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Humanity extinction by asteroid impact

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ABSTRACT

The risk of humanity extinction by giant asteroid impact is addressed. A 100 km sized asteroid impact may transform the Earth into an inhospitable planet, thus causing the extinction of many life forms including the human species. The exact reason for such a result remains nevertheless uncertain. Based on Moon crater history and NEA observations, the probability of a giant impact is between 0.03 and 0.3 for the next billion years. However, as the warning time would be in general relatively long, humanity could have time to settle on other planets with a high probability of success. The greatest threat could come from giant long period comets. We show that the probability of a giant comet impact is 2.2×10^{-12} for the next hundred years with a very short warning time. Many possible causes would lead to a degradation of life support and the extinction of humanity during the decades following the impact. It could be a lack of energy or important resources, other catastrophic events, conflicts and inefficient human organization and the preparatory phase could also play an important role. All in all, the extinction would be highly probable though not totally sure.

1. Introduction

Several questions are addressed in this paper:

1. What is the probability of impact from giant asteroids or comets?
2. What would be the warning time?
3. What is the risk of extinction of humanity by asteroid impact?

There exist thousands of giant asteroids in the solar system (Harris and D'Abramo, 2015; Petit, Kavelaars, Gladman, & Loredo, 2008). If a large enough asteroid, of the order of 100 kilometers in diameter, were to impact the Earth, living conditions could become unsustainable, to the point of threatening all known species and even humanity with extinction (Chapman and Morrison, 1994; Collins et al., 2005; Galiazzo et al., 2019; Marinova et al., February 2011; Mathias, Wheeler, & Dotson, 2017; Napier, 21 March 2015; Rumpf, Lewis, &. Atkinson, 2017a, 2017b; Shoemaker, Williams, Helin, & Wolfe, 1979; Sleep et al., 1989; Siraj and Loeb, 2021; Sloan, Batista, & Loeb, 2017; Toon et al., 1994). However, thanks to available technology, humans have shown themselves incredibly resourceful in adapting to changing situations. Numerous studies on the risk of asteroid impact have been published but few have addressed the risk posed by giant asteroids or comets (Galiazzo et al., 2019; Marinova et al., February 2011; Napier, 21 March 2015; Siraj and Loeb, 2021; Sleep et al., 1989). In addition, there are many biases and uncertainties and neither the probability of impact nor the environmental consequences have been well established. The mean number of casualties is often considered for the estimation of the risk. According to Reinhardt et al., it is more appropriate to use a probabilistic model based on the distributions that cover the range of potential casualties (Reinhardt, Chen, Liu, Manchev, & Paté-Cornell, 2015; Steinhardt, Daniel, & Elizabeth Pate-Cornell, 2014). The warning

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time is another important parameter in the extinction risk. If the impact is predicted long in advance, the object could be deflected or human beings could have time to settle on another planet and the risk of extinction would be mitigated. It is proposed in this paper to investigate these questions and to perform a probabilistic assessment of the extinction of humanity. In the first part, a review of existing methods is presented to estimate the probability of giant impacts, in the order of 100 km in diameter. For an asteroid of this size, Charon-like, with a density of 2,000 kg/m^3 and arriving at a speed of the order of 30 km/s, the kinetic energy is about 4.7×10^{26} Joules. According to Sleep et al., this energy is sufficient to kill all life forms on the surface and to boil the 200-m-thick photic zone of the oceans (Sleep, Zahnle, Kasting, & Morowitz, 1989). This amount of energy, implying a reset of biogenesis and the absence of any safe place to survive (even under the sea), is proposed here as a reference for the extinction of humanity. Importantly, if the velocity is higher, a smaller asteroid or comet would be sufficient to produce the same impact energy. In order to estimate the probability of impact, three different analyses are proposed in the first part. The first is based on crater counting, the second on Near Earth Asteroid (NEA) observations and the third on an analysis of the threat posed by long period comets (LPC). In the second part, the risk of complete extinction of humanity is assessed. It is split into three subparts. Possible mitigation strategies are discussed. Then environmental effects expected after the impact are summarized and, finally, a detailed study of the possible reasons causing humanity extinction is proposed, taking the warning time and survival capabilities into account.

2. Probabilistic risk assessment of giant impacts

2.1. Risk assessment based on crater counting

A well-known risk assessment method is based on crater counting (Ćuk, 2012; David, February 2003; Hergarten and Kenkmann, 2015; Hiesinger et al., 2010; Ivanov, 2008; Ivanov, Neukum, Bottke, & Hartmann, 2002; Jean-Pierre et al., 2018; Le Feuvre and Wieczorek, 2011; Neukum and Ivanov, 1994; Neukum et al., 2001; Öpik, 1960). The size of the crater depends on several complex parameters (Ivanov, 2008). It is assumed here that an asteroid of the category mentioned in the introduction would create a 1000 km wide crater. See methods.

Hartmann proposed an equation to determine the probability of impact as a function of the diameter of the crater (Neukum, Ivanov, & Hartmann, 2001). Let N_h be the number of craters of size D per km^2 that can be observed on the Moon after 4 billion years. Size D is defined by a crater with two boundaries D_L and D_R such that $D_L < D < D_R$, and $D_R/D_L = 1.414$. Hartmann proposed several equations, depending on the diameter of the crater. For D> 64 km, Eq. (2) holds.

$$\log N_H = -2{\cdot}198 - 2{\cdot}20 \log D_L \tag{2}$$

For $D_L > 1000$ km, cumulating all N_H values of the craters between 1000 and 8000 km, the number of asteroids is approximately 3×10^{-9} per km^2, which corresponds to 1.49 impacts for the entire history of the Earth, or a probability of 0.37 for 1 billion years.

Ivanov expanded the work from Hartmann and worked on crater production functions (Ivanov, 2008; Ivanov et al., 2002). Extrapolations from Ivanov's model suggest that there is a 1000 km wide crater 0.1 times in 3.4 billion years (from figure 8 in Ivanov (2008), which represents a probability of 0.03 for such an event in the next billion years. Ivanov nevertheless pointed out that care should be taken when considering production functions for giant craters as any statistical analysis would rely on few examples or no example at all. The proposed extrapolation is therefore approximate.

2.2. Risk from NEAs

2.2.1. Risks from observations

Several authors have tried to determine a Size Frequency Distribution (SFD) of Near Earth Asteroids (NEA), based on different observational methods (Chapman and Morrison, 1994; Gritzner et al., 2006; Harris et al., 2015; Mathias et al., 2017; Shoemaker et al., 1979; Stokes, 2003). An asteroid is termed a Near Earth Asteroid (NEA) when its trajectory brings it within 1.3 AU (IAU definition). They are categorized in Apollo, Amor or Aten. This definition is nevertheless ambiguous as many asteroids in the main belt never come as close as 1.3 AU but might one day enter that zone after perturbations caused by Jupiter or other dynamic effects (e.g., Yarkovsky (Bottke et al., 2002)).

