR, 5th Sess, 302nd Plen Mtg, UN Doc A/RES/377 (3 November 1950) Art. 1.

[104] Outer Space Treaty, op. cit., Art. IV.

of any kind used in warfare or in combat to attack and overcome an enemy" (Oxford English Dictionary)'.[105]

Both these definitions require that the object be used to fight or wage war, which an NED would not. The Ad-Hoc Working Group concedes this point,[106] but then moves past the dictionary definitions to come to the opposite conclusion:

> However, not only the purpose for which something is used determines its qualification as a weapon. Any possible dual-use applications would not change the inherent nature of 'weapons', 'nuclear weapons' or 'weapons of mass destruction', which result from their initial designation. A 'weapon' remains a 'weapon' irrespective of whether it may be used for non-destructive civilian purposes. The problem arising in this context is that it is difficult to construct a device that could be used only against a NEO and not have some applicability against other targets. A planetary defence device could also be used as a weapon.[107]

This then leads the Ad-Hoc Working Group to conclude, 'Since, following the analysis above, NEDs can be qualified as "nuclear weapons", their use in the context of planetary defence missions falls under the scope of this provision' (i.e. Article IV, first paragraph).[108]

Again, this conclusion is contestable. As terrorists have demonstrated, cars and passenger planes can be used as weapons, even though they are not designed or considered as such. More to the point, a kitchen knife is not considered a weapon, unless wielded with hostile intent. Even firearms used for hunting – especially subsistence hunting (i.e. for food) – are not generally considered weapons.

Other international lawyers have taken a more nuanced approach. James Green engages in a lengthy exercise in treaty interpretation, including a foray into the negotiating records (*travaux préparatoires*) of the Outer Space Treaty, before concluding that an NED launched directly from Earth towards an asteroid would be permissible, but an NED stationed in Space in anticipation of an Earth impact emergency would not.[109] He bases

105 SMPAG, 'Planetary defence', op. cit. at 29, SMPAG's emphasis.

106 'Generally, planetary defence devices are not developed for use in warfare to attack or overcome an enemy. They are also not intended to cause widespread devastation and loss of life. On the contrary, planetary defence methods are intended to be specifically targeted at a potentially hazardous asteroid or comet in order to save lives and prevent widespread devastation on Earth.' Ibid.

107 Ibid.

108 Ibid.

109 Green, 'Planetary defense', op. cit.

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the former conclusion on the text of Article IV's first paragraph , as well as the fact that it was negotiated at the height of the Cold War when both the United States and the Soviet Union would have wished 'to retain the possibility of undertaking nuclear strikes against each other via intercontinental ballistic missiles launched out of the atmosphere on a trajectory that then returned them to their terrestrial target'.[110] ICBMs existed before the Outer Space Treaty was negotiated. However, permanently stationing nuclear weapons in Space would have escalated the Cold War, and this, Green explains, was something that both superpowers were cognisant to avoid.

One could quibble with some of Green's analysis. Like the Ad-Hoc Working Group, he argues that an NED cannot be distinguished from a nuclear weapon for the purposes of the Outer Space Treaty, since the components would be identical. But again, these arguments may not actually matter, since another treaty is much clearer on the key point in question.

6.7.5 The Limited Test Ban Treaty

Although the Outer Space Treaty may not necessarily pose an obstacle to the use of an NED against an NEO, Article I(1)(a) of the 1963 Limited Test Ban Treaty is unequivocal:

1. Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control:
   (a) in the atmosphere; beyond its limits, including outer space; or under water, including territorial waters or high seas . . .[111]

Note that the prohibition is not limited to nuclear weapon tests but encompasses 'any other nuclear explosion', including in Space. This conclusion is supported by the Preamble, which states that 'the principal aim' of the Limited Test Ban Treaty is 'the speediest possible achievement of an agreement on general and complete disarmament', and that a further aim is 'to put an end to the contamination of man's environment by radioactive substances.' Moreover, the *travaux préparatoires* reveal that the words 'or any other nuclear explosion' were inserted into Article

[110] Ibid. at 32.
[111] Limited Test Ban Treaty, op. cit.

I(1)(a) to prevent the prohibition being circumvented through an assertion of 'peaceful use'.[112]

Russia, the United States, the United Kingdom and India are all parties to the Limited Test Ban Treaty; China, France and North Korea are not. The Limited Test Ban Treaty thus poses a legal obstacle to four of the states currently able to attempt an NEO deflection with an NED. But China also has nuclear warheads and large Space rockets, while France has warheads and potential access to rockets via ArianeSpace – the European launch provider.

6.7.6 *Nuclear Explosive Devices and Customary International Law*

It is well established that treaty provisions can contribute to parallel rules of customary international law. In the *North Sea Continental Shelf Cases*, the International Court of Justice considered whether a provision in the 1958 Geneva Convention on the Continental Shelf could have given rise to a parallel rule of customary international law.[113] It wrote,

> Although the passage of only a short period of time is not necessarily, or of itself, a bar to the formation of a new rule of customary international law on the basis of what was originally a purely conventional rule, an indispensable requirement would be that within the period in question, short though it might be, State practice, including that of States whose interests are specially affected, should have been both extensive and virtually uniform in the sense of the provision invoked; and should moreover have occurred in such a way as to show a general recognition that a rule of law or legal obligation is involved.[114]

It is significant that, while several states tested nuclear weapons in Space before the Limited Test Ban Treaty was adopted in 1963, none has done so since. Moreover, those states that acquired the capability to test nuclear weapons in Space after 1963 have refrained from doing so. Most significantly, two of these states – China and France – have refrained from nuclear weapon testing in Space despite never having acceded to the Limited Test Ban Treaty. However, it is uncertain whether

[112] Green, 'Planetary defense', op. cit. at 41, citing Arthur H Dean, *Test Ban and Disarmament: The Path of Negotiation*, 1st ed. (New York: Published for the Council on Foreign Relations by Harper & Row, 1966) at 100–10.

[113] Convention on the Continental Shelf, 29 April 1958, 499 UNTS 311 (entered into force 10 June 1964).

[114] *North Sea Continental Shelf Cases* (*Germany* v. *Denmark*; *Germany* v. *Netherlands*) [1969] ICJ Reports 3 at 44, para. 74.

this avoidance of nuclear weapon testing in Space has been driven by 'a general recognition that a rule of law or legal obligation is involved' (in the words of the ICJ),[115] or whether states simply became aware that such tests have dangerous consequences.

The Soviet Union conducted five nuclear weapon tests in Space in 1961 and 1962. The latter of these, which occurred at an altitude of 230 kilometres, generated such a strong electromagnetic pulse that it caused a fire in a power plant on the ground and disabled hundreds of kilometres of telephone lines. That same year – 1962 – the United States detonated a 1.44 megaton thermonuclear weapon at an altitude of 400 kilometres over the Pacific Ocean.[116] The test, dubbed Starfish Prime, was one of five tests in Operation Fishbowl, which sought to determine whether an artificial intensification of the Van Allen radiation belts could disable intercontinental ballistic missiles.[117] It provided a surprising result: the electromagnetic pulse from the explosion shut down power grids in Hawaii and disabled Telstar 1, which had just begun broadcasting live television between the United States and Europe, as well as five other satellites from the US, the United Kingdom and the Soviet Union.[118]

However, even were the subsequent avoidance of nuclear explosions in Space the result of an awareness of risk rather than a specific legal obligation, this avoidance is occurring in a legal context that includes not only the Limited Test Ban Treaty, but also a general obligation in customary international law to not cause damage to the property of another state. The existence of this obligation is recognised in Article VII of the Outer Space Treaty, which provides that launch states are 'internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such [Space] object or its component parts on the Earth, in air space or in outer space, including the moon and other celestial bodies'. The 1972 Convention on the International Liability for Damage Caused by Space Objects (Liability Convention) elaborates on this provision by providing for absolute liability for damage

[115] Ibid.

