ARTICLE IN PRESS

Space Policy xxx (xxxx) xxx

Contents lists available at ScienceDirect

Space Policy

journal homepage: www.elsevier.com/locate/spacepol

The Worst Case: Planetary Defense against a Doomsday Impactor

Joel Marks [1]

Interdisciplinary Center for Bioethics, Yale University, PO Box 208293, New Haven, CT 06520-8293, USA

ARTICLE INFO

Article history:
Received 29 September 2021
Received in revised form
7 March 2022
Accepted 5 May 2022
Available online xxx

Keywords:
Planetary defense
Comet
Asteroid
NEO
Risk
Risk reduction
Probability
Existential risk
Extinction
Nuclear weapon
NED
WMD
National defense
Cost-benefit analysis
NASA

ABSTRACT

Current planetary defense policy prioritizes a probability assessment of risk of Earth impact by an asteroid or a comet in the planning of detection and mitigation strategies and in setting the levels of urgency and budgeting to operationalize them. The result has been a focus on asteroids of Tunguska size, which could destroy a city or a region, since this is the most likely sort of object we would need to defend against. However a complete risk assessment would consider not only the probability of an impact but also the magnitude of its consequences, which in the case of an object of Chicxulub size could be the end of civilization or even human extinction. This paper argues that a planetary defense policy based on a complete (or one could say genuine) risk assessment would justify expenditures much higher than at present.

1. Introduction

Current planetary defense policy prioritizes a probability assessment of risk of Earth impact by an asteroid or a comet in the planning of detection and mitigation strategies and in setting the levels of urgency and budgeting to operationalize them. The result has been a focus on asteroids of Tunguska size,[2] which could destroy a city or a region, since this is the most likely sort of object we would need to defend against. However a complete risk assessment would consider not only the probability of an impact but also the magnitude of its consequences, which in the case of an object of Chicxulub[3] size could be the end of civilization or even human extinction. This paper argues that a planetary defense policy based on a complete (or one could say genuine) risk assessment would justify expenditures much higher than at present.

Let me clarify at the outset that when I speak of "policy" I have in mind *de facto* policy and not just *de jure* policy. *De jure* planetary defense policy typically does make explicit reference to both aspects of risk: probability and consequences.[4] A different way of putting my main claim, therefore, is that the implementation of current planetary defense policy is at odds with its explicit rationale.

I also note that the analysis I will present is not intended to extend to extinction impactors of indefinitely large size. Lubin and Cohen [1] state that "above 40 km diameter, there is not sufficient explosive energy in the entire world's current nuclear arsenal to even gravitationally de-bind the bolide." Unfortunately there likely are potential impactors in our solar system even in excess of this size,[5] and we now know that the galaxy is rife with interstellar objects,

E-mail address: jmarks@newhaven.edu.
URL: http://www.docsoc.com

[1] Permanent address: Professor Emeritus of Philosophy, University of New Haven.

[2] This refers to the largest impact event (an airburst) in recorded history, which took place in 1908 near the Tunguska River in Siberia. The object involved is estimated to have been c. 60 m in size.

[3] This refers to an impact event 66 million years ago centered on the current Chicxulub Pueblo municipality in the Yucatan, which is correlated with a global mass extinction, including of the non-avian dinosaurs. The object involved is estimated to have been c. 10 km in size.

[4] I thank an anonymous reviewer for highlighting this point.

[5] I thank an anonymous reviewer for drawing my attention to this point.

https://doi.org/10.1016/j.spacepol.2022.101493
0265-9646/

including rogue planets. These bring to mind the scenario of Edwin Balmer and Philip Wylie's science-fiction classic, *When Worlds Collide* [2]; and we do not have a Star Wars Death Star available to defend ourselves. But, Lubin and Cohen argue, an impactor of 10 km, the inferred size of the Chicxulub impactor, could be successfully defended against with current technology even at short notice, "if we prepare ahead." Accordingly I limit my analysis to the same size. Thus, the policy I propose is intended to be reasonable in terms of technological feasibility. The question I specifically address is whether it is reasonable *tout court* to "prepare ahead."

2. Current policy

The possibility of catastrophe from collision with an extraterrestrial body has a long history in human consciousness,[6] but the idea that we might prevent such a catastrophe is very recent.[7] The earliest instance I know of is a remarkably prescient episode of the TV program *Adventures of Superman*,[8] aired on December 5, 1953, in which the man of steel first deflects and then, armed with a nuclear device, destroys an incoming asteroid the size of the Chicxulub object. But it was only 27 years later, with the publication of the Alvarez hypothesis [5], that the reality of possible human extinction by collision with such an object hit home and sparked a sense that we ought to and actually could do something about it. In impressively short order there were planning workshops, a Congressional mandate, and, spurred on further by the July 1994 collision with Jupiter of Comet Shoemaker-Levy 9, the carrying out of the remarkable Spaceguard Survey to find 90% of the near-Earth objects (NEOs) larger than 1 km.[9] In the minds of many the failure to find any large NEO on a trajectory to strike Earth for at least the next century put to rest the idea that we were in any imminent danger of the ultimate calamity from that quarter.