Responding to a NASA request, Stokes (2003) proposed a specific power law to represent the SFD of NEA, see Eq. (3).

$$N(\rangle D) = 1148 \times D^{-2.354} \tag{3}$$

It is similar to the power law proposed by Harris (Harris et al., 2015). This power law suits well for small and large NEAs. For D= 10 km, the formula gives 5 asteroids. In the NEA database, there are 4 asteroids greater than 10 km in diameter: Ganymed 1036 (35 km), Don Quixote 3552 (18 km), Eros 433 (17 km) and Eric 4954 (10.8 km). There is therefore a good fit for the category of large NEAs. For giant asteroids greater than 100 km in diameter, the formula gives 10^{-2}. As there is currently no NEA of that size, this is in accordance with reality. However, there are numerous giant asteroids in the main belt. See Methods for a synthetic view of their current number and the size of the reservoir. 10^{-2} can therefore be used as a first order probabilistic estimate.

Harris proposed the same NEA SFD and directly inferred impact probabilities, based on the number of times NEAs are approaching the Earth for a given period of time (Harris et al., 2015). However, he did not consider asteroids greater than 20–30 km in diameter. It is nevertheless possible to extrapolate from the curves he provided. See Fig. 1. For a 100 km sized asteroid, the average interval of impact is estimated at 3×10^{10} years, which corresponds to a probability of impact on the order of 0.033 per billion years. This

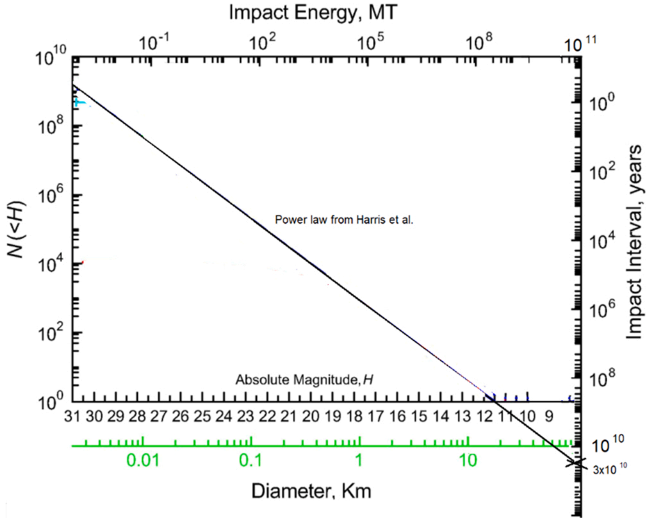

Fig. 1. Extrapolation of the curve from Figure 2.3 of Harris's paper (Jean-Pierre et al., 2018).

estimate is remarkably close to the one calculated by Ivanov, who used the crater counting method.

Once again, this extrapolation must be considered with care. Many factors may cause an increase or a decrease of the proposed estimate (see Methods for possible biases), but it is difficult to determine if there is an overestimation or underestimation of the correct probability. Importantly, as most orbital perturbations are very slow and predictable, it would take in general millions of years for an asteroid to become a NEA and a potential threat. As there is currently no giant NEA in the database, the probability of impact for the next 100 years is therefore much smaller than $1/10^{-7}$ of the probability calculated for 1 billion years. It might happen that an asteroid currently not categorized as a NEA, for instance a Centaur approaching Jupiter, is suddenly sent into the inner solar system on a trajectory impacting the Earth in less than 100 years, but this event is very unlikely. According to Galiazzo et al. (2019), for Centaurs with a diameter greater than 1 km, the Earth impact frequency is one every 14.4 M yr. The fraction of Centaurs greater than 100 km in diameter is of the order of 1 millionth (see Methods) and many of them are known and are following a stable orbit at least for the next 100 years. An upper limit of the probability of impact by a giant Centaur in the next 100 years is therefore 6.9×10^{-12}.

2.2.2. *Warning time*

In the Sentry database provided by the Jet Propulsion Laboratory, many NEAs are listed and tracked. The prediction of impact is generally provided for the next few centuries. One of the most potentially hazardous object is 1950 DA (Giorgini et al., April 2002). For this asteroid, the prediction of impact is the highest for the year 2880, which is more than 800 years in the future, after approximately 400 orbits around the Sun from the present time. The average warning time for NEAs is difficult to estimate but it is probably of this order, about 1000 years or even more, as giant asteroids are easy to detect and observe with great accuracy. Even for Centaurs becoming NEAs, numerous orbits are expected before a very close encounter.

2.3. *Risks from long period comets*

An LPC is defined as a comet with a period longer than 200 years. There are several studies suggesting that giant LPCs are representing a major threat to humanity (Chapman and Morrison, 1994; Fernandez and Sosa, 2012; Morrison, 2006; Weissman, 2006; Wiegert and Tremaine, 1999). As the impact velocity would be higher but the density would be smaller, the impact energy of a 100 km diameter LPC would be approximately the same as that for a NEA. See Methods for explanations.

Davidsson (2016) proposed a model for the formation and evolution of comets. According to these authors, above 1 km in diameter, the SFD follows a power law with a slope of 3.5. Recently, Fouchard et al., as well as Boe et al., analyzed the catalog of observed LPCs and provided another SFD of the Oort cloud objects (Boe et al., 2019; Fouchard, Rickman, Froeschlé, & Valsecchi, 2017). Their main conclusions are:

- The size of LPCs, which is tightly linked to the apparent magnitude, follows as a first approximation the same power law as the one proposed by Davidsson (2016).
- Statistically, there are 6.2 LPCs per year with $D > 1$ km that reach their perihelion with $q < 3$ AU (3 AU is often chosen because it is the starting zone where the tail becomes visible).
- 16% of the LPC with $q < 3$ AU have a perihelion < 1 AU (11 out of 70).
- The number of dynamically new LPCs is estimated at 33% with 50% uncertainties.
- There might exist in the Oort Cloud 1.5×10^{12} objects greater than 1 km in size and a single object of size 600 km.

Based on their power law distribution, it is possible to infer an estimate of the number of large objects greater than 100 km in diameter in the Oort cloud at 1.5×10^3. See Methods for a graph of the size distribution. The set of these potential giant comets represents therefore only $1/10^9$ of the total population of objects greater than 1 km in size.