[116] David Portree, 'Starfish and Apollo (1962)', *Wired* (21 March 2012), online: www.wired.com/2012/03/starfishandapollo-1962.

[117] Daniel G Dupont, 'Nuclear explosions in orbit', *Scientific American* 290:6 (2004) 100; Phil Plait, 'The Fiftieth anniversary of Starfish Prime: The nuke that shook the world', *Discover Magazine* (9 July 2012), online: www.discovermagazine.com/the-sciences/the-50th-anniversary-of-starfish-prime-the-nuke-that-shook-the-world.

[118] Portree, op. cit.

on Earth, and fault-based liability for damage in Space.[119] It is easy to imagine a nuclear explosion that is caused by one state damaging or disabling satellites owned by others – as, indeed, occurred with Starfish Prime. States that can conduct nuclear weapon tests in Space and choose not to do so based on a recognition of the risks to others are, therefore, engaged in state practice and demonstrating *opinio juris* in support of a rule of customary international law prohibiting such explosions.

Further support for the existence of a rule of customary international law prohibiting nuclear explosions in Space can be found in the 1996 Comprehensive Test Ban Treaty, Article I(1) which reads, 'Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control'.[120] The inclusion of Space within this prohibition is confirmed by the Preamble, where the states parties are: '*Noting* the aspirations expressed by the Parties to the 1963 Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water to seek to achieve the discontinuance of all test explosions of nuclear weapons for all time'.

According to Article XIV, the Comprehensive Test Ban Treaty will not come into force until it is ratified by 44 specific states. These 'Annex 2 states' are those that participated in the negotiation of the treaty in 1994–1996 and possessed nuclear reactors at that time. Of these 44 states, eight have not yet ratified the treaty, although five of them – the United States, China, Egypt, Iran and Israel – have signed it. They are therefore obligated to 'refrain from acts which would defeat the object and purpose' of the treaty, with this general obligation in customary international law (binding on the signatories of any treaty) being recognised in Article 18 of the Vienna Convention on the Law of Treaties.[121]

The three remaining Annex 2 states – India, North Korea and Pakistan – have neither signed nor ratified the Comprehensive Test Ban Treaty and seem unlikely to do so. But what is more relevant for the purposes of customary international law is that 168 states have

[119] Convention on International Liability for Damage Caused by Space Objects, 29 March 1972, 961 UNTS 187 Arts. II–III (entered into force 1 September 1972) (Liability Convention).

[120] Comprehensive Test Ban Treaty, op. cit., Art. I(1).

[121] Vienna Convention on the Law of Treaties, 23 May 1969, 1155 UNTS 331 Art. 18 (entered into force 27 January 1980).

ratified the Comprehensive Test Ban Treaty, while another 16 have signed but not yet ratified. This means that 95 per cent of countries – 184 of 193 member states of the United Nations – have thereby indicated their support for a prohibition on nuclear weapon tests that extends to Space. Considering all this, we conclude that a rule of customary international law prohibiting nuclear explosions in Space exists, with North Korea (but not India or Pakistan, because they have ratified the Limited Test Ban Treaty) perhaps remaining outside its scope as a so-called 'persistent objector'.[122]

6.8 Who Decides?

Within this legal context, a number of key questions arise. Who should be responsible for vetting the science, assessing the risks and making decisions if Earth were faced with an actual NEO threat? How can we maximise international co-operation to ensure a positive outcome? Who should be responsible for mounting a deflection mission, and how can we guard against things going wrong?

Depending on the amount of time between detection and potential impact, a deflection mission might need to be launched before the orbit of the NEO has been determined with precision and before any impending impact can be confirmed. Since any deflection mission will be expensive, decision makers may have to spend large amounts of money based on risk rather than on certainty. These challenges of time, uncertainty and expense could be mitigated by forward-deploying spacecraft in cis-lunar orbit, in advance of the detection of any specific threat. The spacecraft could be designed with both scientific and deflection capabilities, enabling operators to determine whether an Earth impact is actually impending, and, if it is not, to collect other kinds of valuable information – including about the risk of an Earth impact on subsequent passes of an NEO.

Improved detection and orbit determination capabilities will also assist decision makers in determining when deflections are unnecessary for other reasons, for instance if the impact will take place in a sparsely populated region. Even then, any potential climate-altering effects, such as through lofting of material into the atmosphere, will have to be assessed. Similarly, impacts at sea could lead to dangerous and damaging

[122] James A Green, 'India and a customary comprehensive nuclear test-ban: Persistent objection, peremptory norms and the 123 agreement' (2011) 51:3 *Indian Journal of International Law* 3 at 9–18.

tsunamis. All of this would need to be further weighed against the risks of a failed or only partially successful deflection.

6.8.1 *Space Agencies Acting Collectively*

The ideal response to an NEO threat would be for Space agencies to collectively determine the feasibility and risks of different mitigation options, decide on the best approach and implement it. As discussed above, Space agencies are already working together on these issues through an International Asteroid Warning Network that reports to the Space Mission Planning Advisory Group, currently made up of representatives from 18 Space agencies. Both bodies were created in 2013 at the recommendation of the UN Committee on the Peaceful Uses of Outer Space.[123] The IAWN connects Space agencies, observatories and other groups engaged in discovering, monitoring and characterising potentially hazardous NEOs; it also serves as a 'clearing house' for NEO observations and recommends criteria and thresholds for notification of emerging threats.[124] The SMPAG prepares for an international response to an NEO threat by exchanging information, developing options for collaborative research and mission opportunities, and conducting threat mitigation planning activities. Yet it is unclear whether Space agencies would be allowed to lead on these issues in the event of an actual NEO threat, given that militaries are also active in Space and often have much greater political influence. However, as we will explain, militaries are poorly suited for planetary defence. For this reason, states should commit in advance to keeping Space agencies in charge during such eventualities, with this commitment expressed in a multilateral declaration or, better yet, treaty. This commitment could then be implemented in national legal systems, to bind militaries directly.

6.8.2 *A Decision-Making Matrix*

The Ad-Hoc Working Group recognised that responses to NEO threats will be complicated because of the absence of international legal instruments explicitly addressing this issue and because of the short time that might be available to make decisions and to act at the international level. For these reasons, it suggested the drafting of a template for decision

[123] SMPAG, 'Terms of reference', op. cit.
[124] Warner, 'History', op. cit.

making that could quickly be adapted and adopted by the international community in the face of a specific threat. This template could include 'modalities for the organization of cooperation among States and intergovernmental organizations', as well as for the dissemination of information regarding NEO threats.[125] As the Ad-Hoc Working Group explained, any such decision-making matrix would have to balance between the need for transparency and inclusion and 'the importance of avoiding a lengthy process that inhibits an effective response and of providing the flexibility and the resilience that is required'.[126]

The Ad-Hoc Working Group issued its report before the COVID-19 pandemic exposed the weakness of multilateral co-operation in the field of global health. Given the rapid sidelining of the World Health Organization, how confident can we be that SMPAG – another voluntary mechanism designed to co-ordinate state responses – will operate effectively during an equally significant global crisis? Will national political struggles or leadership failings impair collective decision making? Will powerful states turn away from international co-operation as they prioritise national preservation? These last questions become even more relevant with regard to the most powerful international body, the United Nations Security Council, where the five permanent members each hold a veto over decision making.