Current planetary defense policy therefore presumes that we have a serendipitous window of opportunity to develop the needed technology and infrastructure to tackle a Chicxulub-size impactor. And in the meantime an acute awareness has arisen of the remaining hazard from smaller objects, large enough to wipe out a city or a region, but far more amenable to mitigation[10] by near-term technology and resources. Objects of Tunguska size and up whose orbits approach that of the Earth are estimated to number over one million [7]. To date we have discovered and are tracking approximately 25,000 of them [8]. The rest await the observing prowess of the NEO Surveyor infrared space telescope and the Vera C. Rubin Observatory in Chile among others, as well as further development of sophisticated tools of analysis, such as the B612 Asteroid Institute's Asteroid Discovery, Analysis, and Mapping (ADAM) platform [9]. Within the next couple of decades we can expect these combined resources and initiatives to have made a significant dent in the population of known unknowns. Furthermore the technology to deflect the smaller objects, should one be found to be heading our way, is soon (as I write) to receive its first proof of concept with the launching of the DART (Double Asteroid Redirection Test) mission.

All in all, then, things are looking pretty good for planetary defense. In a mere handful of decades humanity has gone from blissful ignorance of a celestial sword of Damocles dangling over our collective head to being well on the way to building an impenetrable canopy to protect us should the cosmic horse hair break. At present the policy is to focus on the detection of an ever-larger number of potentially threatening objects, for obviously you can't target an object for mitigation that you don't see. And the longer the lead time one has until a predicted collision, the more time there is to implement the mitigation and thus increase the likelihood of success. This is why planetary scientist Don Yeomans [10] famously proclaimed that planetary defense has three imperatives: "find them early, find them early, and … find them early" (p. 139). According to Lindley Johnson (personal communication, August 26, 2021), Planetary Defense Officer at NASA, Yeomans' dictum excellently encapsulates current U.S. strategy. He expands:

> Our strategy at NASA's Planetary Defense Coordination Office, and that has now be[en] incorporated into the National NEO Preparedness Strategy and Action Plan [11], is to find any hazardous NEO well enough forward in time – before it could present a true impact threat – that we would have sufficient time to deal with it by whatever means space technology at that time allows us.

3. Critique

As much as I am impressed, indeed awed, by this story of progress, I cannot take solace in the current policy, for it presumes no near-term hazard from an extinction-size impactor. I have heard several individuals in positions of knowledge and authority say that they do not lose sleep at night over the prospect of impact apocalypse, considering it unlikely to the point of almost zero probability in any given year. I, on the other hand, live with this as a waking nightmare. Is it just me – a personal sensibility conditioned by too many catastrophe movies[11] – or do my fears have a rational basis? As a philosopher,[12] who considers not individual probabilities but the nature of probability itself, I offer the following reflections.[13]

3.1. The facts

To begin with, everyone involved with planetary defense agrees about the facts. These facts include the following:

1. Sooner or later an extinction-size object is almost certain to collide with Earth if we don't stop it.
2. It is unpredictable when the next such object will come close enough to be detected. The apparition could be today; it could be one million years from now.

[6] Scientific acceptance was long in coming, however, with popular accounts relegated to myth and superstition, and the hypothesis of catastrophism generally frowned upon [3].

[7] Science fiction has certainly recognized the hazard, but the remedies to fictional threats have tended to be ameliorative rather than eliminative, such as getting out of the way [4], which we recognize even today as the civil defense response, or emigrating to another planet [2], which has taken on new life among some environmental catastrophists (witness the 2014 movie *Interstellar*).

[8] Season 2, Episode 12, "Panic in the Sky."

[9] Chapman [6] provides an excellent history of the first two decades of planetary defense. To my knowledge a comparably detailed and insider history of the second two decades has yet to be written and must be pieced together from numerous sources.

[10] Strictly speaking "mitigation" means to lessen the severity of something, but for better or worse it has become the accepted term for rendering a potential impactor harmless by means of deflection or fragmentation. However the term also encompasses civil defense efforts both before and after an unsuccessful mitigation of that sort, as well as precautionary efforts where such mitigation, or even the need for it, is uncertain.

[11] And certainly there are legitimate concerns about the need to avoid misleading exaggerations of the impact hazard in communication by experts with the public and media [12]. However, while I recognize the hyping about known NEOs, I am afraid I fall into the camp of those who see real cause for urgent concern about the unknown ones.

[12] I am primarily what is called an analytic philosopher, which means that I will take a critical look at the logic of arguments and the meaning of concepts, rather than offer answers to the perennial questions.

[13] I know of two other philosophers who have given serious consideration to the impact hazard: Toby Ord [[13] (pp. 67–73, 316-20)], and Peter Singer [[14] (ch. 15)]. Interestingly they take the opposing positions I highlight in this paper, Ord concluding that the risk is low and Singer that it is high.

3. An object the size of the Chicxulub asteroid (or comet) would not be detectable by feasible means until it is approximately as close to the Sun as the orbit of Jupiter.
4. Such an object might well traverse the distance to Earth in less than a year. [10] (p. 19)
5. Implementing an intercept mission from scratch, not to mention with adequate testing, reconnaissance, and redundancy, would require far longer than that [15] [16 (Table 5.1)], [17].
6. The only mature technology available to deflect or destroy such an object is nuclear [16] (Finding, p. 79), [18].

Given this set of facts, it seems fair to say that making anything less than the maximal feasible effort to assure a ready response, including launch-ready or prepositioned NEDs (nuclear explosive devices), is to gamble with the survival of our species or civilization.[14] But life is always a gamble, and also presents us with competing gambles; so rationality dictates that we choose and prioritize our gambles wisely. In order to decide what would constitute a rational planetary defense effort to forestall a large impact, therefore, we must consider the actual costs and risks involved, including any ramifications for other priorities.

