Uncertain Human Consequences in Asteroid Risk Analysis and the Global Catastrophe Threshold

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Abstract

This paper studies the risk of collision between asteroids and Earth. It focuses on uncertainty in the human consequences of asteroid collisions, with emphasis on the possibility of global catastrophe to human civilization. A detailed survey of the asteroid risk literature shows that while human consequences are recognized as a major point of uncertainty, the studies focus mainly on physical and environmental dimensions of the risk. Some potential human consequences are omitted entirely, such as the possibility of asteroid explosions inadvertently causing nuclear war. Other human consequences are modeled with varying degrees of detail. Direct medical effects are relatively well-characterized, while human consequences of global environmental effects are more uncertain. The latter are evaluated mainly in terms of a global catastrophe threshold, but such a threshold is deeply uncertain and may not even exist. To handle threshold uncertainty in asteroid policy, this paper adapts the concept of policy boundaries from literature on anthropogenic global environmental change (i.e., planetary boundaries). The paper proposes policy boundaries of 100m asteroid diameter for global environmental effects and 1m for inadvertent nuclear war. Other policy implications include a more aggressive asteroid risk mitigation policy and measures to avoid inadvertent nuclear war. The paper argues that for rare events like large asteroid collisions, the absence of robust data means that a wide range of possible human consequences should be considered. This implies humility for risk analysis and erring on the side of caution in policy.

1. Introduction

Objects from outer space collide with Earth on a daily basis. The overwhelming majority of these objects are small enough that they burn harmlessly in the upper atmosphere or fall harmlessly to the ground. On rarer occasion, Earth is struck by a larger object capable of significant harm. Most recently, the 2013 collision at Chelyabinsk, Russia, caused around 1,500 injuries and damage to thousands of buildings (Popova et al. 2013). Even more rarely, very large objects collide with Earth, causing severe global environmental damage, such as the Chicxulub collision implicated in the Cretaceous-Paleogene extinction event 66 million years ago (Alvarez et al. 1980).

For several decades, there has been active public policy to address the collision threat. In the early 1990s, the Spaceguard Survey was established via interaction between the US Congress and NASA (Morrison 1992); it continues today as an international project. Spaceguard and related projects detect near-Earth objects (NEOs, defined by convention as asteroids and comets that approach within 1.3 astronomical units of the Sun) and assess their potential to collide with Earth. The detection efforts have had significant success, finding over 90% of the largest NEOs and confirming that they pose no threat to Earth (Stokes et al. 2017). Accompanying the detection projects are proposals to deflect Earthbound NEOs onto safe trajectories in case any such object is detected (Harris et al. 2015).

Quantitative risk analysis has long been central to NEO policy. Spaceguard was framed from the outset in risk terms (Morrison 1992) and has been described as a success because it reduced NEO risk estimates by finding that most large NEOs are not on a collision trajectory (Harris 2008). NASA (Stokes et al. 2003; 2017) and the US National Research Council (NRC 2010) have put risk analysis central to their studies of NEOs. There has also been a robust NEO risk research literature, which seeks to characterize the probability and severity of Earth-NEO collisions (Canavan 1993; 1994; Chapman and Morrison 1994; Collins et al. 2005; Chesley and Ward 2006; Garrick 2008; Bailey et al. 2010; Harris 2010; Mignan et al. 2011; Reinhardt et al. 2016; Rumpf et al. 2016; 2017; Mathias et al. 2017).

This paper assesses the human consequences of NEO collisions as this relates to NEO risk analysis and policy. As with much of the prior literature, this paper focuses specifically on asteroid risk. Comet collisions are rarer and the comets harder to deflect (Stokes et al. 2003). Much of the discussion nonetheless applies to comets. This paper conducts a detailed survey of the asteroid risk literature in terms of its discussion of human consequences. The human consequences have been recognized as a major point of uncertainty,[1] but they have gotten relatively little attention compared to physical and environmental dimensions of the risk—the population of near-Earth asteroids, the physics of asteroid-Earth collision, and the resulting physical and environmental effects. This paper makes some progress on characterizing the human consequences in risk terms and describes policy implications.

This paper pays particular attention to the risk of global catastrophe from asteroid collision. This risk is of considerable research and policy interest both in its own right and as a case study within the broader space of global catastrophic risks. The other global catastrophic risks include some natural hazards, such as comet collisions and supervolcano eruptions, and some anthropogenic hazards, such as global warming and nuclear war. Of all the global catastrophic risks, asteroid collision is notable for being perhaps the most well-quantified. The other natural hazards have been the subject of less risk analysis research and are also harder to monitor and predict than asteroids, while the anthropogenic risks derive from complex and largely unprecedented socio-technological phenomena that are inherently difficult to quantify. This paper shows that asteroid risk is not as well-quantified as it may seem, due to uncertainty in the human consequences.

The paper further applies the concept of policy boundaries as a means of handling the uncertain potential for global catastrophe. Policy boundaries were first developed for anthropogenic environmental threats under the rubric of planetary boundaries (Rockström et al. 2009a; 2009b), and they were subsequently adapted into risk terms (Baum and Handoh 2014). Boundaries are policy constructs used to avoid crossing dangerous social or biogeophysical thresholds. Asteroid risk analysis already makes extensive use of the concept of global catastrophe threshold, making policy boundaries readily applicable.