6.8.3 The UN Security Council

One hundred and ninety-three states have ratified the 1945 United Nations Charter and are consequently bound to accept Security Council decisions made under Chapter VII of that treaty. Chapter VII gives the Security Council the power to 'determine the existence of any threat to the peace, breach of the peace, or act of aggression' and to 'decide what measures shall be taken ... to maintain or restore international peace and security'. Such measures can include 'action by air, sea, or land forces', including within the territory of non-consenting states.[127]

[125] SMPAG, 'Planetary defence', op. cit. at 26.
[126] Ibid. at 59.
[127] Charter of the United Nations, 26 June 1945, Can TS 1945 No 7 (entered into force 24 October 1945).

For decades, the Security Council has taken a broad view of international security. It has invoked Chapter VII to impose an embargo on the racist government of Southern Rhodesia in 1968,[128] to deliver humanitarian aid in Somalia in 1992,[129] and to require measures against terrorist financing in all national legal systems in 2001.[130] In 2010, the Security Council invoked Chapter VII in response to an earthquake in Haiti, authorising the deployment of 680 police to augment the existing UN peacekeeping and humanitarian mission in that country.[131] There is no question that the Security Council could decide that an NEO was a threat to international peace and security and make decisions – such as authorising the use of an NED – that would otherwise violate international law. The Security Council could even provide the acting states with a waiver of liability for any resulting damage, liability that might otherwise flow from the 1967 Outer Space Treaty, the 1972 Liability Convention or customary international law.

The peremptory effect of Chapter VII resolutions comes from Article 103 of the UN Charter, which reads, 'In the event of a conflict between the obligations of the Members of the United Nations under the present Charter and their obligations under any other international agreement, their obligations under the present Charter shall prevail.' The only limiting factor here is that Security Council resolutions require the support of at least nine of its 15 members, including the concurring votes (or abstentions) of all five permanent members. In other words, China, France, Russia, the United Kingdom and the United States all hold vetoes over Security Council resolutions. In the literature on planetary defence, the veto is generally regarded as a bad thing, since it could prevent the Security Council from authorising necessary action. However, the veto can also serve as a check on precipitous or incautious action, such as a deflection mission that is not supported by a careful scientific assessment of the risks involved.

In any event, if Security Council decision making is blocked because of a veto, it is conceivable that one or more states might proceed with an unauthorised deflection mission.

[128] *Question Concerning the Situation in Southern Rhodesia*, SC Res 253, UNSCOR, 1428th mtg, UN Doc S/RES/253 (29 May 1968).
[129] SC Res 794, UNSCOR, 3145th mtg, UN Doc S/RES/794 (3 December 1992).
[130] SC Res 1373, UNSCOR, 4385th mtg, UN Doc S/RES/1373 (28 September 2001).
[131] SC Res 1927, UNSCOR, 6330th mtg, UN Doc S/RES/1927 (4 June 2010).

6.8.4 *Individual States*

The DART mission (discussed above) was led by NASA, with some participation from the European Space Agency and the Italian Space Agency.[132] Although there was no risk that the targeted moonlet would inadvertently be directed onto an Earth impact trajectory, it is noteworthy that the United States did not seek the consent of other states during the mission-planning process. It did consult with them, however, including by informing the SMPAG.

If an NEO is discovered on an actual Earth impact trajectory, one or more states might take it upon themselves to mount a deflection mission. Some experts have pointed to the right of self-defence, a rule of customary international law that is codified in Article 51 of the UN Charter, as providing a legal avenue for unilateral action. However, as Green correctly explains,

> Self-defense, conceptually, is focused on a defensive response to human-authored attacks or threats of attack, and exists as an exception to the *ad bellum* prohibition on the use of force. That prohibition is set out in Article 2(4) of the UN Charter, which outlaws 'the threat or use of force against the territorial integrity or political independence of any state . . . .' Forcible action against an asteroid or comet would not be directed 'against . . . any state,' but, instead, against a large space rock. This means that the prohibition of the use of force would not be breached by a planetary defense action. Resorting to self-defense therefore would amount to an attempt to employ an exception to a rule that would not be violated by the action undertaken.[133]

No rule of international law directly prohibits a unilateral deflection mission directed against an asteroid or comet. Rather, the legal issues concern the rights of other states to be consulted, not to be exposed to increased risk, and to obtain compensation in the event of an accident. There are other legal issues concerning the use of NEDs, concerning the role of the UN Security Council in this regard (and in relation to possible waivers of liability), and concerning the possibility that 'circumstances precluding wrongfulness' might excuse a breach of international law. We will delve deeper into some of these issues below.

The possibility of a unilateral deflection mission is real, given the panic and selfishness that can arise in crisis situations. Adding to the risk,

[132] Andrew F Cheng et al., 'AIDA DART asteroid deflection test: Planetary defense and science objectives' (2018) 157 *Planetary and Space Science* 104.

[133] Green, 'Planetary defense', op. cit. at 52–53.

militaries could insist on being involved in national decision making concerning an NEO threat, because of the scale of the threat, the kind of equipment that could be used – especially NEDs – and the fact that the political influence of militaries always exceeds that of Space agencies.

Militaries, however, are poorly suited for planetary defence. They tend to favour forceful actions over more subtle interventions such as diplomacy. In the context of planetary defence, they might favour kinetic impactors or NEDs over slow-moving mass drivers or gravity tractors. Militaries are not involved in current NEO detection and mission-planning exercises at the international level, notably IAWN and SMPAG, and therefore might not be fully informed on these matters – and more likely to make mistakes. Finally, militaries tend to co-operate with smaller circles of states than Space agencies, making them poorly suited for multilateral initiatives that include non-allies. There is a reason why the International Space Station, where Americans and Russians work side by side, is operated by civilian Space agencies rather than militaries.

Fortunately, even a unilateral military-led response to an NEO threat would be constrained by international law. First, any state planning a unilateral deflection mission would have to consult with other states. Article IX of the Outer Space Treaty reads, in part,

> States Parties to the Treaty shall be guided by the principle of co-operation and mutual assistance and shall conduct all their activities in outer space, including the moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty ... If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment.[134]

Consultation offers many benefits, one of which is an increased likelihood that careful scientific analyses of the risks of any proposed action will take place. Militaries acting unilaterally have done incautious things in the past in Space. For example, between 1961 and 1963, the US military launched 480 million copper needles into orbit, in an attempt

[134] Outer Space Treaty, op. cit., Art. IX.

to create an artificial ring around Earth for relaying radio signals.[135] Most of these needles have long since re-entered the atmosphere, driven by the effects of solar radiation, but clumps of them remain in orbit today – contributing to the serious and growing problem of Space debris. Consultation is critical in the context of an NEO threat since it might well lead to an initial rendezvous mission to determine the asteroid's precise orbit, shape and composition, and thus serve as the basis for a considered response.

In lieu of consulting other states and taking their interests into account, what would happen if a military decided to act unilaterally? What if the NED were launched without pooling scientific knowledge and mission capabilities with other states, and before carefully considering other methods? Does international law empower other states to prevent a powerful state from acting in this way? One possible step would be economic countermeasures, up to and including sanctions, especially if the acting state was a party to the 1963 Limited Test Ban Treaty (which, again, clearly prohibits the use of an NED).[136] However, economic countermeasures are unlikely to have any immediate effect on a powerful state that sees itself responding to a serious threat. A more interesting question concerns pre-emptive self-defence. If other states had scientific evidence that the unilateral deflection mission would increase the risk to their territory and populations, for instance by changing the impact location, could they take pre-emptive military action to prevent the launch?

This scenario, it should be noted, is fundamentally different from discussions of self-defence as a justification for deflection missions, as dismissed by Green at the beginning of this section. Here, the threat comes from another state interfering with the asteroid.