3.2. Nuclear explosive devices

The most obvious attendant risk from the effort to reduce the risk of the next Chicxulub would arise from reliance on NEDs, for, given the history and unpredictability of political relations among nuclear-armed nations, their very existence is a global hazard in its own right. Although one might argue that our having survived the Cold War is testimony to the effectiveness of the nuclear taboo, the liability to accidental not to mention intentional nuclear Armageddon remains a stark reality to this day [19,20]. Indeed, current planetary defense policy could be largely a reflection of this perception and reality, for the focus on smaller objects would be dictated by an aversion to the use of NEDs even aside from the consideration that smaller objects are more frequent impactors than larger ones.[15]

Meanwhile the general nuclear disarmament movement proceeds apace, as evidenced by the going into effect this very year (2021) of a United Nations treaty that bans even the stockpiling of NEDs (by the signatories).[16] Given that the United Nations Committee on the Peaceful Uses of Outer Space has endorsed “the global challenge posed by NEOs, beginning with their detection and tracking and, subsequently, deflection and planetary defence” [[22] (p. 3)], it seems clear that the policy I characterized above as the current one has been adopted by this world body *de facto*, since, as noted in §3.1 above, a nuclear-free world would in present likely circumstances be powerless to defend against a Chicxulub-size impactor.

But are we then content to remain vulnerable to an ultimate catastrophe we have the potential to prevent? Those who counsel against reliance on NEDs typically offer two complementary arguments. One is that the probability of a threat requiring such a response in the near-term is so small as to be virtually non-existent.[17] The other is that, given this lack of urgency, there is ample time for humanity to develop an alternative technology that would protect us from a large impactor without posing a comparable risk of its own.[18] I find both arguments wanting. Let me respond to the second argument first.

As was pointed out in the early days of planetary defense by Sagan and Ostro [25], “Any method that can be devised to destroy or deflect an approaching large near-Earth object can be used, on a much shorter time scale, to do great damage to the global environment” (p. 70). Although they specifically had in mind perverting a deflection technology into an impactor technology by directing an object toward instead of away from Earth, the point is perfectly general and would apply as well to the risk of nuclear war posed by the very existence of a nuclear arsenal (See Harris et al. [26]), or similarly any other weapon of mass destruction (WMD) whose overt purpose was planetary defense. Any such technology would seem potentially to be dual-use.

Furthermore, even without WMDs as part of the planetary defense apparatus, there will always be the risk of a global confrontation spurred on by a deflection (or fragmentation) scenario. As Schweickart [27] has pointed out,

> … in the process of deflecting an asteroid bound for a collision with the Earth, there are substantial legal, political, social, economic, and even military concerns that are introduced. These issues arise independent of the specific deflection techniques proposed. This “real” dilemma arises in that otherwise uninvolved people and property across international boundaries will be put at risk during an asteroid deflection mission.

Thus for example one could imagine that the plan of the United States to deflect an asteroid targeting the homeland would shift the impact point to Moscow *en route* to its passing off the edge of the Earth. Russia would not take kindly to this and might well threaten retaliation or even enact pre-emption, which could itself lead to global catastrophe.

In sum, therefore, it seems plausible that any technology sufficient to do the job of mitigation would lend itself to accidental or nefarious use, whose catastrophic consequences could equal those of an impact. And even a technology that does not pose a comparable risk of its own could, by the very logic of deflection, have political implications that pose such a risk.[19] Therefore, all in all, it is at least unclear what waiting for the next generation of technology would accomplish; and in the meantime our vulnerability to extinction by impact would remain total.[20]

[14] I will refrain from addressing survivalist strategies, on Earth or off-world. If not simply fanciful, they appear to me to be irrelevant, as not averting catastrophe, and in the latter case, question begging as well, as off-world colonies would, presumably, be even more vulnerable to impact catastrophe than we tellurians are today.

[15] It is worth noting, however, that the need for a nuclear response can arise for impactors well below extinction size [16 (Finding, p. 79)]. A relevant observation is that the only successful intervention among the hypothetical impact scenarios addressed at the IAA Planetary Defense Conferences, all of which involved small asteroids, was the one (in 2017) that relied on NEDs rather than kinetic deflection [21].

[16] The Treaty on the Prohibition of Nuclear Weapons went into effect on January 22, 2021.

[17] Cf. Boslough [23]: “The assessed risk of a global impact apocalypse has been virtually eliminated in our time” (p. 214).

[18] Cf. Wirtz [24]: “With a little bit of luck, we might actually enjoy a few hundred years to improve our survey and deflection systems before we have to put our planetary defenses into action to deflect a significant threat” (p. 455).

[19] Indeed, Mellor [28] offers the deeper critique that planetary defense is subservient to a pervasive militarism in U.S. policy. Motivation is not my primary concern in this paper, and I assume any initiative would be undertaken from mixed motives. However, motivations do have consequences, so ultimately they need to be addressed. Meanwhile, a different kind of political risk could arise from the very effort to preclude the risk of national confrontations. Dufek [29] argues that democracy as we know it could be placed in jeopardy by the need to facilitate global decision-making with a world authority having coercive powers.

[20] Deudney [30] makes much the same point in his objections to Sagan's counsel to delay implementation of the most effect planetary defense until world political arrangements mature sufficiently.