An important property of LPCs is that many of them are fading and are entering the inner solar system a limited number of times before their extinction, being absorbed by the Sun, disrupted or deflected after a close encounter with a giant planet (Boe et al., 2019; Davidsson, 2016; Fernandez & Sosa, 2012; Morrison, 2006; Weissman, 2006; Wiegert & Tremaine, 1999). According to several authors concerning fading models, there is an issue with taking the number of observed large LPCs into account (Boe et al., 2019; Neslusan, 2007; Wiegert & Tremaine, 1999). It is even suggested by Wiegert and Tremaine that the best SFD fit is obtained when 95% of the LPCs are fading according to a simple law, while 5% are never fading and survive indefinitely (Wiegert and Tremaine, 1999). Furthermore, Fernandez and Sosa made the following comment (Fernandez and Sosa, 2012): “These authors obtained as the best match to the observed distribution of orbital elements a survival of roughly six orbits for the 95 per cent of the comets, while the remainder 5 per cent did not fade. We may argue that this 5 per cent of more robust comets are associated with the largest members of the comet population." If this is true, the number of giant LPCs might be more important than one billionth of the total. An estimate can be provided by counting the number of new giant LPCs from the start of the solar system, assuming that they are still all there. See Eq. (4).

$$N_{giant\_LPC} = f_{new} f_{yr} r_1 r_2 T \tag{4}$$

With:f_{new}: Frequency of new LPCs (0.33)f_{yr}: Annual frequency of LPCs (6.2)r_1: Rate of giant LPCs among the set of LPCs greater than 1 km in diameter (10^{-9})r_2: Rate of giant LPCs with a perihelion < 1 AU (15.7%)T: Period of time in years (4.5×10^9).

The result is approximately **1.5** Earth-crossing giant LPCs. The two opposing arguments below suggest either that this number is overestimated or that it is underestimated:

- First, if fading models take disruption and deflection into account, the fading rate cannot be zero. The probability may be small but it is linked to the stochastic process of stars’ encounters. According to Bailer-Jones, there is a star encounter (distance less than 2 pc with the Sun) every 46 million years (Bailer-Jones, 2018). Whatever its size, the orbit of a large group of comets would be strongly impacted, which suggests that the probability of not fading for the largest is not negligible.
- Second, after stars’ encounters, a period of comet showers is expected. According to Bailer-Jones, the average number of new LPCs could be increased by one order of magnitude during a few million years (Bailer-Jones, 2018). This increase has not been taken into account in the previous estimation, which suggests that 1.5 could be underestimated. In addition, a star encounter could bring numerous new celestial bodies into the solar system and these have not been taken into account.

All in all, 1.5 seems to be a very approximate, but possibly correct, estimate of the number of Earth-crossing giant LPCs. The risk is then tightly linked to the period of these comets. If the semi-major axis is only 1000 AU, the period is only 31,700 years, while if it is 20,000 AU, the period is 2.8 M years and the risk is much less. It is proposed here to consider the median semi-major axis of observed LPCs. According to Vokhroulick’s study, the median semi-major axis of LPCs is 3000 AU, which corresponds to a period of approximately 165,000 years (Vokrouhlický, Nesvorný, & Dones, 2019). According to Weismann, on average, an LPC has a 2.4×10^{-9} probability of hitting the Earth per perihelion passage (Weissman, 2006). The risk of a giant impact for the next 100 years can thus be inferred as 2.2×10^{-12} and as 2.2×10^{-5} for the next billion years.

3. Risk of complete extinction

3.1. Risk reduction

The first important question is to determine if it is possible to avoid the predicted impact. Numerous ideas have been proposed to deflect or destroy asteroids (Ahrens and Harris, 1992; Megan et al., 2013; Peter, Barton, & Robinson, 2004; Schmidt, 2019). As the destruction of very large asteroids is not possible with current technologies, the feasibility of a small modification of the orbit is addressed in this section. Theoretically, a shift of only 12000 kilometers (diameter of the Earth) would be sufficient to avoid the collision. However, orbital positions are not known with great accuracy and the prediction of impact is probabilistic, especially hundreds of years in advance. In addition, NEAs generally make regular passages close to the Earth and there is a probability of impact for each close encounter. Small orbital changes may therefore avoid an impact but would not eliminate the threat for the following passages. A relatively safe distance is of the order of 1 million km. This is indeed a first approximation of the distance where the gravitational force of the Sun is greater than the gravitational force of the Earth. This distance does not guarantee that the threat would be completely eliminated. However, it would be sufficient enough to avoid significant gravitational perturbations from the Earth and, unless the orbit comes close to a giant planet, the object would not represent a threat in subsequent centuries. In the case of giant asteroids, the three main options are a) stand-off explosions, b) mass driver and c) billiards shot (the billiard shot option consists of deflecting a small asteroid in order to hit the one that threatens the Earth) (Ahrens and Harris, 1992; Megan et al., 2013; Peter et al., 2004; Schmidt, 2019). Other options, like coating the asteroid’s surface would provide very little thrust and could be interesting only if the warning time is extremely long (Paek, 2012). Whatever the option, it would be very difficult to deflect the object. As the stakes are very high, a global effort might nevertheless be undertaken but with a low probability of success. See methods.

3.2. Effects of giant asteroid impact

A 10 km sized asteroid could threaten large populations on Earth but there would still exist safe places on Earth to survive (Chapman and Morrison, 1994; Collins et al., 2005; Mathias et al., 2017; RUMPF et al., 2017; Sloan et al., 2017; Toon et al., 1994). In the case of a 100 km diameter asteroid, there would be catastrophic changes in the global ecosystem. According to the model by Collins, Melosh, and Marcus (2005), the first effect would be an immense crater, possibly greater than 1100 kilometers in diameter. In less than one minute, a terrible fireball would irradiate and burn almost everything up to 4800 km from the impact. A terrific air blast would also cause massive destructions very far from the impact. Meanwhile, tremendous amounts of ejecta would climb very high and fall around the world, destroying forests, cities, causing tsunamis and earthquakes. According to Marinova et al., with such high energy impacts, there would be an antipodal crustal removal and melting (Marinova, Aharonson, & Asphaug, February 2011). While all life would be killed in a few seconds within a few thousand kilometers from the impact site, some life forms located on the other side of the Earth would survive the immediate effects of the catastrophic event. However, the situation would soon become much more difficult with a global increase of temperatures up to several hundred Celsius degrees due to several factors:

- The impact would cause melting in different places on Earth (Marinova et al., February 2011).
- There would be shooting stars and fires all around the globe (Toon, Zahnle, Turco, & Covey, 1994).
- The planet would be quickly enveloped by about 100 bar of hot rock vapor (Sleep et al., 1989).
- Part of the ocean would boil off, forming a layer of hot steam (Lowe and Byerly, 2015; Sleep et al., 1989).
- Giant volcanoes may appear all around the globe (Toon et al., 1994).