The existence and extent of a right of pre-emptive self-defence is hotly contested in international law, with the United States leading the push for a more expansive approach, and many smaller, less powerful states

[135] NASA Orbital Debris Program Office, 'West Ford needles: Where are they now?' (2013) 17:4 *Orbital Debris Quarterly* 3, online: orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv17i4.pdf.

[136] On countermeasures, see 'Draft Articles on the Responsibility of States for Internationally Wrongful Acts' in *Yearbook of the International Law Commission 2001*, vol. II, part 2 (New York: UN, 2007), Arts. 22, 49–54 (UN Doc A/CN.4/SER.A/2001/Add.1 (Part 2)), online: legal.un.org/ilc/publications/yearbooks/english/ilc_2001_v2_p2.pdf.

resisting its efforts.[137] We will not repeat that debate here. It is, however, readily conceivable that a state might claim pre-emptive self-defence in circumstances where it feels threatened by another state interfering with a natural force. Imagine if a state had reason to believe that another state was preparing to attack a hydroelectric dam upstream from a population centre. However, if a right of pre-emptive self-defence exists, and if it were invoked to justify military action to prevent the launch of an asteroid deflection mission by another state, that action would still be subject to the usual constraints imposed on self-defence under customary international law, namely that the response must be both 'necessary' and 'proportionate'.[138]

Although the issue of pre-emptive self-defence is interesting in this context, it is unlikely ever to arise. Militaries cannot simply launch their existing nuclear missiles against incoming NEOs, since ballistic missiles cannot achieve escape velocity. There will always be time to consult with other states, receive additional scientific input and engage in sober second thought. As this happens, international law will move to the forefront of the deliberation process, not least because of rules on state responsibility and liability, rules that would apply to any damage caused on Earth by a failed deflection mission.

6.9 State Responsibility

As the Ad-Hoc Working Group on Legal Issues explained, 'Any violation of an international obligation in the course of a planetary defence mission, such as the use of NEDs, entails the international responsibility of the States involved and may provide the basis for claims for compensation'.[139] 'State responsibility' is governed by rules of customary international law that were codified by the International Law Commission in its 2001 Draft Articles on State Responsibility, as commended to governments by the UN General Assembly later that

[137] For an overview of the pre-emptive self-defence debate, see Christine Gray, *International Law and the Use of Force*, 4th ed. (Oxford: Oxford University Press, 2018) at 248–253.

[138] The right of self-defence, including the criteria of necessity and proportionality, are discussed at length in Chapter 8 in the context of anti-satellite weapons.

[139] SMPAG, 'Planetary defence', op. cit. at 3.

same year.[140] The rules on 'circumstances precluding wrongfulness' are of primary interest in the context of planetary defence.

6.9.1 Circumstances Precluding Wrongfulness

Sometimes in the international realm, just as in the domestic, lawbreakers are excused for their actions because of the unusual circumstances they found themselves in. If a state chose to violate international law while engaging in planetary defence, for example by using an NED, it is possible that the violation would be excused because it took place under 'circumstances precluding wrongfulness'. The different circumstances that can preclude wrongfulness are identified in the International Law Commission's Draft Articles on State Responsibility, with 'consent' and 'necessity' being of greatest potential relevance here.[141] It is also important to note that, according to Article 27 of the Draft Articles, the invocation of a circumstance precluding wrongfulness does not relieve the acting state of any obligation to provide compensation for any material loss caused by the otherwise illegal act in question. In other words, being excused for the wrong does not relieve the state of any obligation to pay compensation.

6.9.1.1 Consent

Article 20 of the International Law Commission's Draft Articles on State Responsibility reads, 'Valid consent by a State to the commission of a given act by another State precludes the wrongfulness of that act in relation to the former State to the extent that the act remains within the limits of that consent.'[142] This means that, if a state facing an NEO threat consents to another state using a planetary defence method that violates international law, that act will no longer be wrongful as between those two states. As the Ad-Hoc Working Group explains, consent can either be expressed or implied, for example through the provision of support for the mission.

[140] 'Draft Articles on the Responsibility of States for Internationally Wrongful Acts', in *Responsibility of States for Internationally Wrongful Acts*, GA Res 56/83, UNGAOR, 56th Sess, 85th Plen Mtg, UN Doc A/RES/56/83 Annex (28 January 2002), online: undocs .org/en/A/RES/56/83.

[141] Ibid., Arts. 20, 25.

[142] Ibid., Art. 20.

This is not the end of the issue, however, since the international rule being violated will still apply between the acting state and third states, unless each of them has also consented. For this reason, the Ad-Hoc Working Group suggests that a UN General Assembly resolution could be used to express 'broad consent to a particular planetary defence mission'.[143]

6.9.1.2 Distress

The Ad-Hoc Working Group also identifies 'distress' as a condition precluding wrongfulness that might be relevant to planetary defence. Article 24 of the International Law Commission's Draft Articles on State Responsibility reads,

1. The wrongfulness of an act of a State not in conformity with an international obligation of that State is precluded if the author of the act in question has no other reasonable way, in a situation of distress, of saving the author's life or the lives of other persons entrusted to the author's care.
2. Paragraph 1 does not apply if: (a) the situation of distress is due, either alone or in combination with other factors, to the conduct of the State invoking it; or (b) the act in question is likely to create a comparable or greater peril.[144]

As the Ad-Hoc Working Group explains, 'Thus, in situations where the lives of persons are threatened by the possible impact of an NEO, the use of a planetary defence method in violation of international law could be justified if there is "*no other reasonable way*" of saving the lives'.[145]

It is questionable, however, whether distress would ever be a relevant circumstance precluding wrongfulness in the context of planetary defence. Distress is most often invoked when ships or aircraft are suddenly forced to enter another state's airspace or internal waters because of a storm or accident.[146] The discovery of an NEO threat is unlikely to require similarly sudden action, since spacecraft will have to be built and launched. For this reason, the opportunity to seek consent will almost

143 SMPAG, 'Planetary defence', op. cit. at 38.
144 'Draft Articles on the Responsibility of States', op. cit., Art. 24.
145 SMPAG, 'Planetary Defence', op. cit. at 38, SMPAG's emphasis.
146 International Law Commission, 'Draft Articles on Responsibility of States for Internationally Wrongful Acts, with Commentaries 2001' (2008) at 78–80, *United Nations*, online: legal.un.org/ilc/texts/instruments/english/commentaries/9_6_2001.pdf.

always be available. The more appropriate circumstance precluding wrongfulness for situations where the issue is not the time available to secure consent but rather the use of an illegal method, such as an NED, would seem to be necessity.

6.9.1.3 Necessity

Article 25(1) of the International Law Commission's Draft Articles on State Responsibility reads,

> Necessity may not be invoked by a State as a ground for precluding the wrongfulness of an act not in conformity with an international obligation of that State unless the act:
>
> a. Is the only way for the State to safeguard an essential interest against a grave and imminent peril; and
> b. Does not seriously impair an essential interest of the State or States towards which the obligation exists, or of the international community as a whole.[147]

As the Ad-Hoc Working Group notes, necessity as a ground for precluding wrongfulness was recognised by the International Court of Justice in the 1997 *Case Concerning the Gabčíkovo-Nagymaros Project*.[148] The dispute concerned Hungary's abandonment of a joint project to construct a dam and a series of locks on the river Danube, and the Slovak Republic's decision to proceed with its part of the project – the dam, located on its territory – regardless. Hungary argued that its decision to abandon the project was justified under the criteria for necessity, and particularly the existence of an 'imminent peril'. The ICJ disagreed, and Hungary was therefore not excused for violating the treaty that served as the legal basis for the joint project. The absence of an imminent peril provided Hungary with time to find another, legal way in which to safeguard its 'essential interest'.