3.3. Risk and probability

Suppose, contrary to my rebuttal above, there were a foreseeable non-nuclear technology that would give us the best of both worlds: reducing the risk of apocalypse by impactor without increasing the risk of apocalypse by political response. Nevertheless, the anti-nuclear position also presumes that there is no great rush to operationalize a planetary defense against a Chicxulub-size object. The argument for non-urgency rests on the premise that the probability of an imminent extinction-size impact even if we took no steps to stop one is so low as to be for all practical purposes zero. But this argument I find both strange and wrong. It is wrong because it ignores the logic of risk, and it is strange because planetary defense was founded on the logic of risk. Let me explain.

Risk is generally understood to have two components. One is the magnitude or value of some negative consequence, which in this case would be an existential catastrophe, possibly human extinction. The other is the probability of its occurrence within a designated time period. It should be noted that the word "risk" is sometimes used to refer to probability alone, but this seems misleading to say the least. For example, in the prepublication draft of National Academies [31] one came across the apparently authoritative assertion that "The risk of impact by long-period comets (LPCs) is much lower than the risk of impact by NEOs [which are mostly asteroids]."[21] This seemed to me simply false unless it was referring only to comparative frequencies of intrusion into the inner solar system; for, as Nuth et al. [17] point out, "While asteroidal impacts are of order 100 times more likely than cometary impacts, comet impacts can carry more than 100 times the energy of a typical asteroid threat, making their destructive power nearly equal" (p. 197). Thus the risk posed by both may be equivalent, since, by the following mainstream definition, "the notion of risk, i.e. the expected value of an undesirable outcome, relates not only to the probability of an accident occurring, but also to the expected loss in case of the accident" [32].

But aside from simply conflating probability with risk, the argument for non-urgency is commonly premised on prioritizing probability over consequence; for example:

> "The probabilities of such a cosmic catastrophe are very small, smaller than we can really comprehend. But the stakes are truly staggering: Not only our lives, and yours, but hundreds of millions if not billions of lives, and the very future of civilization itself hang in the balance. *A wise gambler sticks with the straight odds*. By that measure, society should pay more attention to banning cigarettes, and stopping drunk driving, rather than expending its resources on discovering and protecting us from comets and asteroids. But the annualized threat to each individual from a cosmic impact is higher than risks from TCE, asbestos insulation, saccharin, firecrackers, or nuclear power" (Chapman and Morrison [33], pp. 285-6; my emphasis).

But, I would contend, urgency should be governed by risk and not by probability alone[22]. That is, after all, the justification of planetary defense. For no one can point to any clear instance in all of human history of a city, not to mention a region and of course the whole species, being wiped out by an impact or meteor fall[23]; and even whether there has been a single human fatality is contested. Yes, there have been numerous impacts and bolides, but given that most of Earth's surface is water and most of the land is uninhabited or very sparsely populated by human beings, it has been acknowledged from the get-go that, in human terms, dangerous impacts are rare. So the argument for embarking on a program of planetary defense has always been based on the concept of risk and not on probability alone.

That is especially the case when the consequence is virtually infinite, which is how one might rate the elimination of our species. Yeomans [10] makes this point in a way that serves as a counterpoint to the quotation from Chapman and Morrison above:

> "[O]ne could claim that even over very long time intervals, the average annual number of those killed by Earth impacts is comparable with the fatalities due to shark attacks or fireworks accidents, and there are far more fatalities due to, say, automobile accidents. So why be concerned? The point is that near-Earth object impacts, unlike shark attacks, fireworks accidents, automobile accidents, and any number of more familiar disasters, have the capacity to wipe out an entire civilization in a single blow" (p. xii).

In other words, contrary to Chapman and Morrison, a "wise gambler" would not "stick with the straight odds" if human survival hung in the balance.

Now, as a philosopher, I grant that it may not be literally true that the extinction of Homo sapiens has infinite negative value. There are several reasons that might be given for this qualification. One is that there is no such thing as objective value to begin with. The universe is indifferent to us and everything else. It is living beings who bring value into the world precisely by valuing things; but this is a subjective response by those beings. Thus, in the case of human beings, it is we who place value on the continued existence of our species.

Furthermore, there are certainly some people who do not place a high value on humanity's existence, or who even believe it would be a good thing if we ceased to exist. For example, there is an ethical position known as anti-natalism, which argues in rational terms for our not having children [36]. Any number of reasons can be given, such as human nature making us a scourge to ourselves and to other species, or simply the difficulties and harshness of life in an indifferent universe, making the gift of life to children of dubious benefit to them, unless we delude ourselves to the contrary. Finally, even ordinary human beings who do not harbor such extreme thoughts seldom appear to value the continued existence of our species very highly, at least not into the indefinite future beyond the lives of their children and grandchildren. The profligacy with which we continue to pollute, deplete, and generally wreck the biosphere attests to that.

Nevertheless it would seem to be an assumption of planetary defense that the preservation of human life for the long haul has very high value and perhaps even the highest possible value, even if it is only *for "us"*. And it is easy enough to see why this would be so simply in terms of numbers. For if we go extinct, it is not "only" that the eight billion existing human beings would die – that is, die prematurely, since of course we are all going to die sooner or later – but also that countless billions who might have succeeded us into the indefinite future won't come into existence at all. If we therefore take this "consequence" into consideration when calculating the risk of imminent human extinction by impact, the low probability of the event is put into perspective as not the sole deciding factor of how urgent our response to the hazard should be.[24]

[21] After I pointed this out to the chair of the main contributing group (personal communications, July 8, 2019), the text in the final draft was changed to, "The probability of impact by long-period comets (LPCs) is much lower than the probability of impact by NEOs."