Without human intervention (see next section), all life forms on the surface and under the ocean would be killed, with the possible exception of extremophiles in deep hydrothermal vents, if they are not killed by the heat or the acidification of their medium, and bacteria located far down in the crust (Sleep et al., 1989). Importantly, during a period of several years, perhaps dozens of years, sub-micrometer dust particles would remain in the atmosphere, darkening the surface and preventing a possible restart of photosynthesis. After several years, it is expected that the heat would slowly be radiated to space and the drop of temperatures would carry on as long as the sunlight is blocked by dust particles. A cold global winter would thus follow the hyperthermia period and last for centuries. According to the literature, there are important uncertainties in this scenario. The atmosphere could remain unbreathable during decades or perhaps centuries. Volcanic activity also could play an important role in climate evolution and the noxious nature of the environment.

3.3. Survival on another planet

If the warning time is very long (at least one century) and if survival on Earth is unsure, the first solution is to settle on another planet and to achieve full autonomy before the impact. Obviously, this option does not preclude trying to survive in shelters on Earth. Numerous studies have been carried out on the different ways to undertake a settlement, especially on the Moon or Mars (Crossman, 2019; Hein, Pak, Pütz, Bühler, & Reiss, 2012; Salotti, 2020; Smith, November 2015; Zubrin and Wagner, 2011). For Mars, which is the planet with the greater quantity of resources, provided that some industrial assets are built and appropriate tools and resources are provided for the first years, the minimum number of settlers for survival could be as small as 110 people (Salotti, 2020). The idea is to exploit local resources (solar energy, underground water ice, carbon dioxide of the atmosphere, ores, etc.) and to rely on greenhouse farming and simple technologies to produce different tools and objects that are required for survival. However, according to the reviewers of the present paper, it is hard to believe that high technology systems would not be needed, for instance for life support or energy production. For that reason, this minimum could be too optimistic. Importantly, even if it were a correct estimate for survival on Mars, as solar energy would not be available in Earth shelters, another source of energy would be needed for survival on Earth and a greater number of people would certainly be required, perhaps in the order of several thousands.

If the warning time is long and if there is a concerted global endeavor, several thousands of people could easily be sent to Mars during that period. As the survival parameters are numerous and complex, there is no guarantee that a settlement process would succeed. However, the main problems would be encountered before the impact and solutions could be found very early. For example, if there are unexpected difficulties in the management of hydroponics cultures, it could be decided to stop hydroponics and to create different soils according to certain categories of plants. Another example, if the production of iron objects is much too low and the scaling up is difficult, it is possible to totally change the means of production by relocating the mining industry and importing from the Earth the tools and systems allowing this implementation. A long warning time makes thus possible the testing and adaptation of extraterrestrial shelters during several decades. It might also help a lot in the design and testing of shelters on Earth. For that reason, if there is a long warning time and the settlement of other planets were attempted, the probability of survival would certainly be relatively high.

3.4. Survival in shelters on Earth

If the warning time is short, the only option would be to try to survive in shelters on Earth. This problem has been addressed by several authors (Baum et al., 2015; Beckstead, 2015; Hanson, 2008; Turchin and Green, 2017). Shelters may save people in case of local catastrophes, but if it is required to live inside a very long period of time, probably decades, their use is questionable. In the literature, different types of shelters are considered. They can be more or less isolated, subterranean, aquatic (e.g., a submarine) or extraterrestrial. An important requirement is self-sufficiency, at least for a given period of time. According to Baum et al., surface-independent refuges, which are required here, are the gold standard of refuge excellence (Baum et al., 2015). The authors suggest that numerous qualities have to be considered for their design, especially secrecy, self-sufficiency, accessibility, pleasantness, monitoring, sufficient founder population and resources for civilization. They focus on two important issues, which are food production and waste heat rejection. In the context of a giant comet impact, as an important rise of temperatures is expected outside, temperature control inside the shelter may be the most difficult problem to solve. However, to some extent, technical solutions exist. Another problem is the dependence of humans on the existence of rich ecosystems that are home to many other life forms. According to Tonn, a catastrophic die-off of species could indeed lead to the extinction of the human species (Tonn, 2002). Shelters might therefore include many species, possibly in the form of seeds, embryonic cells or in a state of hibernation for some animals.

In order to examine the feasibility of survival, it is proposed here to consider three steps. The first step is the preparatory phase, which consists in the construction of shelters, the second is the impact and its direct consequences and the third is the survival phase, which must last centuries before a possible restart of biogenesis.

- Preparatory phase: In the case of an LPC threat, the warning time would depend on our ability to detect it. A giant comet is usually detected when it begins to be active, typically when it approaches the sun at about the height of Saturn's orbit, as was the case for a recently detected comet (Farnham et al., 2021). Using high resolution telescopes, they can be detected much earlier. The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS1) detected for instance 150 long period comets and hundreds of asteroids between 40 and 60 astronautical units (Boe et al., 2019). However, for an all-sky survey, these observations necessitate the use of numerous giant telescopes during several years, at the expense of other scientific observations. Even if an effort is made and it is detected early, as the velocity of a LPC is of the order of the third cosmic velocity (42 km/s), the warning time would not exceed 6 years. This is very little time to build giant underground shelters. In addition to that, there are uncertainties about the exact location of the impact, which depends on the accuracy of orbital parameters, the shape and compactness of the comet, the spinning parameters, the loss of material due to its activity and eventually the impact of explosions triggered by humans. With time, the prediction of the location would nevertheless be more and more accurate, perhaps with an uncertainty of one thousand kilometers three years before the impact. With the help of machines in an emergency situation, it is possible to excavate large areas in a relatively short time, or to exploit existing caves, old mines and large tunnels. Another idea is to build shelters under the glaciers of Antarctica (provided that it is far enough from the impact), using the ice as an important resource of water and a temperature heat sink (David Denkenberger). Many people might also try to survive in small shelters. A considerable number of shelters could certainly be built close to the zone corresponding to the antipodal point of the impact. Mountains may offer a better protection than plains, which could be flooded by giant tsunamis. For long term survival, giant shelters would be equipped with energy sources, life support systems, reserves of water, food, plants, livestock, industrial systems, minerals, etc. For the production of food, though the obvious mechanism is artificial light photosynthesis, other options exist, such as the use of hydrogen-oxidizing bacteria (Alvarado et al., 2020), electrically powered bacteria to produce acetic acid, and direct chemical synthesis of glycerol or sugar (García Martínez et al., 2021). Then much smaller amounts of stored or photosynthetic food would be required for a complete diet.