The paper is organized as follows. Sections 2-4 discuss the human consequences of various effects of asteroid collisions. Section 2 covers direct physical effects, such as air blast and tsunami waves. Section 3 covers indirect social effects deriving from the direct effects, such as systemic economic disruption and the onset of war. Section 4 covers global environmental

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[1] For example, Chapman and Morrison (1994, p.35) write "there are large uncertainties in the environmental consequences of impact and, even more, in the effects on human civilization". Mellor (2010, Section 2) also presents some similar critique of the treatment of human consequences in asteroid risk analysis, though with less detail than is presented in this paper.

effects from large asteroid collisions, with emphasis on the concept of a global catastrophe threshold. Section 5 considers how to set a policy boundary relating to the threshold. Section 6 discusses other policy implications, including asteroid detection and deflection and measures to avoid inadvertent nuclear war. Section 7 concludes.

2. Direct Physical Effects

There are two basic types of direct physical effects of asteroid collisions. First, there are effects in the local vicinity of the collision deriving from the asteroid exploding in the atmosphere and/or smashing into the surface. Referred to in this paper as *local effects*, they include air blast, thermal radiation, cratering, and seismic shock. They are physically similar to the effects of human-made explosives. Second, there is water displacement for asteroids that collide at sea. For sufficiently large collisions, the effect is a tsunami. As with tsunamis caused by other processes, the waves travel long distances and can cause disruption across wide coastal areas, though with different properties than other tsunamis.

Compared to indirect social effects and global environmental effects, the human consequences of the direct physical effects are relatively simple and well understood. They include medical harms and infrastructure damage in the directly affected areas. There are also reasonable proxies available in the form of human-made explosives and non-asteroid tsunamis. Indeed, much of the asteroid risk literature bases its characterization of the human consequences of local effects on studies of nuclear weapons, in particular the work of Glasstone (1962) and Glasstone and Dolan (1977).[2] Harris (2010) and Rumpf et al. (2017) also draw on data from tsunamis for their characterizations of human consequences, and Rumpf et al. (2017) further uses data from earthquakes, tornados, and volcanoes.

The most common approach is to define a damage area and calculate human consequences as a function of the population or economic production within the area. This approach traces to Hills and Goda (1993, p.1132), who define a damage area for local effects as the area within which the blast overpressure of the asteroid explosion exceeds 4 pounds per square inch (4 psi = 2.8×10^5 dynes/cm^2). Subsequent studies have used a damage area at either 4 psi (Garrick 2008; Stokes et al. 2003; 2017; Mathias et al. 2017) or 2 psi (Canavan 1993; 1994). For tsunamis, the damage area has been defined as the land area reached by the waves (Canavan 1994; Chelsey and Ward 2006; Harris 2010; Garrick 2008).

A shortcoming of the existing implementations of the damage area concept is that they all assume a binary distribution of effects inside and outside the area. Within the area, damage is uniform, while outside the area, damage is zero. However, the actual distribution of human consequences is not binary. Instead, the approximate distribution is a decay from the collision ground zero (for local effects) or the coastline (for tsunamis).[3] There are also various heterogeneities due to local geography, some of which can be quite important. The binary distribution is defended by Mathias et al. (2017, p.109) on grounds that it "provide(s) a reasonable balance between survivors within and casualties without", which may be correct for a well-calibrated model, though calibration can be difficult without considering local heterogeneities.

Accounting for local heterogeneities adds significant complexity to the analysis, which makes the analysis more difficult, especially if it is to cover a range of collision sizes and

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[2] Studies based on this work include Canavan (1993; 1994); Stokes et al. (2003; 2017); Collins et al. (2005); Reinhardt et al. (2016); Mathias et al. (2017); and Rumpf et al. (2017).

[3] Stokes et al. (2017) uses a decay function for blast damage in a cost-benefit analysis of NEO detection programs (Section 8) but not in its primary risk analysis (Section 3).

locations. This creates a breadth-vs.-depth tradeoff for risk analysis. Most asteroid risk analyses have focused on breadth of collision scenarios, with no depth in local heterogeneities. Exceptions include Garrick (2008) and Mignan et al. (2011), which both study collisions in the US using some local data. The Mignan et al. (2011) study is especially detailed, using geographic data for population and property value, though this study also only considers collisions of one size, around 5 to 10MT.

Rumpf et al. (2017) present a model that has relatively detailed treatment of human consequences and can be applied to a wide range of collision scenarios. The model calculates the probability of an individual being killed by several local effects (overpressure, winds, thermal radiation, cratering, seismic shock, and ejecta deposition) and tsunamis, drawing heavily on the nuclear weapon study of Glasstone and Dolan (1977), as well as data on earthquake, tornado, tsunami, and volcano fatalities. For example, the probability of an individual being killed by the tsunami is assumed to be a function of the water height where the tsunami reaches the person, based on data from non-asteroid tsunamis presented in Berryman (2005). Rumpf et al. (2017) also include some social factors, such as whether people are indoors (and thus less vulnerable to some collision effects) and whether there are advance warnings that enable preventive measures. The modeling of advance warnings is of particular policy interest because it can help assess the value of asteroid detection and communication programs.