[22] Melamed and Melamed [34] argue similarly on behalf of planetary defense by drawing analogies to wise planning for other sorts of hazards.

[23] Although, again, Lewis [3] demurs; and a scientific report has just been published of the likely destruction of a city in the Bronze Age by an airburst [35].

[24] Furthermore, even if we discounted the value of future human lives as such, the confidence in the indefinitely long continuation of humanity has high value for those living today [37].

Well, then, what is the risk of extinction by impact? The event has a low probability but a high consequence. This sort of situation can be notoriously difficult to assess. Sometimes it seems the two extremes simply cancel out, leaving us to flip a coin. Let me respond first by making an analytical point about probability. The current low probability of an imminent extinction-size impact is a way of speaking and is not literally indicative of what is going to happen. For even the day before we discovered such an object, the probability of such an impact would be tiny; whereas the very next day the probability of impact by that object could be 1.0, even with no change having occurred in the behavior of the object or of Earth. All that would have changed is our state of knowledge.

This point cannot be stressed enough: Probability in the sense relevant here is first and foremost a matter of knowledge, not reality. One way unclarity on this score is shown to have practical consequences is in the frequent use of the term "risk reduction" to refer to the results of surveys that decrease the number of undetected NEOs. This accounts for why some people do not lose sleep over the impact hazard. But my point now is that reducing the number of undetected NEOs does not, by itself, reduce the probability of our being impacted by whatever object, known or unknown, is in fact on a trajectory to strike us. The only way to reduce the probability (and hence risk) of that impact is to establish an effective planetary defense infrastructure.

The assignment of low probability to an extinction-level impact is based on the average frequency of this type of event over a given period of time, say the most recent geologic era. But it is fallacious to infer therefrom that these events occur like clockwork on a regular schedule. On the contrary, as the cliché goes, there can be hundred-year floods two years in a row.[25] Just so, there is nothing whatever in the probability assessment to rule out that a once-in-ten-million-year impact will occur one year from now, even if the previous one occurred only one million years ago.[26] More salient than the low probability, then, I submit, is that we simply have no idea when the next one will occur.[27] And what follows in practical terms is that if something terrible is very likely to happen but we know not when, it is eminently prudent to take whatever precautions are reasonably available as soon as possible: to be safe rather than sorry. Humanity's recent experience with the COVID-19 pandemic speaks eloquently to this point.

3.4. Cost-benefit analysis

But what precautions would be reasonable regarding planetary defense against an extinction-size impactor? That is precisely the question at issue. Current policy presumes that what is already being done is sufficiently reasonable. To embark on a full-scale effort at this time to defend against a Chicxulub-size impactor would be unjustifiably expensive and rely on a technology that presents comparable risks of its own, argue those who are satisfied with present progress. I have already answered the second objection by arguing that no risk-free mitigation technology or strategy seems feasible no matter how long we continue to expose ourselves to the existential hazard of a large impact. I will now address the first.

Sunstein [40] recommends employing a straightforward cost-benefit analysis in deciding what is a justifiable expenditure in a situation where probability and consequences are known. Matheny [41] has worked out the numbers for the hazard of extinction by impact.[28] For ease of calculation, Matheny assumes that there are 10 billion human beings alive in any given year.[29] Citing relevant regulatory documents, Matheny found that health programs in the United States commonly value one year of life for one person at $100,000. Meanwhile, citing NASA data, he postulated the probability of an extinction-size impact at one in a million over the next century, while the cost of a system to detect and deflect large impactors (albeit with imperfect reliability) could be as much as $20 billion. Then even if the system never had to be used, he concludes, it would be highly cost effective. For example, assuming humanity will go extinct anyway a mere 1000 years from now, the cost would be only $4000 per life-year to protect us over the next century. Imagining our indefinitely long continuation, not to mention proliferation, would bring down the cost to an indefinitely small amount.

This calculation, although schematic and hypothetical, surely makes the point that investing in a robust planetary defense will not break the bank. Furthermore meeting this hazard will not force abandonment of efforts to meet the many other hazards humanity faces. Consider that the United States alone has in recent years funded a huge tax cut, two discretionary wars in the Middle East, massive COVID-19 relief, and may soon embark on a major overhaul of its nuclear arsenal, extensive repair and improvement of transportation infrastructure, unprecedented social spending, and an all-out effort to combat the causes and effects of climate change. Every one of these is a trillion-dollar item. Yet a single rock from outer space could make all of those efforts pointless at any moment. So even if the cost to eliminate that impact risk was also a trillion dollars, can it seriously be argued that we can't afford it or that it's not worth the expense? Furthermore, the United States could expect financial collaboration with other nations.

The current budget of NASA's Planetary Defense Coordination Office is 150 million dollars. This is impressive in that it represents a forty-fold increase over planetary defense spending a decade prior [42]. However, this is still less than one percent of NASA's budget, which, in accordance with NASA's mandate, is targeted mainly on science and exploration. Just what would a budget in the billions buy for planetary defense that the current budget can't? There is no shortage of proposals for how an enhanced allotment could be spent (e.g. Refs. [1,17,43,44]). A comparison will reinforce this point. In national defense against a foreign adversary, the United States does not let its guard down for one second. Radar and other devices scan the horizon continuously for incoming missiles, and with backups in case of failures. Furthermore, the United States is prepared to respond massively to any detection at once.