Whether all the criteria have been met in the case of any NEO threat, including the existence of a grave and imminent peril and an essential interest, will depend on the specifics of the threat. Moreover, as the Ad-Hoc Working Group explains, the fulfilment of these criteria must be 'objectively established and not merely apprehended as possible'.[149]

[147] 'Draft Articles on the Responsibility of States', op. cit., Art. 25(1).
[148] *Gabčikovo-Nagymaros Project* (*Hungary* v. *Slovakia*) [1997] ICJ Reports 7 at 37, para. 51.
[149] SMPAG, 'Planetary defence', op. cit. at 39.

In other words, it is not sufficient for the acting state simply to believe that the criteria for necessity have been fulfilled. We should also note that circumstances precluding wrongfulness are generally considered after the fact, when there will be ample time to determine whether the criteria were actually met.

The Ad-Hoc Working Group identifies an example, again from the ICJ, of how the very survival of a state could constitute a situation of necessity. Asked by the UN General Assembly to provide an advisory opinion on the *Legality of the Threat or Use of Nuclear Weapons*, a split decision – ultimately determined by the casting vote of the court's president – saw the ICJ advise that it 'cannot conclude definitively whether the threat or use of nuclear weapons would be lawful or unlawful in an extreme circumstance of self-defence, in which the very survival of a State would be at stake'.[150] While recognising the very different context of this advisory opinion, the Ad-Hoc Working Group claims that the ICJ's failure to come to a clear conclusion 'can nevertheless support the argument that a use of planetary defence methods which is not in conformity with international obligations could be justified if it is, in extreme situations, the only way to safeguard the survival of a State or the entire planet'.[151] We disagree, because a judicial *lacuna* (failure to decide) does not provide support for anything. Each potential circumstance precluding wrongfulness must be assessed on its own facts, not on the basis of any precedent or, in the case of this advisory opinion of the ICJ, an absence thereof.

One might also ask whether necessity could justify the use of an NED as a first choice of deflection method rather than as a last resort, for example after kinetic impactors had failed to alter the asteroid's orbit sufficiently to prevent an Earth impact. What if an NED was the most likely method to give a successful outcome? Again, Draft Article 25(1)(a) specifies that the act must be '*the only way* for the State to safeguard an essential interest against a grave and imminent peril'.[152] In the 2017 table-top exercise undertaken at that year's Planetary Defense Conference on which the Ad-Hoc Working Group based their later legal analysis, several states (fictionally) decided to use an NED without UN Security Council authorisation and without having first attempted a kinetic deflection.

[150] *Legality of the Threat or Use of Nuclear Weapons*, Advisory Opinion, [1996] ICJ Rep 226 at 44.

[151] SMPAG, 'Planetary defence', op. cit. at 40.

[152] 'Draft Articles on the Responsibility of States', op. cit., Art. 25(1)(a), added emphasis.

Although the use of the NED proved successful in this hypothetical scenario, it was, in the circumstances, almost certainly illegal.

More realistically, an NEO threat might be identified too late for any deflection method other than an NED. Kinetic impactors will take time to build, and multiple impactors might be needed. Low-impulse methods would take even longer, unless (in the case of mass drivers) they are already deployed for Space mining purposes on asteroids that are dynamically accessible (i.e. from which a small Δv would be sufficient to redirect the spacecraft onto a rendezvous orbit), with a means – and sufficient fuel – for transporting them to the threatening asteroid. A gravity tractor might take even longer again, both to build and launch and to have the necessary, slowly accumulating effect on the asteroid's orbit. In the absence of any viable alternative, the use of an NED could, perhaps, meet the criteria of necessity.

Then there is Article 25(1)(b) of the International Law Commission's Draft Articles on State Responsibility, which specifies that necessity may only be invoked as a circumstance precluding wrongfulness if it does not 'seriously impair an essential interest of the State or States towards which the obligation exists, or of the international community as a whole'.[153] In other words, necessity cannot excuse an action, by one state, that causes serious harm to other states. On this, the Ad-Hoc Working Group wrote,

> it must be ensured that the deflection of the asteroid does not lead to an impact on other States and that no other serious dangers are caused to the international community as a whole, such as harm to the Earth or to the Earth and outer space environment through radioactive contamination or space debris.[154]

Given the uncertainties associated with asteroid deflection, we have to question the Ad-Hoc Working Group's addition of the words 'must be ensured' to this criterion. Clearly, the acting state must do *everything practicable* to ensure that the deflection mission does not 'seriously impair an essential interest', including by characterising the asteroid and precisely determining its orbit in advance of the deflection attempt. 'Everything practicable' will also include conducting the deflection in the least risky way by, for instance, using a gravity tractor if sufficient time is available and, if it is not, a kinetic impactor rather than an NED. But to read a higher standard of care into Article 25(1)(b) seems like a mistake.

153 Ibid. Art. 25(1)(b).
154 SMPAG, 'Planetary defence', op. cit. at 91.

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It may also be unnecessary, since the consequences on Earth of a Space-based action are subject to absolute liability under the Liability Convention. Absolute liability could be a powerful incentive for cautious, science-based action, as will be discussed below.

6.9.2 *States Are Responsible for Non-State Actors*

There is one important difference in the international law of state responsibility as it applies in Space as compared to elsewhere, and this concerns non-state actors. Generally speaking, the conduct of private actors is not attributable to a state under international law. But according to Article VI of the Outer Space Treaty,

> States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty. When activities are carried on in outer space, including the moon and other celestial bodies, by an international organization, responsibility for compliance with this Treaty shall be borne both by the international organization and by the States Parties to the Treaty participating in such organization.[155]

It is easy to imagine SpaceX mounting an asteroid-deflection mission if Elon Musk felt that national governments were moving too slowly or taking the wrong approach. But if SpaceX undertook such a mission, responsibility for complying with international law and providing compensation for any damage would rest with the US government, since SpaceX is incorporated in the United States. The same rule would apply, self-evidently, to the conduct of any private contractor taking part in a state-led mission. The point, however, is to ensure that national governments have a strong incentive to regulate private companies, and exercise strong oversight, because it is the governments that will carry the legal and financial burdens internationally if something goes wrong.

[155] Outer Space Treaty, op. cit., Art. VI.

6.10 Liability

A state is liable for damage caused by any Space object for which it is a 'launching state', with this term being defined in Article I(c) of the 1972 Convention on the International Liability for Damage Caused by Space Objects (Liability Convention) as meaning:

(i) A State which launches or procures the launching of a space object;
(ii) A State from whose territory or facility a space object is launched.[156]

It will be clear from this that an individual Space object can have several launching states.

Any deflection attempt against an asteroid or comet would take place beyond Earth orbit and necessarily entail the use of 'space objects', which the Outer Space Treaty makes clear is any object launched into Space.[157] As mentioned above, an ICBM would not suffice because such missiles do not achieve escape velocity.

As also mentioned, liability is based on 'fault' when the damage is inflicted on other Space objects. However, when the damage is inflicted on Earth, the liability is 'absolute', in that it exists even without wrongdoing. For this reason, a deflection mission that goes wrong – causing the asteroid to strike a different location, or perhaps fragmenting it and creating multiple large airbursts with a wider scope of destruction (in terms of the number of people killed or the amount of damage to infrastructure) – would entail liability for damage even if the damage was unforeseen or the result of an accident.