There is undoubtedly room for improvement in the modeling of human consequences of direct physical effects. Treatment of economic effects in particular remains fairly crude—it has been calculated variously as the entire economic product within the damage area (Canavan 1993; 1994) or an amount of $100,000 per person within the damage area (Chelsey and Ward 2006). Most studies neglect economic effects entirely. And while the Rumpf et al. (2017) study is a good start, more can be done to calibrate models with data from analogous disaster scenarios. Similarly, modeling should account for the effects of efforts to reduce the severity through disaster management, as discussed by Garshnek et al. (2000). That said, the modeling of human consequences of direct physical effects is still more robust than other parts of asteroid risk.

3. Indirect Social Effects

Indirect social effects are those that derive from the direct physical effects but occur some distance away. The indirect effects can include wider economic disruption, political reaction, and cultural effects. Depending on the details, these effects could be quite large, possibly even larger than the initial effects. However, to date, there have been no attempts to quantify indirect social effects in asteroid risk analysis.

One type of indirect effect can come from damage to civil and economic infrastructure. Damage to select infrastructure can often have cascading effects that spread widely in adjacent or even distant areas. For example, a 2003 blackout across the entirety of mainland Italy was caused by a single power line failure in southern Switzerland (Buldyrev et al. 2010), while a 2016 blackout across Kenya was caused by a monkey falling on an electrical transformer (BBC 2016). Similarly, the business practice of just-in-time inventory management leaves global supply chains vulnerable to disruption. For example, following the 2011 Tōhoku earthquake and tsunami, General Motors had to shut down production at a plant in the US because it ran out of components from Japan (Fiksel et al. 2015). Given the scarce attention to direct economic effects in asteroid risk analysis, it is unsurprising that these indirect effects are not modeled.

There is one important type of indirect effect that has received some attention in the broader asteroid literature, though not in any risk analysis. That is the prospect of an asteroid explosion being misinterpreted as a hostile attack with human-made explosives, thereby triggering violent conflict (Morrison 1992, p.9; NRC 2010, p.26). Were such an event to occur, the secondary effects could be much more severe than the direct effects.

Remarkably, there is precedent for the concern of asteroid collision triggering conflict via the 2013 Chelyabinsk event. Harris et al. (2015, p.838) explain:

> If it had been cloudy in Chelyabinsk that morning, it may not have been immediately apparent to locals or outsiders that this was a cosmic airburst. The bright flash and huge blast, followed by the sound of heavy artillery, and parts of the city shrouded in dark smoke, could have been misperceived as an act of aggression. Snezhinsk, to the north, is the Russian equivalent of Lawrence Livermore National Laboratory in the U.S., and the region is of nuclear strategic importance. Russia, unlike its neighbor Kazakhstan in the direction from which the asteroid came, is still a nuclear-armed state. It is hard to know what would happen in the heat of the moment when there is great uncertainty about the cause of a half-megaton explosion over a Russian city.

Could such an event lead to conflict, even nuclear war? A careful study of the history of nuclear war suggests that yes, this is a possibility. In the decades since nuclear weapons were first developed, there have been several incidents in which non-military events were misinterpreted as a possible nuclear attack, initiating nuclear weapon launch decision procedures. These events include a moonrise, an ill-timed passage of a satellite, an unusual reflection of sunlight off clouds, and the launch of a scientific weather rocket (Baum et al. 2018). How close these incidents came to actual nuclear war is a matter of historical debate (Lewis et al. 2014; Tertrais 2017). Regardless, if these seemingly innocuous events can get at least partway to nuclear war, then it is not unreasonable to believe that an asteroid explosion could get all the way.

Factoring the possibility of nuclear war into the risk of asteroid collision is not straightforward. This is because the risk of nuclear war is itself not well quantified. Whether nuclear war starts depends on a series of human judgments that are sensitive to particular geopolitical circumstances and the personalities involved. Nuclear war is also a rare phenomenon, with World War II being the only data point. Furthermore, much of the relevant historical information is classified. Quantifying nuclear war risk is therefore a difficult task. There have also been few attempts to do so.[4]

For asteroid risk, the most relevant prior study is Barrett et al. (2013), which models the probability of inadvertent nuclear war between Russia and the United States. Inadvertent nuclear war occurs when one side mistakenly believes it is under nuclear attack and launches nuclear weapons in what it believes is a retaliation but is actually the first strike. Nuclear war caused by asteroid collision would be inadvertent. Barrett et al. (2013) use declassified US false alarm data from 1977-1983 and probability distributions for uncertain model parameters. The study finds the annual probability of Russia-US inadvertent nuclear war to fall, with 90 percent confidence, within the range of 0.0002 to 0.07 if the war could occur at any time, and from 0.00001 to 0.05 if the war could only occur during times of heightened tensions between the two countries. The wide range of results, spanning several orders of magnitude, speaks to the uncertainty inherent to this risk. The presentation of separate results for whether the war can occur during low tensions further speaks to the uncertainty about the circumstances in which this type of war can occur.

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[4] For reviews, see Baum et al. (2018); Baum and Barrett (2018).

The severity of nuclear war is also uncertain, for reasons similar to the uncertainty about the global environmental effects of large asteroid collisions (discussed below). In addition to the direct medical casualties from the local effects of the nuclear explosions, there could be extensive global economic disruption from the destruction of major cities and additional harms from nuclear winter and related global environmental effects. Agricultural productivity reductions could put billions at risk of famine (Helfand 2013), and while human extinction may appear unlikely (Robock 2010), it is also difficult to rule out (Baum 2015).[5]

The uncertainty about nuclear war carries over into asteroid risk. Indeed, recognizing this uncertainty makes it more understandable to see the general neglect of complex indirect social effects in the asteroid risk literature. However, asteroid risk analysis should nonetheless endeavor to include this important dimension of the risk.