[25] Indeed, this is an essential feature of randomness, as Pinker notes (quoted in Ref. [38], albeit in the context of debunking the impression that we live in especially parlous times; my claim is that all times are parlous): "It's a statistical phenomenon that when events are randomly sprinkled in time they cluster. That sounds paradoxical, but unless you have a nonrandom process that spaced them apart — *We're going to have a crisis every six months but we're never going to have two crises in a month* — events cluster. That's what random events will always do."

[26] Compare this remark by the Russian Emergency Minister Vladimir Puchkov regarding the lack of preparedness for what took place in Chelyabinsk: "We thought that humanity would not have to face such an attack for another couple of thousand years, but the opposite happened and Russia was hit with a large-scale natural emergency" (RT News 2013). And what makes this sort of dismissal not merely fallacious but downright absurd in the case of an extinction-size impact is that, even by the fallacious reasoning, we are "due" for the next one.

[27] Another way to think about this is that in some cases the consequence is so great that probability is irrelevant and the mere possibility is sufficient to warrant significant response; cf. ([39], ch. 17).

[28] Singer [14] makes a similar calculation (pp. 167-9).

[29] One reviewer noted that, as with Chicxulub, other species would be impacted direly as well. Attributing value to their lives too would only increase the import of the following calculation.

Now consider planetary defense[30]: We have only incomplete surveillance; for example, even the proposed NEO Surveyor, by design (since its job is survey, not surveillance), and the Vera C. Rubin Observatory, of necessity (given its fixed location on the Earth), will have only partial coverage of the celestial sphere, and yet a long-period comet or an interstellar object can approach from any direction. In addition, the surveillance is mostly without backups; witness the recent collapse of the Arecibo Telescope, which has significantly impaired NEO characterizations. I also find it embarrassing if not outright scandalous (although certainly impressive in its own way) that to this day amateur astronomers discover asteroids and comets (e.g., Ref. [46]). Even NEO Surveyor, an infrared space telescope that would meet Congress's own mandate to discover, characterize, and track 90% of the estimated 25,000 NEOs that are big enough to cause regional damage[31] (not to mention a smaller percentage of the estimated one million that are big enough to wipe out a city), and whose cost [47] is a fraction of the cost of a single B-2 Spirit stealth bomber [[48] (Table 1.1)], has taken many years to overcome bureaucratic hurdles [49]. Furthermore, should an incoming impactor be discovered with relatively short warning, we have at present zero response capability regarding even a city buster not to mention a civilization buster (cf. [50]).

4. Conclusion

The lesson to be drawn for apocalypse by impactor is therefore, I submit, the same as for the COVID-19 pandemic or for global climate change, namely, that it is unwise to let the tail of expense wag the dog of prevention. The expense is manageable. It is true that, over and above expense, there will be risks in such an undertaking. But this presents humanity with two options: continue to leave ourselves open to the loss of everything we value from a preventable catastrophe, or, as with any real-world situation, roll up the blouse sleeves and come up with a workable way forward.[32] I submit that the bigger risk right now is complacence due to misconceiving risk in the face of this ultimate choice.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author statement

Joel Marks: Conceptualization, Methodology, Writing – Original draft preparation, Writing – Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[30] I find it of great pertinent interest as a matter of historical fact that the very term "planetary defense" was coined with the national defense model in mind. Lindley Johnson's seminal white paper [45] places emphasis on the natural role of the Department of Defense in planetary defense, in conjunction with NASA and other government agencies (p. R-15).

[31] Approximately two-fifths have been discovered to date (see e.g. Adamo 2020).

[32] Deudney [30] suggests establishing "an international consortium of spacefaring states" to have joint and not unilateral control of the needed infrastructure (pp. 251-2). Su [32] tracks the prospects of current international legal regimes to deal with the political challenges of planetary defense and, finding them insufficient, calls for "the establishment of an international body." The different types of global political arrangements that might be suitable for this task, with both their promises and perils, are the subject of a unique collection of essays edited by N. Schmidt [51].

Acknowledgments

This paper has benefited immensely from consultation with a host of experts at NASA and elsewhere, as well as very helpful commentaries by the editor and three anonymous reviewers. For their graciousness and generosity over the years to this philosophical outsider in their midst, I would like to give particular thanks to Brent Barbee, Paul Chodas, Alan Harris (USA), Lindley Johnson, Matthew Knight, Dan Mazanek, Joseph Nuth, and the late Michael A'Hearn. In addition I received excellent feedback on ideas expressed herein from other members of the Goal 2 update team of NASA's Small Bodies Assessment Group (May–June 2018), members of the graduate engineering course ENAE603 Near-Earth Object Exploration at the University of Maryland (5 October 2021), members of the Planetary Defense Research Group at Goddard Space Flight Center (29 October 2021), and a final read-through by Thomas Pölzler, Cynthia Sederquest, and Mitchell Silver. Finally, a special tip of the hat to AMMAD/D, gadfly to the gadfly. Of course any conclusions drawn or errors committed herein are my own.