At the same time, the extent of liability takes on a potentially surreal dimension in the context of failed or only partially successful asteroid deflections. It is possible to imagine a state paying for damage on the scale of the Chelyabinsk airburst or even the Tunguska event. States have paid very large reparations in the past, for instance after losing a war in which they were the aggressor. But an asteroid large enough to justify a deflection attempt could cause damage on a scale that is beyond the financial ability of any state to compensate.

6.10.1 Liability for False Alarms?

Another liability issue identified by the Ad-Hoc Working Group concerns false alarms. A warning about an NEO threat could cause a government to

[156] Liability Convention, op. cit., Art. 1(c).
[157] Outer Space Treaty, op. cit., Arts. VII–VIII, X.

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launch a deflection mission or evacuate a city or region. Is anyone legally responsible for the associated expenses and disruptions if the warning proves to be a false alarm? But while this question is interesting, it is only of limited relevance, since the astronomical community quickly verifies or disproves any newly identified NEO threat, thus reducing the time during which an alarm which turns out to be false is perceived to be real enough to entail unnecessary expenses or disruptions.

For more than three decades, Brian Marsden directed the Central Bureau for Astronomical Telegrams, the body created by the International Astronomical Union to serve as an international clearing house for information on transient astronomical events. In 1992, Marsden warned of a possible Earth impact from Comet Swift Tuttle in 2126.[158] This would have been an extinction-level event, because Swift Tuttle has a nucleus with a diameter of about 26 kilometres, making it the largest object in the Solar System that repeatedly passes close to Earth, doing so with a relative velocity of about 60 kilometres per second. Fortunately, information obtained from historical Chinese reports in 69 BCE and 188 CE, combined with further observations, enabled the astronomical community to rapidly determine that there is, in fact, no impact risk from Comet Swift Tuttle for the next two millennia.[159]

In 1998, Marsden issued another warning that also turned out to be a false alarm, this time concerning a possible impact with the asteroid 1997 XF_{11} in 2028. The warning caused a media frenzy, partly because it was issued by press release rather than circulated within the astronomical community, and partly because 1997 XF_{11} has a diameter of approximately one kilometre. Fortunately, it took less than a day for other astronomers to resolve the asteroid's orbit with greater precision, after one of them found an eight-year-old image of the same asteroid. It will indeed pass by Earth in 2028, but at about 2.4 lunar distances (930,000 kilometres) from us.[160]

These false alarms demonstrated how quickly the astronomical community reacts to possible Earth impacts, by providing new data and analysis and almost immediately verifying or disproving the existence of a threat. The cost of a false alarm is therefore quite limited, while the

[158] Brian G Marsden, 'International Astronomical Union Circular, 5536: 1992t' (15 October 1992), *Central Bureau for Astronomical Telegrams*, online: www.cbat.eps.harvard.edu/iauc/05600/05636.html.

[159] John Maddox, 'Comfort for next century but one' (1994) 367:6465 *Nature* 681.

[160] Tony Reichhardt, 'Asteroid watchers debate false alarm' (1998) 392:6673 *Nature* 215.

benefit of an early warning of an actual strike – i.e. more time in which to act – would be preserved.

In any case, as the Ad-Hoc Working Group points out, the issue of liability for false alarms does not fall within the scope of the Outer Space Treaty or the Liability Convention, since there is no 'space object' – in the legal sense of a human-made spacecraft or parts thereof – involved here. Rather, the issue is governed by the general rules of international law on state responsibility and liability, at least in cases where the warning has been issued by a state, including a national Space agency, or experts acting on behalf of a group of states or Space agencies, as with IAWN. These rules involve fault-based rather than strict liability, leading the Ad-Hoc Working Group to conclude,

> NEO threat warnings may be treated similar to warnings regarding the likelihood of (other) natural disasters, tsunami warnings serving as a potential analogy. As long as States do not willingly or in a grossly negligent manner provide false data, it will be difficult to hold them internationally responsible or liable, it being understood however that any concrete legal appraisal depends on the context and circumstances and no general rule or conclusion can therefore be established.[161]

But if states and Space agencies are protected, what about false alarms issued by non-governmental organisations? Brian Marsden, for example, worked for a non-governmental organisation, namely the International Astronomical Union. Many other astronomers work for universities, some of them private. What about amateur astronomers, hundreds of whom are actively and very ably involved in NEO detection?

International law principally applies among nation states. As a result, the question of liability for false alarms issued by non-state groups and individuals is one of national law, which varies from state to state. The good news is that liability in most national legal systems is fault-based, and as a result a warning issued in good faith will not generate liability. Just as importantly, a warning issued by a reputable non-governmental organisation or amateur astronomer will attract the attention of the astronomical community almost as fast as a warning issued by a state, meaning that new data and analysis will be brought to bear quickly – before a false alarm can result in unnecessary expenses or disruptions. For all these reasons, liability for false alarms is not much of an issue. Astronomers, it turns out, have each other's backs.

161 SMPAG, 'Planetary defence', op. cit. at 54.

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6.11 Developing Capabilities for Planetary Defence

Effective planetary defence demands a wide range of capabilities, from improved NEO detection, characterisation and orbit resolution to the development of safe and effective technologies for use in deflections. All these things require international co-operation, with telescopes located around the planet, as well as redundant detection and deflection capabilities in the event that equipment fails – or that the commitment or decision-making capability of a leading state falters. The ways in which different states can contribute to planetary defence will vary greatly, but clearly it is necessary to have an internationally organised, well-tested, widely accepted system for NEO detection and threat response.

More Space-based NEO detection telescopes are needed, including from countries other than the United States. In 2013, Canada launched the Near Earth Object Surveillance Satellite (NEOSSat), equipped with a 15-centimetre telescope especially designed to detect NEOs approaching from the direction of the Sun. Unfortunately, NEOSSat was launched prematurely, without the 'fine-pointing' software module required to fulfil its primary mission, and while subsequent efforts to upload software fixes reduced the problem, they did not fully solve it.[162] Canada has not replaced NEOSSat, even though it cost only CA$25 million to build and launch.

Developing mission-ready planetary defence assets should also be a priority. It would be relatively easy for a consortium of states, companies, universities or private foundations to provide a set of low-cost but still reliable flyby spacecraft with interchangeable instrumentation and rapid launch capabilities, and to test them by conducting flybys of non-hazardous NEOs. Particularly dangerous asteroids could be tagged in some way, or have small spacecraft stationed around them, to enable long-term monitoring of their orbital evolutions. Information gained in this way would also contribute greatly to scientific knowledge of asteroid behaviour and therefore planetary defence in general. Finally, a widely accepted decision-making protocol on NEO threats is needed, in the form of either a soft law declaration, a binding treaty or a UN Security Council resolution. Such a protocol might require that any deflection effort (1) be based on science and respect the precautionary principle, (2)

[162] Canadian Space Agency, 'Evaluation of the Near Earth Object Surveillance Satellite (NEOSSat) project' (February 2014), *Government of Canada*, online: https://open.canada.ca/data/en/dataset/dd76f7c5-42e7-4b8e-846b-0a227150ad7b.

employ the safest technology possible in the time frame available, (3) be led by national Space agencies rather than militaries and (4) be multilaterally rather than unilaterally organised and implemented.

6.12 Precautionary Planetary Defence

So far, we have been discussing different interventions that could be attempted if an asteroid were about to strike Earth. In this section, we discuss interventions with asteroids that are not on immediately dangerous trajectories. In particular, we consider two possibilities: (1) limiting missions to an asteroid due to the risk of creating a human-caused Earth impact, and (2) actively managing asteroids to place them in 'safe harbours', even when impact risks are otherwise below 'decision-to-act' thresholds. We use Apophis as a case study for illustrative purposes and address the two possibilities in turn.