4. Global Environmental Effects

Large asteroid collisions have significant global environmental effects by sending dust and soot into the atmosphere, reducing the amount of sunlight reaching the surface and damaging the ozone layer, and by causing global firestorms (Toon et al. 1997; 2016). The largest collisions can cause global mass extinctions, such as the 10km Chicxulub impactor implicated in the Cretaceous-Paleogene event. Somewhat smaller collisions can still cause sufficient global environmental disruption to be of major human concern.

The primary focus of the asteroid risk analysis literature has been on the concept of a threshold collision size above which global catastrophe would occur. Most studies assume a binary distribution, in which there is the same damage for all collisions above the threshold and zero damage for collisions below it. The damage level has not been rigorously derived, but instead is based on assumption. Damage levels used include the death of 25% of the human population (Morrison 1992; Chapman and Morrison 1994; Chapman 2004), one billion deaths (NRC 2010), and the entire global economic product during a 20 year damage period, after which the environmental disruption dissipates and recovery occurs (Canavan 1993; 1994). One study simply calculates the frequency of collisions above a physical threshold without characterizing human consequences, citing uncertainty in the human consequences (Reinhardt et al. 2016). Two studies that do not use a binary distribution are Stokes et al. (2003; 2017), which assume zero fatalities from global environmental effects below a threshold and increasing fatalities as the threshold is exceeded by larger and larger amounts.

A closer analysis of both the global environmental effects and the corresponding human consequences suggests that the global catastrophe threshold as found in the literature is arbitrary and without evidentiary support. There are some distinct environmental thresholds, but these are at the wrong level of severity for the global catastrophe threshold. Additionally, there could be threshold effects within the human response to the global environmental effects, but these are unlikely to match the particular threshold levels used in the literature.

One environmental threshold is the tropopause. Collisions must send material above the tropopause and into the stratosphere in order to have global effects; otherwise the material will quickly fall down to the surface. However, Toon et al. (1997, p.35) report that collisions as low as 1MT can send material into the stratosphere, which is 10^4 to 10^6 times lower than the typical global catastrophe thresholds. Furthermore, as collision size increases above the minimum

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[5] There are also important uncertainties about the physical and environmental effects of nuclear war. For example, a recent study conducts detailed simulations of fires caused by nuclear explosions, finding an approximately fivefold reduction in the amount of particulate matter reaching the stratosphere relative to previous studies, and correspondingly weaker global environmental effects (Reisner et al. 2018).

needed to cross the tropopause, the corresponding stratospheric perturbation increases smoothly (Toon et al. 1997). Collisions just above the tropopause threshold should produce mild human consequences. This point is evidenced, for example, by the 1991 Mount Pinatubo eruption, which sent 20MT of SO_2 into the stratosphere (Bluth et al. 1992), resulting in a 0.5ºC surface temperature decrease (Parker et al. 1996), which may have caused some human consequences but nothing that would rate as a global catastrophe. The tropopause could be the basis for a steadily increasing distribution such as in Stokes et al. (2003; 2017), though these studies use thresholds of approximately 10^5MT, which is far above the tropopause threshold. It follows that the tropopause is not a meaningful global catastrophe threshold for asteroid risk analysis.

Another environmental threshold is the minimum light needed for photosynthesis. Toon et al. (1997) report that this threshold is crossed for collisions of around 10^6 to 10^7 MT, with the effect lasting for a time on the order of a few months. In human terms, this threshold could cause a massive decline in the food supply, potentially large enough to rate as a global catastrophe. However, the food supply decline at or above the photosynthesis threshold may not be significantly larger than the decline just below this threshold. This is because smaller collisions can still block enough sunlight to reduce food supply via lower surface temperatures and precipitation (Toon et al. 1997). That food supply decline could be large, potentially large enough to rate as a global catastrophe. Indeed, the asteroid risk literature generally assumes a global catastrophe threshold below the photosynthesis threshold. Thus, the photosynthesis threshold would be a poor choice for a global catastrophe threshold.

In between the tropopause and photosynthesis thresholds, there are no significant environmental thresholds. However, there could be a threshold in the human response to the intermediate environmental effects. In other words, perhaps at some amount of environmental disruption there is a discontinuity in the human harm, such as a collapse of human civilization. Some precedent for this can be found in historical civilization collapses, which appear to have been caused at least in part by environmental stressors (Butzer and Endfield 2012). Likewise, the increasing interconnectedness of modern human civilization has driven concerns about global civilizational collapse (Helbing 2013; Centeno et al. 2015). An asteroid collision could cause environmental stress unprecedented in the history of human civilization. It is thus reasonable to suspect the existence of a human response threshold from asteroid collisions of a certain size.

However, whether there is a human response threshold is deeply uncertain, as is the question of where the threshold would be if it does exist. There is an intrinsic lack of data—modern global human civilization has never collapsed before. Historical analogs are all preindustrial and regional and thus of limited relevance. Furthermore, the historical cases display complex interplays of social and environmental factors (Butzer and Endfield 2012). Ongoing research into the resilience of modern global civilization may nonetheless shed some light, but specific conclusions on human response thresholds to asteroid collisions would at this time be premature.