References

[1] P. Lubin, A.N. Cohen, Don't forget to look up, arXiv:2201.10663v4 [astro-ph.EP], 2022. (Accessed 28 February 2022).
[2] P. Wylie, E. Balmer, When Worlds Collide, University of Nebraska Press, Lincoln NE, 1999 (1932).
[3] J.S. Lewis, Rain of Iron and Ice: The Very Real Threat of Comet and Asteroid Bombardment, Helix Books, Reading MA, 1997.
[4] C. Flammarion, Omega: the Last Days of the World, University of Nebraska Press, Lincoln NE, 1999 (1893).
[5] L.W. Alvarez, W. Alvarez, F. Asaro, H.V. Michel, Extraterrestrial cause for the Cretaceous-Tertiary extinction, Science 208 (1980) 1095–1108.
[6] C.R. Chapman, History of the Asteroid/comet Impact Hazard, 1998. https://www.boulder.swri.edu/clark/ncarhist.html. (Accessed 29 September 2021).
[7] M. Rees, Know Thy Enemy: The Million Space Rocks We Must Find, NewScientist, 2014. https://www.newscientist.com/article/dn26655-know-thy-enemy-the-million-space-rocks-we-must-find/#ixzz75sHrD938. (Accessed 29 September 2021).
[8] Center for Near-Earth Object Studies (CNEOS), Discovery Statistics, 2021. https://cneos.jpl.nasa.gov/stats/totals.html. (Accessed 29 September 2021).
[9] S. Greenstreet, E. Lu, M. Juric, J. Moeyens, et al., The Asteroid Discovery, Analysis, and Mapping (ADAM) Platform, B612 Asteroid Institute, University of Washington, Poster presented at the 2021 conference of the Division for Planetary Sciences of the American Astronomical Society. https://b612foundation.org/dps-iposter-the-asteroid-discovery-analysis-and-mapping-adam-platform/ (accessed 29.09.21).
[10] D.H. Yeomans, Near-Earth Objects: Finding Them Before They Find Us, Princeton University Press, Princeton, 2013.
[11] National Science and Technology Council (NSTC), National Near-Earth Object Preparedness Strategy and Action Plan, 2018. https://www.nasa.gov/sites/default/files/atoms/files/ostp-neo-strategy-action-plan-jun18.pdf. (Accessed 29 September 2021).
[12] L. Billings, Words matter: a call for responsible communication about asteroid impact hazards and plans for planetary defense, Space Policy 33 (2015) 8–12.
[13] T. Ord, The Precipice: Existential Risk and the Future of Humanity, Hachette Books, New York, 2020.
[14] P. Singer, The Most Good You Can Do: How Effective Altruism Is Changing Ideas about Living Ethically, Yale University Press, New Haven, 2015.
[15] M. A'Hearn, Testimony at April 10 House Science Committee Hearing on Threats from Space, Part II: A Review of Private Sector Efforts to Track and Mitigate Asteroids and Meteors, 2013. https://www.youtube.com/watch?v=bO8ThA-iXdw(video). (Accessed 29 September 2021).
[16] National Research Council (NRC), Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies, The National Academies Press, Washington DC, 2010, https://doi.org/10.17226/12842. (Accessed 29 September 2021).
[17] J.A. Nuth, B. Barbee, R. Leung, Defending the Earth from long-period comets and sneaky asteroids: short term threat response requires long term preparation, J. Space Saf. Eng. 5 (2018) 197–202.
[18] M. A'Hearn, Protecting Earth: Four Recommendations, UMHNews, 2010 (video), https://youtu.be/Ccsb4wWQups. (Accessed 29 September 2021).
[19] D. Ellsberg, The Doomsday Machine: Confessions of a Nuclear War Planner, Bloomsbury, New York, 2017.
[20] M. Smetana, Weapons of mass protection? Rogue asteroids, nuclear explosions in space, and the norms of global nuclear order, in: N. Schmidt (Ed.), Planetary Defense: Global Collaboration for Defending Earth from Asteroids and Comets, Springer, 2019, pp. 231–244.