Apophis will pass within approximately 38,010 kilometres of Earth's centre (the 'geocentre') in 2029,[163] bringing it momentarily about as close as communications and Earth observation satellites in geosynchronous orbit. The 'near miss' will present rare science opportunities for studying how very close encounters can both alter the way in which asteroids spin and lead to changes in their surfaces. It may even create opportunities for probing the asteroid's interior structure.

But the rarity, at least as measured in human lifetimes, does not lie in Apophis's close approach alone. Close approaches have been observed before, including the even closer flyby of the 30-metre asteroid 367943 Duende (2012 DA14) in 2013.[164] Rather, it is the size of Apophis (about 340 metres in diameter) that makes this particular approach so interesting. Indeed, portions of the world's population will be able to see Apophis with the unaided eye, appearing like a bright satellite moving across the sky. We can therefore expect that governments and scientists will engage in considerable outreach before the event, both as an educational opportunity and as a pre-emptive move against inaccurate reporting and public anxiety.

[163] See Apophis close approach tables: Jet Propulsion Laboratory, 'Small-body database lookup – 99942 Apophis (2004 MN4)' (29 June 2021), *NASA*, online: ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=Apophis.

[164] Tony Greicius, 'Asteroid 2012 DA14 – Earth flyby reality check' (15 February 2013), *NASA*, online: www.nasa.gov/topics/solarsystem/features/asteroidflyby.html.

The science potential associated with Apophis's close approach is currently motivating many different teams to propose a variety of missions,[165] including rendezvous and flybys, with some proposed missions being primarily technology demonstrations rather than research efforts. All are potentially problematic because Apophis's B-plane for the 2029 encounter (recall the discussion above) has multiple 'keyholes'[166] – as shown in Figure 6.8.

The curve in Figure 6.8 is generated by taking Apophis's nominal (best-fit) orbit and perturbing (nudging) it along and against its orbit using systematically increasing Δv's.[167] This is done to explore the parameter space of the encounter. The reported minimum distance in the figure (y axis), given in Earth radii, is the closest approach distance that Apophis would have with Earth in the next 100 years following the 2029 flyby if it were to go through the given B-plane location. The minimum distances are shown with respect to the ζ co-ordinate of the B-plane (Figure 6.5 above), with $\Delta\zeta$ representing the deviation relative to the nominal orbit.

The keyholes are those areas on a B-plane where, were an asteroid to pass through one during a given flyby, its orbit would evolve in such a manner that it would hit Earth on a subsequent encounter. Different keyholes are associated with different impact dates, and while the specific locations of keyholes are intricately connected to the dynamics of the asteroid, the existence of keyholes is a general property of any close encounter.

For impact hazard assessment, the immediate priority is to rule out an impact during the encounter in question. Once it is determined that the asteroid will pass safely by Earth, attention can turn to the much more

165 For example, see the T-9 Apophis workshop program conference abstracts at Lunar and Planetary Institute, 'Apophis T-9 Years: Knowledge opportunities for the science of planetary defense' (virtual, November 2020), *Universities Space Research Association (USRA)*, online: www.hou.usra.edu/meetings/apophis2020.

166 Davide Farnocchia, Steven R Chesley, Paul W Chodas, M Micheli, DJ Tholen, A Milani, GT Elliott and F Bernardi, 'Yarkovsky-driven impact risk analysis for asteroid (99942) Apophis' (2013) 224:1 *Icarus* 192.

167 Simulations were run using a modified version of Rebound/X. See Hanno Rein and David S Spiegel, 'IAS15: A fast, adaptive, high-order integrator for gravitational dynamics, accurate to machine precision over a billion orbits' (2015) 446:2 *Monthly Notices of the Royal Astronomical Society* 1424; This included GR, Earth's J2 and J4 components, and perturbations from the list of asteroids given in Farnocchia et al., op. cit. The initial conditions for Apophis are the Horizons orbit solution ref. JPL211, epoch 2021-April-7.0.

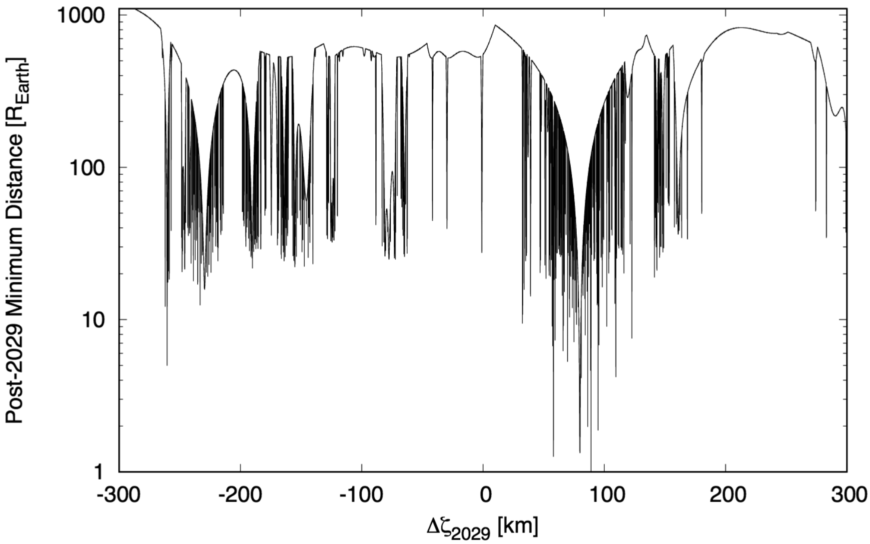

Figure 6.8 Keyhole map for the 2029 flyby of Apophis. The *x* axis shows the change in the ζ co-ordinate on the B-plane, relative to the location of the nominal orbit. The *y* axis shows the closest to Earth that Apophis would come after the 2029 encounter for the next 100 years upon passing through the noted location on the B-plane. The downward spikes represent the orbital structure. Spikes that get within about 10 per cent of Earth's radius will collide with Earth in that 100-year timeframe, depending on the amount of gravitational focusing (which draws the asteroid even closer to the planet). The broad downward dip with multiple spikes is an example of a 'keyhole complex', where there is the potential for multiple keyholes to reside. To a very high degree of certainty, the orbit of Apophis will not pass through a keyhole in 2029.

difficult task of ruling out keyhole passages. Indeed, it was not until 2021 that a keyhole passage by Apophis in 2029 was ruled out, using ground-based radar measurements.[168]

But even with such a reassurance, we still need to ask: to what degree are missions to the asteroid wise, if even a small perturbation could knock the asteroid into a keyhole? For if a mission to an asteroid like Apophis, with a rich set of keyholes, goes awry and the spacecraft unintentionally collides with the asteroid, there is a risk (albeit a low-probability one) that

[168] Ian J O'Neill and Joshua Handel, 'NASA analysis: Earth is safe from asteroid Apophis for 100-plus years' (26 March 2021), *NASA*, online: www.nasa.gov/feature/jpl/nasa-analysis-earth-is-safe-from-asteroid-apophis-for-100-plus-years.

this will create a future impact emergency.[169] Of course, one could just as easily knock the asteroid away from a keyhole. The point, however, is that the result is uncertain. For this reason, if we know the asteroid is on a safe orbit, any uncontrolled alteration – and any possibility of an uncontrolled alteration – involves an unnecessary gamble.

The perturbation required to knock an asteroid into a keyhole will depend on multiple factors, including the distance between the actual B-plane intersection and the location of the keyhole on that plane. As discussed above, the lead time of the perturbation and the strength of the Δv are all critical details. Some asteroids are safer to 'play' with than others. Fortunately for us, Apophis, as best as we can tell, is a relatively safe one.