Another complication is that whether civilization collapses could depend on the success of efforts to cope with the environmental disruption. For example, a major effect of the global environmental disruption would be a potentially dramatic decline in the food supply due to reduced sunlight and precipitation. However, there are several options for surviving through global food supply catastrophes, including shifting agriculture from livestock feed to direct human consumption, drawing down food stockpiles, and growing food from energy sources other than the Sun (Baum et al. 2015). Additional policy options for surviving the global environmental disruption include medical triage, mobilization for recovery, evacuation of the most devastated areas, and air filtration (Garshnek et al. 2000). How successfully these sorts of options are pursued is a complex socio-technological question that is difficult to assess in advance. Thus, it is not clear whether there is a human response threshold, or where it would be if it does exist.

Despite the pervasive uncertainty, some generalizations can be made with at least moderate confidence. First, human harms from global environmental effects are likely to increase with collision size above the tropopause threshold. Second, if there are any global catastrophe thresholds, they are likely to be based largely or exclusively on a human response threshold, in particular civilization collapse, with environmental thresholds playing at most a partial role. Third, any thresholds are more likely to be crossed for larger collisions. Fourth, wide probability distributions should be drawn for human harm from a given global environmental perturbation. And last but not least, there is potential for extensive global human harm. While there might or might not be a global catastrophe threshold, it does appear that asteroid collision poses a substantial global catastrophic risk to the human population.

5. A Global Policy Boundary

This section assesses the policy implications of a possible but uncertain global catastrophe threshold for asteroid collisions. It applies the concept of a global policy boundary to asteroid risk.

The global policy boundary concept was developed for precisely this type of situation in the context of other global catastrophic risks. The concept was introduced by Rockström et al. (2009a; 2009b) for handling the policy implications of uncertain thresholds associated with environmental changes caused by human action, such as global warming and biodiversity loss. Rockström et al. (2009a; 2009b) distinguish between biogeophysical thresholds in the global Earth system and policy boundaries set to avoid crossing the thresholds. In other words, thresholds are properties of the natural world, whereas boundaries are normative constructs set by humans for policy purposes. As normative constructs, boundaries ultimately derive from ethical considerations. Rockström et al. (2009a; 2009b) propose setting boundaries so as to have an acceptably low risk of crossing the threshold, given some socially determined ethical judgment about what would be acceptably low.

As formulated by Rockström et al. (2009a; 2009b), planetary thresholds are biogeophysical in nature. However, for policy purposes, it is typically the human consequences that are ultimately of interest. Therefore, Baum and Handoh (2014) extend the concept of thresholds to the global human system. They propose that boundaries are set to ensure an acceptably low probability of global catastrophe to human civilization. It is this version of the boundaries concept that will be applied here to asteroid risk.

An essential question for policy boundaries is what would be an acceptably low probability.[6] Given the high severity of global catastrophe, the acceptable probability should presumably be quite low, but how low?

The literature on the ethics of global catastrophic risk has a case for a very low boundary, in particular for catastrophes capable of causing major permanent harm to human civilization, such as by causing the collapse of civilization or human extinction (Sagan 1983; Ng 1991; Tonn 2002; Bostrom 2013; Maher and Baum 2013). Essentially, if human civilization manages to avoid a sufficiently large global catastrophe, it (and its descendants) can survive and flourish for an

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[6] Given limited resources for reducing global catastrophic risk and pursuing other policy objectives, it may not always be possible to achieve acceptably low probabilities. In such cases, it may be appropriate to prioritize policies based on their cost-effectiveness and/or other criteria. Analysis along these lines is beyond the scope of this paper.

extremely long time into the future. Earth will remain habitable for around a few hundred million to a few billion more years, until the Sun becomes too warm for life as we know it to persist (O'Malley-James et al. 2014; Wolf and Toon 2015). This long-term astrobiological perspective is especially salient in the context of asteroid collision, which derives from astronomical processes and is capable of altering the evolutionary history of life on Earth over geologic time scales. Likewise, a collision that alters the long-term fate of human civilization would be a massive loss. In ethical terms, the value of the massive future loss depends on one's degree of concern for future outcomes. This is a highly contested issue (Cowen and Parfit 1992; Weinberg 2008). Even absent significant concern for future outcomes, global catastrophic risk can still be important, just not to the same extent (Posner 2004).

Tonn (2009) presents several procedures for calculating the acceptable probability of global catastrophe, the first of which (Section 3.1 in Tonn 2009) adapts readily into risk terms. This procedure is based on the observation that individuals are willing to accept a certain probability of their own death in risk tradeoffs, with 10^{-6} being a figure commonly used in risk analysis. Assuming an ongoing population of 10^{10} and an additional ~10^{8} generations over the next ~10^{9} years (roughly Earth's habitable lifetime), this gives an acceptable probability of 10^{-16} if one only cares about the present generation and 10^{-24} if all generations are valued equally. These various assumptions are all debatable, but they nonetheless provide a starting point for thinking about acceptable probabilities.