[21] Center for Near-Earth Object Studies (CNEOS), Hypothetical Impact Scenarios, 2021. https://cneos.jpl.nasa.gov/pd/cs/. (Accessed 29 September 2021).
[22] United Nations Office for Outer Space Affairs (UNOOSA), Near-Earth Objects and Planetary Defence, 2018. https://www.unoosa.org/documents/pdf/smpag/st_space_073E.pdf. (Accessed 29 September 2021).
[23] M. Boslough, Uncertainty and risk at the catastrophe threshold, in: N. Schmidt (Ed.), Planetary Defense: Global Collaboration for Defending Earth from Asteroids and Comets, Springer, 2019, pp. 205−215.
[24] J.J. Wirtz, Will planetary defense change a realist world? in: N. Schmidt (Ed.), Planetary Defense: Global Collaboration for Defending Earth from Asteroids and Comets Springer, 2019, pp. 453−460.
[25] C. Sagan, S.J. Ostro, Long-range consequences of interplanetary collisions, Issues Sci. Technol. 10 (1994) 67−72.
[26] A.W. Harris, G.H. Canavan, C. Sagan, S.J. Ostro, The deflection dilemma: use versus misuse of technologies for avoiding interplanetary collision hazards, in: T. Gehrels (Ed.), Hazards Due to Comets and Asteroids, University of Arizona Press, Tucson, 1994, pp. 1145−1155.
[27] R.L. Schweickart, The Real Deflection Dilemma, Presentation at the 2004 Planetary Defense Conference, Orange County, CA, 2004, https://doi.org/10.2514/6.2004-1467. (Accessed 29 September 2021).
[28] F. Mellor, Colliding worlds: asteroid research and the legitimization of war in space, Soc. Stud. Sci. 37 (2007) 499−531.
[29] P. Dufek, Why a world state is unavoidable in planetary defense: on loopholes in the vision of a cosmopolitan governance, in: N. Schmidt (Ed.), Planetary Defense: Global Collaboration for Defending Earth from Asteroids and Comets, Springer, 2019, pp. 375−399.
[30] D. Deudney, Dark Skies: Space Expansionism, Planetary Geopolitics, and the Ends of Humanity, Oxford University Press, New York, 2020.
[31] National Academies of Sciences, Engineering, and Medicine, Finding Hazardous Asteroids Using Infrared and Visible Wavelength Telescopes, The National Academies Press, Washington, DC, 2019, https://doi.org/10.17226/25476. (Accessed 29 September 2021).
[32] J. Su, Measures proposed for planetary defence: obstacles in existing international law and implications for space arms control, Space Policy 34 (2015) 1−5.
[33] C.R. Chapman, D. Morrison, Cosmic Catastrophes, Plenum Press, New York, 1989.
[34] N. Melamed, A. Melamed, The terrestrial example: natural disasters as model for planetary defense planning, J. Space Saf. Eng. 7 (2020) 67−77.
[35] T.E. Bunch, et al., A Tunguska sized airburst destroyed Tall el-Hammam, a Middle Bronze Age city in the Jordan valley near the Dead Sea, Sci. Rep. 11 (2021) 18632, https://doi.org/10.1038/s41598-021-97778-3. (Accessed 29 September 2021).
[36] D. Benatar, Better Never to Have Been: The Harm of Coming into Existence, Clarendon Press, Oxford, 2006.
[37] S. Scheffler, Death and the Afterlife, Oxford University Press, Oxford, 2013.
[38] D. Marchese, Steven Pinker Thinks Your Sense of Imminent Doom Is Wrong, New York Times Magazine, 2021. https://www.nytimes.com/interactive/2021/09/06/magazine/steven-pinker-interview.html. (Accessed 29 September 2021).
[39] R.E. Goodin, Utilitarianism as a Public Philosophy, Cambridge University Press, Cambridge UK, 1995.
[40] C.R. Sunstein, Averting Catastrophe, New York University Press, New York, 2021.
[41] J.G. Matheny, Reducing the risk of human extinction, Risk Anal. 27 (2007) 1335−1344.
[42] C. Dreier, How NASA's Planetary Defense Budget Grew by More than 4000% in 10 Years, Planetary Society, 2019. https://www.planetary.org/articles/nasas-planetary-defense-budget-growth. (Accessed 29 September 2021).
[43] D.R. Adamo, Toward Greater Preparedness and Resilience in Planetary Defense, ATIG_116, 2020. http://www.aiaahouston.org/adamo_astrodynamics/. (Accessed 29 September 2021).
[44] A. Mainzer, et al., The future of planetary defense in the era of advanced surveys. White paper for the 2023-2032 Planetary Science and Astrobiology Decadal Survey, in: Small Bodies Assessment Group (NASA), 2020. https://neos.arizona.edu/sites/neos.arizona.edu/files/data/TheFutureofPlanetaryDefense.pdf. (Accessed 29 September 2021).
[45] L.N. Johnson, Preparing for planetary defense: detection and interception of asteroids on collision course with Earth, in: J.W. Kelley (Study Chair) (Ed.), Spacecast 2020 vol. 1, Air University, Maxwell Air Force Base, Alabama, 1994. R-1 R-33, https://ia800108.us.archive.org/20/items/DTIC_ADA295142/DTIC_ADA295142.pdf. (Accessed 29 September 2021).
[46] National Astronomical Observatory of Japan (NAOJ), New Comet Discovered by Japanese Amateur Astronomer, 14 January 2020. https://www.nao.ac.jp/en/news/topics/2020/20200114-comet.html. (Accessed 29 September 2021).
[47] M. Wall, NASA Asteroid-Hunting Satellite Clears Hurdle on Path to 2026 Launch, 2021. https://www.space.com/nasa-asteroid-hunting-satellite-neo-surveyor-milestone. (Accessed 29 September 2021).
[48] United States General Accounting Office (GAO), B-2 Bomber: Cost and Operational Issues, GAO/NSIAD-97-181, 1997.
[49] J. Foust, NASA to Develop Mission to Search for Near-Earth Asteroids, SpaceNews, 2019. https://spacenews.com/nasa-to-develop-mission-to-search-for-near-earth-asteroids. (Accessed 29 September 2021).
[50] B. Barbee, et al., Space mission options for the 2021 PDC hypothetical asteroid impact scenario, in: Presentation to the 7th IAA Planetary Defense Conference on Behalf of the Space Mission Planning Advisory Group (SMPAG), Vienna (virtual), 27 April 2021. https://cneos.jpl.nasa.gov/pd/cs/pdc21/pdc21_day2_briefing2.pdf. (Accessed 29 September 2021).
[51] N. Schmidt (Ed.), Planetary Defense: Global Collaboration for Defending Earth from Asteroids and Comets, Springer, 2019.