An important ethical problem, not addressed here, would be to determine the restricted list of persons who will be accepted in each giant shelter. Special attention would have to be paid to the skills of such persons, something that would be soon understood. Wild animals and plants may also have to be considered for inclusion in the shelters.

- In the hours following the impact, when the ejecta has fallen back onto the surface all around the globe, billions of people would be dead, including many people in shelters destroyed by the fall of meteoroids or earthquakes (Meschede, Mihrvold, & Tromp, 2011). Nevertheless, it can be reasonably assumed that numerous shelters would remain intact. Among them, many small shelters may offer a safe haven for several weeks or months, but without regenerative life support, at some point their occupants would suffer from heat or from a lack of oxygen, water, food, or energy and would finally die.
- For giant shelters, as many technologies may provide solutions for survival in harsh conditions, the exact reason for the collapse is not clear. The problem is discussed in the next section.

3.5. Cause of extinction

As proposed in a recent study about survival on Mars, the main survival issues can be categorized into five major domains: Energy, Ecosystem, Industry, Building and Human factors (Salotti, 2020). There are variables in these domains that are linked to life support systems. Failure to control, maintain, repair or adapt these systems would condemn the group of humans. A short review of the issues in each of the five domains is presented here:

1. Energy: Huge amounts of energy would be required for life support systems, especially for air conditioning but also to be able to grow plants using artificial lighting (Zubrin and Wagner, 2011). Since the dust would darken all the surface, solar energy would not be available. It is also doubtful that a nuclear reactor could be built and used underground. As the surface would be heated up, geothermal energy could be used. For instance, a pipe could reach the surface and the water inside would be transformed into steam, which could be used in a steam turbine to produce electricity. It is also possible to use the natural heat of the Earth. Solutions do exist, but their robustness and long term maintainability are questionable. For instance, it would be difficult to change a pipe or a pump if it is required to go outside.

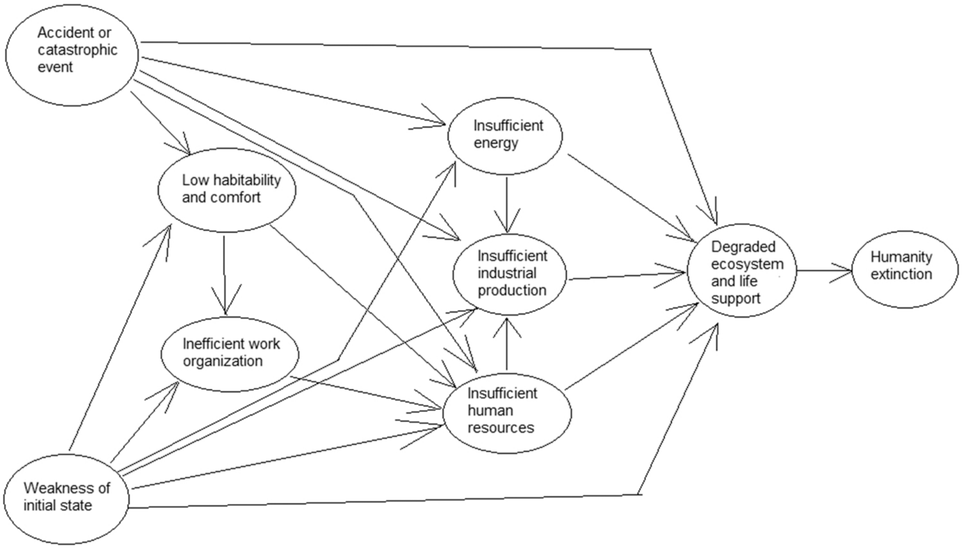

Fig. 2. Orbital velocity changes in m/s as a function of the fraction of the mass that is ejected. ΔV1, ΔV2 and ΔV3 are obtained when the matter is ejected respectively at 100 m/s, 1000 m/s and 10,000 m/s. The orbital velocity has to be modified by at least 100 m/s to obtain a change of 1 million km for the semi-major axis (circular orbit assumed in first approximation), which would send the celestial body to a relatively safe zone.

2. Ecosystem: Humans can survive only if the atmosphere is safe (pressure, temperature, composition of air), if there is enough water for humans, plants, animals and if there is an appropriate environment for growing plants, which are required for the production of food once all reserves are consumed. Numerous technologies, such as those used in the International Space Station (e.g., water recycling, carbon dioxide removal, etc.), would be essential to maintain life support and environmental variables in acceptable ranges in the shelter. For long term survival, however, maintainability is questionable. For instance, it is impossible to achieve a 100% rate for water recycling. Without a complementary source of water (which could eventually exist, but might be fragile (World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP), 2021)), survival is impossible.
3. Industry: Without help from another world, it would be necessary to implement chemical and industrial processes in the shelter in order to be able to produce spare parts and maintain and eventually replace all objects that are essential for survival (e.g., steam turbine, water recycling system, artificial lighting system for plants, etc.). It would require many different resources and involve many skilled people. In order to minimize the needs, everything should be made as simple as possible but the exact requirements are unknown. The location of the shelter, the amount and type of accessible resources and tools, and the starting state would determine industrialization capacities and eventually limit survival capabilities (Salotti, 2020).
4. Habitat: Spending several years in the same confined place would certainly be depressing. The living environment of the shelter must therefore be large, comfortable and inspiring. A possible solution would be to carry on excavating rocks and to create new living zones. Another possibility would be to build a vehicle or a protected suit that would allow going out of the shelter to explore the surface, perhaps connecting with other shelters. This is however very speculative, as the outside temperature could be too high for decades to enable any useful activity.
5. Human factors: They include all difficulties linked with human activities in such environments, such as medical care, raising children, work organization, conflict management, human resources management, decision making, etc. It also includes typical human factors that are cited to explain the end of societies, such as war, degradation of environment, lack of an important resource due to the end of collaboration, etc. (Bostrom, 2002; Diamond, 2011; Tainter, 1988).

A degradation of life support is expected in many situations. It can be fast after a catastrophic accident or very slow due to a lack of resources, system failures without repairing capabilities, or insufficient population. A detailed analysis of the causal chain leading to humanity extinction is presented in Fig. 2. Interestingly, according to Diamond, one of the main cause of a civilization collapse is the lack of adaptability to adverse conditions (Diamond, 2011). It seems indeed theoretically possible to build a giant underground city and to organize the society such that the needs of each domain are fulfilled. However, there are many possible failure reasons and as it is almost impossible to anticipate all difficulties in the five domains, the weakness of the initial state might finally drastically reduce adaptation capabilities, which are imperative for long term survival. For that reason, the probability of extinction is certainly high, though less than 1.

4. Conclusion

The risk of humanity extinction by giant asteroids or comets larger than 100 km in diameter has been assessed. A synthesis of our results is presented in Table 1.