Even the higher 10^{-16} figure is still an extremely low probability. It forces the question of whether a collision below some threshold would have a probability of global catastrophe below (e.g.,) 10^{-16}. For example, Chapman and Morrison (1994, p.35) set the global catastrophe threshold at asteroids of 0.6km diameter on grounds that "It would take a very unfavorable combination of parameters coupled with an assumption that human society is very fragile, to imagine that an object with a diameter of ≲0.5km could produce a global catastrophe". Essentially, they are saying that there is a low probability of global catastrophe from asteroids smaller than 0.6km. But their analysis may not indicate a probability as low as 10^{-16}. Such an incredibly small probability can push the burden of evidence in the opposite direction: while it may be difficult to imagine global catastrophe below some threshold, may be even more difficult to imagine what evidence would provide enough confidence to believe the probability is below 10^{-16}. In other words, unless one can effectively rule out the possibility of global catastrophe, the threshold has been set too high.

Where, then, should the global policy boundary for asteroid risk be set? To address this question, some interpretation of the literature is needed. Studies typically propose a global catastrophe threshold in the 10^{4} to 10^{6}MT range, or around 500m to 2km diameter, on grounds that such events would put enough material into the stratosphere to cause global environmental effects with potentially significant human consequences (Chapman and Morrison 1994; Toon et al. 1997; Stokes et al. 2003; 2017; NRC 2010). This range is somewhere between the tropopause and photosynthesis thresholds.

Reinhardt et al. (2016) take a different approach, combining thresholds for collision energy and the mass of ejected material.[7] The collision energy threshold is just 200MT, apparently corresponding to the tropopause threshold. The ejected material threshold is 1.28×10^{14}kg. While the meaning of the 1.28×10^{14}kg figure is not clear from the text of Reinhardt et al. (2016), a plausible interpretation is that it is a calibration in order to ensure 100% probability of global

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[7] The mass of ejected material variable may refer specifically to the mass ejected into the stratosphere, though this is not clear from the text of Reinhardt et al. (2016).

catastrophe for collisions involving asteroids of 1km or larger. Collisions with asteroids in the range of 250m to 1km are found to have a probability of global catastrophe between zero and one, depending on other properties of the collision such as asteroid density and collision angle. This is a notable result because 250m is a substantially lower minimum diameter for global catastrophe. Reinhardt et al. (2016) claim, quite plausibly, that this lower result follows from this study's consideration of a wider range of possible physical properties of collisions, i.e. using probability distributions instead of point estimates for physical collision parameters. However, this study does not model the human consequences of global environmental effects, for which even wider probability distributions are warranted. This suggests that the minimum diameter for global catastrophe could be even lower than 250m.

For policy purposes, the most important variable is asteroid diameter. Diameter is the basis for programs to detect and potentially deflect large Earthbound asteroids, such as the Spaceguard program. Asteroids with larger diameters are generally easier to detect but more difficult to deflect. Therefore, the policy boundary should be set at a diameter below which there is a sufficiently low—perhaps extremely low—probability of global catastrophe. A reasonable upper bound for the boundary is 250m, which is the minimum diameter threshold reported in the prior literature. Given the considerable uncertainty in the human consequences, in addition to unclear and unresolved details regarding the physical and environmental dimensions, a suitable boundary should be lower than this.

Taking all these factors into account, this paper proposes a policy boundary of 100m diameter. At 100m, very few asteroids would have globally catastrophic effects, and possibly none at all. Indeed, a typical 100m asteroid would collide with energy around 100MT (e.g., Harris et al. 2015, Figure 2), which would typically put a rather negligible amount of material into the stratosphere. There may not be any 100m asteroids capable of causing global catastrophe. Such a boundary would achieve the goal of a very low probability of global catastrophe from asteroid collision.

The above is specifically for global catastrophe from the global environmental effects of asteroid collisions. However, it is also possible for local effects to cause global catastrophe, such as by triggering nuclear war (Section 3). This possibility suggests an even lower policy boundary. The 2013 Chelyabinsk explosion was around 500KT (Popova et al. 2013). This is substantially larger than the smallest nuclear weapons in current arsenals, which are around 10KT (Kristensen and Norris, 2015a; 2015b), let alone the smallest ever produced, which was 10 tons (the US W54). These explosive energies are substantially lower than those considered for global environmental effects of collisions.

An important factor is that small asteroids explode in the upper atmosphere. Estimates for the lower bound of the diameter of asteroids capable of causing surface damage include 150m (Hills and Goda 1993), 40m (Stokes et al. 2003), and 10m (Harris et al. 2015). Even a 1m asteroid could produce an explosion substantially larger than 10 tons. (For comparison, the 500KT Chelyabinsk asteroid was 20m.) This suggests that a threshold of around 10 to 150m, above which there could be a near-surface explosion with the force of a nuclear weapon. Given uncertainty in the threshold, and especially noting that threshold estimates have lowered over time, a policy boundary should be set lower, perhaps around 1m. A 1m policy boundary may seem quite low; this is by design, in order to ensure a very low probability of inadvertent nuclear war.