Other asteroids will not be so safe. Although well-co-ordinated missions to riskier asteroids could be conducted safely and, from a planetary defence point of view might in fact *need* to be conducted, the prospects of competition between actors could result in a relaxation of the necessary stringent caution. Moreover, the publicity associated with very close approaches, like that already starting for Apophis, could prompt non-state actors to launch their own missions – as technology demonstrations or profile-raising exercises, much like the infamous launch of a Tesla car by SpaceX in 2018.

Applying the precautionary principle and exercising restraint might be the best policy in these cases. This would by no means preclude missions to asteroids such as Apophis,[170] but it would demand a high level of co-ordination among all Space actors, including governments, industry and other non-governmental entities. It would also require that some missions be modified and, in extreme cases, severely limited – notwithstanding the scientific or technology demonstration benefits that might otherwise be obtained. This leads us to ask, who should make such decisions?

As discussed above, SMPAG does not have decision-making authority. Not even SMPAG members themselves require permission from the group to carry out a mission. Rather, national governments make the

[169] S Chesley and D Farnocchia, 'Apophis impact hazard assessment and sensitivity to spacecraft contact' (paper delivered at the Apophis T-9 Years workshop, virtual, November 2020), Lunar and Planetary Institute Contrib No 2242, *USRA*, online: www.hou.usra.edu/meetings/apophis2020/pdf/2049.pdf.

[170] Again, Apophis itself appears to be in a reasonably safe-for-Earth position on the B-plane.

decision whether to proceed with a mission, either on their own or in co-operation with others. But while SMPAG lacks decision-making authority, it serves – much like the International Space Station – as a focus for co-operation among spacefaring states. It is therefore an appropriate venue for sharing information about planned missions to asteroids and having those plans and the associated scientific assessments vetted by experts from other states. If that process reveals the need for limitations on a particular mission, and the launch state is reluctant to change its plans, the usual range of diplomatic pressures and incentives could be deployed (as they are daily among states on thousands of other issues).

A completely new dimension to decision making comes with NewSpace, an era defined by the growing reach and influence of Space companies, with some private actors expected to possess advanced exploration capabilities well before 2029. In 2019, SpaceIL became the first non-state entity to place a spacecraft on the Moon, albeit via a hard landing. SpaceX is already flight-testing Starship, a reusable spacecraft for Earth orbit, the Moon and Mars. Multiple tourism ventures are under way, with trips to the ISS occurring already and trips around the Moon likely to occur soon. One or more of these increasingly capable private Space actors may wish to use Apophis or other asteroids for their own purposes. The prospect of eventual asteroid mining adds yet another dimension, as this could be a benefit or a risk to planetary defence, depending on the degree to which companies share information (some of which they may consider proprietary) and guard against the risk of knocking an asteroid into an Earth impact orbit.

Although the Outer Space Treaty makes the 'launching state' responsible for the actions of non-state actors, such actors might have different approaches to scientific uncertainty and risk. They might not engage, or be required to engage, in the same level of co-ordination as national Space agencies do through SMPAG. Nor are all national regulatory frameworks necessarily prepared for a much higher level of commercial Space activity. For these reasons, national regulators should be strongly encouraged to take planetary defence considerations into account when issuing launch licences to non-state actors, including adopting practices that require both the non-state actor and the regulator to consult with IAWN and SMPAG. This approach could be encouraged and bolstered by a United Nations General Assembly resolution on planetary defence, which could, among other things, recommend that any state planning or licensing an asteroid mission consult with SMPAG and satisfy any concerns they might have.

Having made the case for restraint, we can also ask whether the purposeful redirection of asteroid orbits might sometimes be warranted even when the asteroid does not pose a clear impact risk. Such active management or ‘shepherding’ would ideally be conducted with a gravity tractor to ensure minimal interference with the asteroid. This possibility was explored in the context of Apophis when there was still some worry that it might pass through a 2029 keyhole.[171] One of the ideas addressed in that research was the so-called ‘safe harbour’ for an asteroid, i.e. placing it on an orbit that precludes it entering a keyhole. Building on this idea, we might ask whether there is an accessible orbit that not only misses keyholes but also minimises the long-term risk posed by a given asteroid. Put differently, any harbour will do in a storm, but if we have fair weather, what harbour should we pick?

Again, Figure 6.8 illustrates some of the dynamical complexities involved in understanding the long-term risk posed by an asteroid. From this keyhole map we can see that Apophis is close to a downward spike in the minimum-distance profile (corresponding to the year 2116 encounter), potentially dropping below a 30 Earth radii minimum distance. Importantly, it is not an impact keyhole, so the location is safe despite the potential for a future close encounter. At slightly higher ζ, Apophis can be kept farther from Earth over the next 100 years than at its current nominal location. However, such a change would place the asteroid closer to a keyhole complex. At lower ζ, a small ‘hill’ exists that is free from close encounters and known keyholes.

If you could choose, where would you want Apophis to pass on the B-plane? Which is the safest harbour?

One could argue against moving Apophis to higher ζ on the ground that this is closer to a keyhole. A response to this concern might be that a rendezvous with a gravity tractor should enable a precise orbit to be determined, in which case the shepherding could always be reassessed. This might include aborting the mission if the orbital uncertainty remains too high. Moving to lower ζ does not raise the same concern, though it also does not lead to a much better situation than the current orbit. Perhaps more interesting, one might question whether some of the downward spikes (not keyholes) could be used to help keep track of the

171 D Yeomans, S Bhaskaran, SB Broschart, SR Chesley, PW Chodas, TH Sweetser and R Schweickart, ‘Deflecting a hazardous near-Earth object’ (paper delivered at the 1st IAA Planetary Defense Conference, Granada, Spain, 27–30 April 2009), *NASA*, online: cneos .jpl.nasa.gov/doc/PDC_proceedings_062009.pdf.

asteroid, ensuring that it has a regular close but safe approach to Earth. Finally, we might further re-pose the question by imagining what our reaction would be if Apophis were in a narrow, safe region within the keyhole complex at, for example, $\Delta\zeta_{2029} = 75$ km. Would this motivate deflection to lower ζ to find a safer harbour?

Two things are clear. If we have the means to safely decrease the long-term risk of an asteroid strike, then we should at least consider doing so. And if we do not have the means to safely decrease the long-term risk, the asteroid should be left alone.

Despite raising these intentionally provocative questions, we acknowledge that the precautionary principle could support an argument against any active management because such an approach might create new risks. For example, if a failure happened while using a gravity tractor, a given asteroid could be dropped into a keyhole.[172] It is also possible that there are as yet unknown risks that we do not therefore understand. For these reasons, any decision to actively manage an asteroid into a safe harbour should only be taken after peer-reviewed scientific assessment, full international collaboration and broad agreement.

A detailed model for a gravity tractor has been developed by others, with Apophis deflection scenarios shown to be feasible with a 1,000-kilogram spacecraft.[173] We note that SpaceX's Starship is about 100 tonnes empty, and that it is fully automated and reusable. Designed to transport and land cargo and people on the Moon and Mars, a version of Starship could be reconfigured as a highly effective and reusable gravity tractor. The Starship HLS, the version designed for lunar landings with high-thrust oxygen- and methane-fuelled thrusters located mid-body, might be a good place to start.

'The dinosaurs did not have a Space program' is an oft-used phrase in planetary defence. Woodpeckers, eagles and other birds are proof that a few species of dinosaurs survived. And yet the direction of life on Earth was radically changed when, without astronomy, rockets and worldwide co-ordination, their ancestors were unable to ward off the tremendous energy locked into asteroids.

172 Ibid.
173 Ibid.