Table 1
Probabilistic assessment.

Method or asteroid category	Probability of impact in the next billion years	Probability of impact in the next 100 years	Warning time	Probability of humanity extinction in the next 100 years
Crater counting	Between 0.37 and 0.03	Between 3.7×10^{-8} and 3×10^{-8}	N/A	N/A
NEA observations	0.033	$< 6.9 \times 10^{-12}$	In general several centuries	Negligible (enough time for Mars settlement)
Long Period Comets	2.2×10^{-5}	2.2×10^{-12}	< 5 years	2.2×10^{-12}

As our estimates are based on numerous assumptions (see methods for possible biases), these results have to be taken with care. There are perhaps one or two orders of magnitudes for uncertainties. To our knowledge, it is however the first attempt to provide a probabilistic assessment of humanity extinction by giant asteroids. The greatest long term impact risk comes from NEOs, which are already in the Inner Solar System or will enter that zone in the future (e.g., Centaurs). As the warning time would be in general relatively long, there would be enough time to settle on another planet and the extinction risk would be much lower than the probability of impact. The greatest extinction risk is associated with long period comets. For the next 100 years, the probability of impact is low, of the order of 10^{-12}, but the warning time is so short that it is doubtful that any action could mitigate the consequences. In addition, this risk is cumulative with other hazards. Denkenberger mentioned other existential risks, for instance a black hole or the Earth turned into a strangelet (Turchin and Denkenberger, 2018). For decision makers, is that sufficient to justify the settlement on other planets? The question remains open. However, if no effort is made to settle on other planets, extinction probability increases with time. For instance, without extra-terrestrial settlement and only for the threat posed by giant comets, for the next million years, the probability of extinction is greater than 10^{-8}, which is high considering the possible consequences. In addition, apart from the uncertainties and possible biases (see Methods) that could lead to an underestimation of the risk, there might exist other biases that could completely change probabilities. For instance, unexpectedly, the solar system could enter a galactic zone with a high density of small bodies and the threat could suddenly be increased by several orders of magnitude. Current size frequency distributions of interstellar objects suggest that the threat posed by such objects is very low, but as models are based on very limited data, the best answer to the assessment of the risk is that we know almost nothing about it (Engelhardt et al., 2017; Moro-Martín, Turner, & Loeb, 2009; Raymond, Armitage, Veras, Quintana, & Barclay, 2018).

5. Methods

5.1. Possible methodological biases

5.1.1. Crater counting methods

For the Moon, for the last 200 million years' period, only one giant crater is known, Tycho, with a diameter of 86 km, which corresponds to an asteroid about 10 km in size (Hiesinger et al., 2010). For the Earth, it is expected that the number of collisions is greater and the impact velocity is higher. An important issue is to make a correct estimate of the diameter of the crater as a function of the size, velocity, angle of attack and density of the asteroid, as well as the type and density of the impacted ground (Toon et al., 1994; Collins et al., 2005; Marinova et al., February 2011; Neukum and Ivanov, 1994). As there exists no asteroid data, estimations are based on theoretical models, which might be erroneous. In addition, for the Earth, though several authors have tried to determine the impact risk from crater counting, this method is not effective because of the loss of information due to impact in oceans, geological activity and rapid erosion (David, February 2003; Gritzner et al., 2006; Harris et al., 2015; Hergarten and Kenkmann, 2015; Jean-Pierre et al., 2018; Stokes, 2003).

5.1.2. LHB

The late heavy bombardment (LHB) observed on the Moon suggests that the impact rate fluctuated a lot in the past (Ćuk, 2012; Hiesinger et al., 2010; Ivanov, 2008; Ivanov et al., 2002; Le Feuvre and Wieczorek, 2011; Neukum and Ivanov, 1994; Neukum et al., 2001; Öpik, 1960). All basins (30 have been identified) have been caused by the impact of a giant asteroid. According to standard cratering models, as a first approximation (it depends on many parameters), if a basin is larger than 600 kilometers in size, which is the case in a majority of them, the diameter of the asteroid was likely greater than 100 kilometers in size. However, all of them without exception are very old and from the Imbrian period, which lasted less than a billion years and occurred more than 3 billion years ago (Ćuk, 2012; Le Feuvre and Wieczorek, 2011). The LHB is a small period in the Imbrian period. Moreover, even during that period, fluctuations of the impact rate may have occurred, the youngest basin being Mare Orientale, which is dated from the Late Imbrian epoch (Le Feuvre and Wieczorek, 2011). Since then, large impact craters have been observed but only a very small number in comparison with what occurred during the LHB and none of them with enough energy to create an impact basin. The LHB period suggests that the rate of impact is stochastic and that extrapolations from smooth curves might be misleading.

5.1.3. Production functions

Several production functions have been proposed to predict the number and size of Moon craters per square kilometer. The Hartmann and Neukum production functions (HPF and NPF) are very similar for small craters with a relatively good fit with observed data but they are quite different for large ones (Ivanov et al., 2002; Neukum et al., 2001). This problem has been highlighted by several authors. Ivanov, for instance, quoted (Ivanov, 2008): “In the crater diameter range $1 < D$ (km) < 40 the NPF is well below the HPF, giving a main discrepancy of a factor of 3 at $D \sim 6$ km. One should be cautious using PFs in this diameter range, as data published by various authors show very different SFD behaviors for impact craters.” For giant craters greater than 40 km in diameter, probabilities based on statistics are even less relevant as the number of occurrences is very small. Another study suggests that “Asteroids were born big” (after accretion process), greater than 100 km in size, which could significantly affect the distribution in this category (Morbidelli, Bottke, Nesvorný, & Levison, 2009). Care should therefore be taken with crater statistics, especially for the production function associated with giant impacts.

5.1.4. *Discrete events*

According to Cuk, a series of giant impacts could be caused by the discrete event of a giant collision in the asteroid belt, which would produce a family of large asteroids orbiting on an orbit intersecting the orbit of the Earth Moon system (Ćuk, 2012). If this assumption is correct, estimations based on the crater counting method or NEA observations would be biased by two factors:

a) A sudden increase in the risk during a limited period of time due to the temporary presence of a family of potentially dangerous asteroids, which would disappear after a collision with the Earth Moon system or after a drift towards other orbits.
b) A specific size frequency distribution due to the characteristics of the colliders and the type of collision.

5.1.5. *Role of the Roche limit*

The Roche limit is the distance from a massive body within which an asteroid or comet disintegrates due to the tidal forces (Bottke et al., April 1997). This disintegration is facilitated if the material of the small body is weakly linked by electromagnetic forces, which is the case with comets and rubble pile asteroids. This mechanism may cause the disruption of the body passing close to the Earth, breaking it into many pieces, which would fall in different regions. This mechanism is usually not taken into account in the environmental effects.