A quirk with this logic is that nuclear war plans often call for high-altitude nuclear explosions due to the resulting electromagnetic pulse, which can cause broad damage to electrical infrastructure. The altitude needed is above 40km and optimally around 110km (Miller 2005). This range is similar to the altitude of some asteroid explosions, such as asteroid 2008 TC3, a 4m diameter asteroid that exploded 37km above Sudan (Jenniskens et al. 2009), in a 1.2KT explosion (Jenniskens 2013). A high-altitude asteroid explosion could be mistaken for an electromagnetic pulse attack, thereby triggering war. Indeed, there is historical precedent for this in the 1995 "Norwegian rocket incident" in which a high-altitude scientific weather rocket launched by Norway and the US off the Norwegian coast was picked up by Russian radar as a potential electromagnetic pulse attack. Russia reportedly reacted by putting its nuclear forces on full alert and notifying President Yeltsin for instructions on whether to retaliate, though how close of a call this was is debated (Lewis et al. 2014; Tertrais 2017).

There are several reasons to discount the possibility of a high-altitude asteroid explosion being mistaken for an electromagnetic pulse attack. First, the nuclear weapons used for an electromagnetic pulse attack are likely to have a higher yield, in the 100KT to 10MT range. Second, military monitoring systems could quickly distinguish a high-altitude asteroid explosion from an electromagnetic pulse attack. The electromagnetic pulse effect derives from gamma ray emissions from a nuclear explosion (Miller 2005). Asteroid explosions do not emit gamma rays and thus would not release an electromagnetic pulse. Third, historical data suggests that high-altitude asteroid explosions tend not to raise military concerns. These explosions occur frequently, but none were identified in a detailed review of the history of nuclear war false alarms (Baum et al. 2018). It is possible that there have been such false alarms—details of them may be undocumented or classified—but the lack of known historical incidents does provide some measure of confidence. Therefore, the threshold for asteroid collisions causing nuclear war is likely to be at the size capable of causing surface damage, found to be at asteroid diameters around 10 to 150m, with the policy boundary set accordingly, perhaps at asteroid diameters around 1m.

6. Other Policy Implications

Perhaps the most basic policy question for asteroid risk is how aggressively the risk should be mitigated. All else equal, larger risks merit more aggressive mitigation. (There are other factors, such as the costs of mitigation.) A more careful consideration of the considerable uncertainty in the human consequences of asteroid collisions shows that the risk is probably being misestimated. But is it underestimated (suggesting more aggressive mitigation) or overestimated (suggesting less aggressive mitigation)?

One reason why the risk has likely been underestimated is that risk analyses have not accounted for all of the human consequences. For example, this paper documents potential indirect social effects of asteroid collisions, such as systemic economic disruption and inadvertent nuclear war. This is an entire category of human consequence that will tend to increase the severity of asteroid collisions (i.e., the indirect social effects will tend to be harms, not benefits). There may also be other types of human consequences not yet accounted for. Superficially, one would expect these to tend to increase the severity as well. A full accounting of human consequences would point to more aggressive risk mitigation policy.

There is a more ambiguous effect from the general uncertainty about the human consequences. Perhaps humans will be successful at coping with the various effects of collisions, in which case the risk has been overestimated, or perhaps they will be unsuccessful, in which case the risk is underestimated. The policy boundary perspective argues that, in the face of such uncertainty, policy should err on the side of caution. That means a more aggressive risk mitigation policy, especially to reduce the risk of global catastrophe.

In practice, this means, among other things, continuing to detect more near-Earth asteroids. The original Spaceguard goal was to detect 90% of near-Earth asteroids of 1km or larger (Morrison 1992). More recently, the 2005 NASA Authorization Act (US Public Law No. 109-155) included the George E. Brown, Jr. Near-Earth Object Survey, instructing NASA to detect 90% of near-Earth objects (asteroids and comets) of diameter 140m or larger. The current detection rate is estimated at estimated 93% for NEOs 1km or larger, 5% for NEOs approximately 100m, and less than 0.1% for NEOs approximately 20m (Stokes et al. 2017, Table 2-1). A policy boundary of 100m for global environmental effects requires further detection past the 2005 NASA instructions.

A 1m boundary for inadvertent nuclear war has a different set of policy implications. To prevent global environmental effects, the asteroid collision must be prevented, hence the detection effort is accompanied by plans to deflect Earthbound asteroids away (NRC 2010; Harris et al. 2015). To prevent inadvertent nuclear war, all that is needed is to ensure that the collision is not misinterpreted as a nuclear attack. To that end, two types of policies could be productive.

First, the asteroids community educate military personnel, political leadership, and the public about asteroid collision, to help avoid misinterpretations. Morrison (1992, p.9) writes that “Although it is expected that sophisticated nuclear powers would not respond automatically to such an event [an asteroid explosion], the possible misinterpretation of such a natural event dramatizes the need for heightening public consciousness around the world about the nature of unusually bright fireballs.” The history of nuclear war false alarms suggests that the reaction of nuclear powers cannot be taken for granted. A heightened consciousness for military personnel, political leadership, and the public would be an important goal for asteroid policy to pursue. Existing efforts to raise awareness about asteroid collisions provide a good starting point for this.

Second, communications links could be established between asteroid detection systems and military systems for monitoring for incoming attacks. Whereas plans to deflect incoming asteroids away from Earth require lengthy lead times to execute, potentially years or even decades, alerting militaries about incoming asteroids can be done within minutes. Shorter lead times can make the detection problem easier: only asteroids that are relatively close to Earth need to be identified. Recent precedents are asteroids 2008 TC3, 2014 AA, and 2018 LA, which were each detected by the Catalina Sky Survey telescope in Arizona. 2008 TC3 was detected 19 hours before it exploded above Sudan (Jenniskens et al. 2009); 2014 AA was detected 21 hours before it exploded above the Atlantic Ocean (Farnocchia et al. 2016); and 2018 LA was detected 8 hours before it exploded above Botswana (CSS 2018). Additionally, the new Asteroid Terrestrial-Impact Last Alert System (ATLAS) can provide days to weeks of advance warning (Tonry 2011). With an effective communications system, 19 hours should be sufficient to notify military personnel to expect an asteroid explosion, helping them avoid misinterpreting it as an attack. There is loose precedent for this sort of communication in the US Defense Support System, a military surveillance satellite program that, until 2009, shared data on collisions from outer space with the astronomy community (Brumfiel 2009). Programs like this can be adapted for avoiding inadvertent nuclear war, especially if they include all nuclear-armed states.

Finally, asteroids policy should include a research agenda to better handle the uncertain human consequences of asteroid collisions. A two-part agenda is warranted. First, more sophisticated risk analysis can help characterize the uncertainty, crafting probability distributions for key parameters and assessing boundaries and other policy variables. Second, social science research on the human consequences can help reduce the uncertainty, exploring the human consequences in greater detail. This research agenda should leverage synergies with similar risks, especially comet collisions, volcano eruptions, nuclear war, and (non-asteroid) tsunamis, all of which have similar human consequences.

One category of human consequences not covered by this paper but worthy of further attention is the consequences of advance warnings about upcoming asteroid collisions. For example, if it is announced that an asteroid is on trajectory to destroy a major city, then that city is likely to sustain significant emigration and economic decline. Authorities often issue mandatory evacuations and similar preparatory policies when there is advance warning of other types of natural disasters, such as hurricanes. Asteroids are distinctive in that the advance warning could come years before the disaster occurs. Additionally, any efforts to deflect an Earthbound asteroid could generate international cooperation and goodwill that has consequences beyond the deflection mission itself. Indeed, there are already calls for international asteroid deflection missions under the auspices of the United Nations (Schweikart et al. 2008). As capacity for detecting asteroids and generating advance warnings improves, this category of consequences could become increasingly important.

7. Conclusion

The risk of Earth-asteroid collision is not straightforward to quantify. Several physical and environmental factors facilitate quantification: data on historical collisions, an increasingly robust knowledge of the population of near-Earth asteroids, and the relatively tractable physics of collision and the subsequent environmental response. These factors feature prominently in existing asteroid risk analyses. However, the human consequences are more uncertain, and yet they have received less attention in the risk analyses, even though it is the human consequences that are typically of ultimate interest for policy purposes. This paper documents these phenomena and takes steps towards addressing them.

There is a deeper lesson here, one that applies to a wide range of risks, not just asteroids. A risk analysis is only as good as its ability to capture the distribution of possible human responses to the event that is at risk of occurring. Humans can display a wide range of behaviors, and so this distribution may be similarly wide. For risks of events that occur frequently, the distribution of human responses can be characterized from the event data. However, many events are too rare for robust data. Asteroid collisions above a certain size are in this category, as are the other global catastrophic risks, and risks that derive from certain anthropogenic environmental change or emerging technologies, and more. Whereas the physical dimensions of these risks may follow simple processes that can be mathematically modeled with high confidence (e.g., the physics of asteroid collision), the human dimensions are often highly complex and cannot be modeled so readily. Risk models should incorporate these human dimensions with correspondingly wide probability distributions, sensitivity analyses, and other means for capturing the uncertainty.

In policy terms, this lesson has several implications. First, one should have a sense of humility about the risk, recognizing that the current best-guess understanding may be far off the mark. At times, the best guess may be needed, such as when certain decisions must be made. Decision makers cannot afford to wait until every uncertainty has been resolved. But in general, one should be quick to identify the uncertainties and slow to make assumptions about what the correct parameter values actually are. It can be tempting to start with what is best understood and expand out towards other possibilities. This may explain, for example, why early asteroid risk analyses used point estimates for model parameters, with probability distributions only being used more recently (Reinhardt et al. 2016). However, a more reliable approach would be to start with wide probability distributions and steadily narrow them as new information accumulates via ongoing research.

Second, when the stakes are high, it is often important to err on the side of caution. Instead of requiring evidence that a catastrophic outcome would occur, it may be prudent to require evidence that it would *not* occur. Unless the possibility of catastrophe can be ruled out, policy should account for this possibility. In practice, this can mean, for example, setting policy boundaries that are clearly a safe distance from potential catastrophe thresholds, especially when there is uncertainty about where the thresholds may be. This point applies for all types of thresholds, but it applies particularly strongly for thresholds above which global catastrophe could occur. For asteroid risk, this means a relatively aggressive policy to detect and potentially deflect asteroids that could cause global environmental effects, as well as dedicated policy to prevent smaller collisions from triggering inadvertent nuclear war.

In practice, this means an interdisciplinary research agenda that includes specialists of that particular risk, social scientists knowledgeable of the human consequences, and risk analysts capable of characterizing the uncertainty, in conversation with relevant policy makers, stakeholders, and the public. In cliché form, asteroid risk is too important to be left to the astronomers, though they must play a central role. In some respects, asteroid risk is an exemplary case, especially via its longstanding policy engagement. If risks such as this are to be managed well, there will need to be more efforts along these lines.

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