5.1.6. *Influence of Jupiter*

Jupiter is a strong attractor and numerous asteroids have been drifted, captured and destroyed (or eventually ejected from the inner solar system) by the giant planet (Horner and Jones, 2008). Jupiter could act as a protecting body reducing the rate of asteroid impacts or it could also redirect many asteroids towards the Earth (Horner and JONES, 2008; Ward and Brownlee, 2000). Its role is not well understood.

5.1.7. *Asteroids were born big*

Obviously, if the number of giant asteroids regularly decreases, so does the risk. An interesting complementary question is the possibility that the SFD could be biased by the accretion process which could favor the creation of large asteroids (Morbidelli et al., 2009). Johansen et al. (2014) Morbidelli et al. proposed a modeling of planetesimal formation. They suggested that the protosolar nebula may only have produced planetesimals larger than a specific diameter, which could be close to 100 km. Smaller objects would have appeared only later due to collisional fragmentation. This hypothesis has been confirmed by a recent study, which shows that there is a lack of small TNO observations (Lawler et al., 2018; Shankman, Gladman, Kaib, Kavelaars, & Petit, 2013 February 10). The SFD could therefore be biased precisely for giant asteroids. A correction factor, if any, remains to be determined.

Possible biases are summarized in Table 2.

5.2. *Number of NEOs and size of the reservoir*

See Table 3 for the 10 largest and Table 4 for a synthetic SFD of the biggest NEOs in the main belt. According to our count, 83 asteroids are larger than 100 km. As none of them comes closer than 0.3 AU from the Earth, they do not represent a threat but, in a distant future, their orbit might change and the risk could become real.

An important complementary question is to determine the size of the reservoir of giant asteroids that may become an NEA and pose

Table 2
List of possible biases that may lead to overestimates or underestimates of the probability of impact with a giant asteroid.

Bias	Possible cause	Type of consequence
Errors in cratering models	Error in the average asteroid velocityError in the average asteroid densityError in the average impact angleError in the crater size as a function of the energy of the asteroid	Not clear, overestimation or underestimation of impact probability
Evolution of impact rate	Number of giant asteroids slowly increasing or decreasing	Not clear, possible overestimation of impact probability
Specific size distribution of impacting objects	Asteroids were large when created, Roche limit effect, Yarkovsky and York effects different for large asteroids (Bottke et al., 2002), tendency to join or leave a resonance orbit, specific influence of Jupiter, etc.	Not clear, overestimation or underestimation of impact probability

Table 3
List of the 10 largest asteroids in the main belt.

Name of asteroid	Diameter (km)
Ceres	940
Vesta 4	526
Pallas 2	512
Hygiea 10	434
Interamnia 704	332
Europa 52	304
Davida 511	290
Sylvia 87	286
Euphrosyne 31	268
Eunomia 15	256

Table 4
Size distribution of asteroids larger than 100 km in the main belt. These numbers may be slightly different depending on astronomical measurements and estimations of the average diameter.

Diameter of asteroids	> 100 km < 200 km	> 200 km < 400 km	> 400 km	Total > 100 km
Number of asteroids in the main belt	60	19	4	**83**

a threat to humanity. Apart from asteroids in the main belt, the most dangerous asteroids belong to the class of Centaurs. An important feature of the Centaurs is the instability of their orbit. Their average lifetime is relatively low, of the order of a few million years. According to several authors, a large part of the group of Centaurs is formed by objects entering this region from the Scattered Disk (Di Sisto and Brunini, 2007; Morbidelli, Emel'yanenko, & Levison, 2003). Di Sisto and Brunini (2007) analyzed the origin and distribution of Centaurs and reached the following conclusions:

- The rate of Scattered Disk Objects (SDO) becoming a Centaur is 5.2×10^{-10} NSDO/yr, where NSDO is the total number of SDOs with diameter > 1 km.
- NSDO (R > 1 km) = 7.5×10^9 (from Fernandez (Fernández et al., 2004)).
- The mean lifetime of Centaurs is 72 Myr.
- They inferred a rate of SDOs becoming a Centaur around 3.9 per year and a total number of Centaurs in the range $4.4 \times 10^7 <$ Nc (R>1 km) $< 2.9 \times 10^9$, with a mean estimation at $\mathbf{2.8 \times 10^8}$.
- Once they are in the Centaurs zone, 30% of them are still following an unstable orbit leading to entrance into the Inner Solar System. The influence of the Centaurs in the Inner Solar System and especially on asteroids in the main belt has been confirmed by Galiazzo (Galiazzo et al., 2019).
- The total number of Centaurs larger than Chiron (107 km) is between 360 and 650.

In addition to the above, the number of TNOs greater than 100 km in diameter is very high. According to Petit et al., there are probably more than 100,000 trans-Neptunian objects (TNOs) greater than 100 km in diameter in the classical belt (Jean-Marc et al., Aug 24, 2011; Petit, Kavelaars, Gladman, & Jones, 2008). The orbits of these TNOs are relatively stable as their perihelion is far from Neptune. Some of them may nevertheless slowly evolve towards the Centaurs zone because of their eccentricity and their high inclination. They do not represent a direct threat but may be considered a reservoir of potential Centaur asteroids over the very long term.

5.3. *Size frequency distribution of Long Period Comets*

As Jupiter Family Comets and Halley Type Comets have relatively short periods, most of them have already been identified, especially the largest, and they are therefore considered in the study of NEOs presented in a previous section (Whitman, Morbidelli, & Jedicke, 2006). Most LPCs, however, remain undiscovered. An important question is to determine the size of comets for the same energy at impact as asteroids. LPCs are in general much less dense but their relative velocity is much higher. According to several authors, the average density is between 400 and 600 kg per cubic meter (Boe et al., 2019; Fouchard, Rickman, Froeschlé, & Valsecchi, 2017; Kaib & Quinn). As we are interested in giant comets, the gravitational force is stronger and their density is probably closer to the upper estimation. It is proposed here to consider an average of 600 kg/m3. According to Weissman, the average velocity at impact is 53.5 km/s (Weissman, 2006). Given the kinetic energy calculated in the introduction of the paper for asteroids, the diameter of the comet for the same energy must be 102 km. As uncertainties on the average density of giant asteroids and comets are very high, a difference of 2% for the size is not significant. For the sake of simplicity, the same size is considered for the risk assessment.

Boe et al. (2019) analyzed the size and frequency distribution of LPCs. They used a power law for their model with $\alpha = 3.5$. The same law has been used to infer the number of comets greater than 100 km in size, see Fig. 3. The cumulative total is approximately 1500.

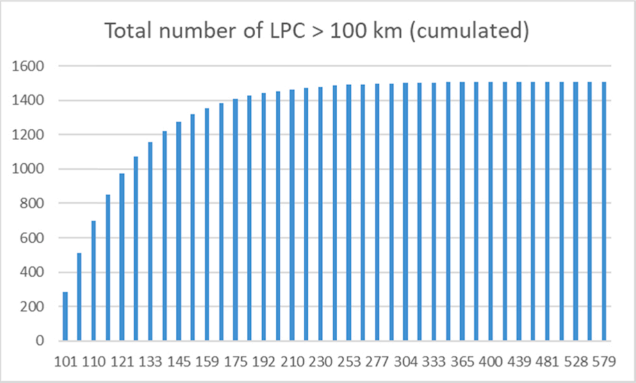

Fig. 3. Causal chain of humanity extinction.

5.4. Risk reduction

Two cases have to be considered: First, if the threat is a NEA with a relatively short orbit, for instance with an aphelion close to Jupiter and a perihelion close to the Earth, and if it enters at least once in the gravitational zone of the Earth (less than one million kilometers), it means that the Earth and the NEA reach approximately the same point in space with a different orbital period. Nevertheless, depending on the ratio of the two orbits, there is a new close encounter periodically. For instance, asteroid named 2021QM1 (see *https://neo.ssa.esa.int/risk-list*) approached the Earth in 1961 at 255 000 km distance and it is expected to approach once again in 2052 with a nominal distance of one million kilometers. However, despite our efforts to determine its orbital parameters with high accuracy, there are important uncertainties on that prediction and the impact is possible with a probability close to 10^{-4}. As the same rules of celestial mechanics apply to all objects, we would not be able to predict ten years before the event that a NEA would definitely miss or impact the Earth. If we try to deflect a giant NEA a long time before the close encounter, and if the deflection is only a shift of a few thousand kilometers, we might just reduce a little bit the probability of impact, but it would not guarantee zero impact and we might as well understand some years later that the deflection finally increased the probability of impact. In addition, there would be other close encounters several decades later, each time with important uncertainties about the probability of impact. We might try to improve the accuracy of orbital parameters and the model that predicts the position of the Earth and the NEA years in advance. However, this is very difficult because the laws of orbital mechanics are very complex and uncertainties of a few kilometers quickly increase with time, especially if the NEA comes close to a planet, which is expected after each Earth encounter. This is the reason why the deflection must be significant or not attempted at all.

Second, if the object is a long period comet (orbital period of several thousand years), even if an effort is made and it is detected early, as the velocity of a LPC is of the order of the third cosmic velocity (42 km/s), the warning time would not exceed 6 years, which is much too low for a deflection mission. If the Earth is missed, the threat would still exist, but it might take several thousand years before the object comes back with high uncertainties on the exact timing and trajectory of that return (too far for telescopes), therefore still with a very short warning time and no time for a deflection mission.

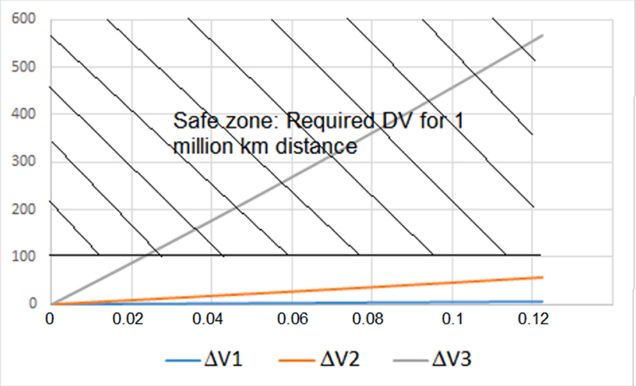

Fig. 4. Cumulative number of LPCs greater than x km in diameter, starting with x = 101 km. Curve extrapolated from the power law proposed by Boe et al. (2019).

For the deflection, only three options are considered here:

- Stand-off or underground nuclear explosions: In both cases, the fragmentation may be an option only in very special circumstances, depending on the shape, the density and the binding energy of the constituent parts (Ahrens and Harris, 1992; Schmidt, 2019). The most effective option is to place nuclear warheads under the surface in appropriate locations. A series of nuclear explosions could eject large amounts of matter more or less in the same direction and this strategy would have to be repeated several times. However, as shown in Fig. 4, the velocity of the ejected mass must be very high and the fraction of the ejected mass must also be significant to produce any noticeable change to the orbit. Would it be possible to excavate dozens of cubic kilometers of rocks using nuclear explosions? Let us take an example. If a single nuclear explosion removes 10^{-3} km^3 (a cube of 100mx100mx100m) and the average velocity of the ejected mass is 1000 m/s (optimistic), one million explosions would remove 10^3 km^3, or only one thousandth of the object. The velocity change would therefore be on the order of 1 m/s, which is not sufficient. Ten million explosions is probably an optimistic minimum requirement. Another important problem is that the threatening object might be reached only at specific moments according to the laws of astronautics, with important constraints on launching windows, for instance, a few weeks every ten years. This means being able to launch several hundred thousand rockets in two weeks, each of them carrying numerous nuclear warheads, and to iterate the process until the warning time is exhausted. Since the stakes are very high, such a colossal industrial effort might be attempted, but the feasibility seems uncertain. (Megan, Dearborn, & Schultz, 2013).
- Mass driver: The advantage of this option is to provide a continuous action on the object and to control the ejection velocity (Ahrens and Harris, 1992; Schmidt, 2019). As shown in Fig. 4, if the matter is ejected at 10 km/s, which is possible using existing technologies such as ion thrusters, 2% of the asteroid must be excavated to move its orbit towards a safe zone, about 1 million km distance from the original prediction. In terms of energetic efficiency, this strategy is better, but 2% is nevertheless a huge amount of matter. Assuming a 100 km sized asteroid, it would represent about 10^{13} tonnes. Even if numerous nuclear power plants are installed on the asteroid and many ejection systems are used at the same time, it would be necessary to eject each second 331 tonnes of material during 1000 years to achieve such a quantity. The feasibility of this option is therefore doubtful.

- Billiards shot: This option consists of deflecting a smaller asteroid, putting it on a collision course with the Earth-threatening NEO (Peter et al., 2004). In order to deflect the giant asteroid, the smaller one must also be very large, at least of the order of 2% of the former's mass (extrapolation from Fig. 3 for a ΔV of 10 km/s). Deflecting the smaller would therefore be almost as difficult as the previous options, unless it is already very close to a collision course with the threatening NEO.

All in all, except in very special circumstances, even if the warning time is very long, it seems difficult and uncertain to deviate a giant asteroid from its collision course.

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