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Survival Issues after Giant Asteroid Impact

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Abstract

Consequences of a gigantic asteroid impact with the Earth and survival issues are examined and discussed. Two survival scenarios have been analysed, based on the state of the art of the physical involved phenomena, human needs and the capacities and limits of the available technologies. The possible causes of human extinction may come from the direct consequences of the impact, linked to the size or the different characteristics of the asteroid. They can also come from the indirect consequences of the impact, such as the struggle for resources, generalised anarchy, or the mental distress of survivors, who no longer find the desire to fight for survival in very difficult conditions. Various parameters have been considered, including the diameter of the asteroid and the location of the impact. It is shown that survival is very difficult. Human extinction is nevertheless expected in the worst case scenario, if outside living conditions remain unliveable during decades or centuries.

Keywords: giant asteroid impact, giant comet impact, human extinction

1. Introduction

Numerous authors examined the consequences of asteroid impacts [4,9,11,17,23,26]. It is well known that if the energy of the impact is high enough, numerous plant and animal species may be in danger of extinction, humanity included [24]. However, as humans may build shelters and use dedicated technologies to survive in harsh environments, the exact cause of human extinction is not clear. The use of shelters for survival has been proposed by several authors in case of global disasters and risk of human extinction [2,3,27]. These risks include:

- Risks related to global warming (addressed by Turchin and Deckenberger [27]). In the context of survival, technology and research will take a step back, as will the climate, which will be disrupted by the phenomenon of perpetual winter. Then the

notion of global warming would become meaningless since there would be no climate to speak of.

- Risks linked to conflicts with artificial intelligence systems. However, according to other authors, the use of shelters might not be a useful solution [3].
- Risks related to nuclear weapons or biological / chemical warfare. In the 21st century, nuclear weapons are considered the potential trigger for a third world war. However, in the context of survival, the nuclear weapon states would all be subdivided into shelters. Furthermore, these states would no longer represent any "power" or "threat", since the global economic and political system would no longer exist. Modern societies would therefore collapse, but the risk of extinction would be low.

- Risks of pandemics. Shelters can be efficient against the spreading of dangerous viruses. However, another solution is to wear hermetic clothes and to follow strict procedures to avoid contamination. Pandemics could therefore cause sanitary disasters but probably not the end of humanity.
- Risks related to the variability of physical constants and other exotic threats. Turchin and Deckenberger classify certain risks as theoretical, such as those related to the variability of physical constants [27]. Indeed, there are studies suggesting that the values of the physical constants which govern our universe might in fact fluctuate. If such a change were to occur, nothing would ensure that the atmosphere would still be breathable and the Earth easily habitable. In this case, the construction of shelters might be a solution for survival.

It is proposed here to review the global effects of a gigantic asteroid or comet impact and then to discuss the possible construction of shelters for survival, taking into consideration the selection process, the preservation of lifeforms and the humanity heritage. Two case studies are finally examined to better understand survival issues. In the first case, survival is possible, and in the second, humanity disappears. The exact cause of extinction is discussed.

2. Expected direct impact effects

2.1 Energy transfer at impact

When the object touches the ocean or the ground, part of its energy is converted into a shock wave, tsunami or seismic waves [4]. But most of the energy is released both in the form of thermal energy, which heats the impactor and the impact zone, and in the form of kinetic energy transferred to the ejecta.

When the object hits the ocean or the ground, a series of shock waves are generated and propagate through the object and the impact zone. The pressure of these shock waves is sufficient to toss some pieces of the object back into space.

According to Schultz, the heat is sufficient to vaporise and / or melt 1 to 10 times the mass of the impactor (depending on the impactor velocity, typically between 15 and 50 km / s) [23].

If a meteorite falls into the ocean, then objects with a diameter of more than 1/12 of the depth of the ocean will crater the ocean floor. In addition, water will be sent into the atmosphere and to space [16].

2.2 Shock wave

The most important local effect occurs when the object enters the atmosphere, creating a powerful shock wave. Shock waves are devastating and may cause great damages thousand kilometres away from the impact zone. However, as their effect decreases with the distance to the impact zone, they do not represent a threat to populations located very far and cannot be the primary cause of human extinction.

2.3 Ejecta

When the impactor is very big, the size and number of ejected rocks are very important [4,18,24]. With very large objects, heavy rocks can be sent above the atmosphere and fall back onto the Earth almost everywhere, even at the antipodal zone of the impact location [16]. As they would be heated up during atmospheric re-entry, they would cause forest fires all over the world, killing almost all terrestrial plants and participating in a global increase of temperatures.

2.4 Global heat and winter impact

A global increase of temperatures is expected after the impact. The intensity and duration of this period depends on numerous parameters (size and structure of the asteroid, velocity, impact location, etc.). Even if humanity survives this period, there would be a prolonged period of cold weather due to the dust and clouds that would block the sunlight [5,7,17,18].

3. Preparation before impact

3.1 Main issues

If the warning time is long enough, thousands of people could be sent to the Moon and Mars in an attempt to settle there and achieve full autonomy [22,25,28]. This would be expected in the case of most categories of asteroids, whose orbit is precisely known hundreds of years in advance, but it would be almost impossible in the case of long period comets, with a warning time of 3 to 10 years, depending on the date of first observation [17,26]. Nevertheless, even if extra-terrestrial settlements are successful, billions of people would still live on Earth and would try to survive. During the years of preparation, different behaviours would be observed. Part of the population would live in denial; they would not accept the idea that an asteroid is about to collide with Earth. In general, however, many shelters would be built and lots of consumables and tools would be accumulated into them. Several important issues would have to be addressed:

- As the number of shelters would be very small and not sufficient for the population of Earth, how to select the individuals who would be allowed to come in and how to avoid conflicts?
- Is it necessary to include other life forms and if yes, how?
- How to protect the heritage of humanity?
- Even though the shelters would have been tested, how to maximise the probability of their resistance at the time of impact and the resilience over time?

3.2 Selection process

We are faced with two facts. Firstly, only the humans protected in the shelters will have a chance of survival. Secondly, only a small fraction of the human population will be able to take advantage of the most efficient shelters. In fact, the number of shelters that will be built is constrained by :

- The geographical area where the shelters are installed, which is located thousands of kilometres away from the impact zone.
- The complexity of the systems to be set up (digging of underground tunnels, construction of habitats, the integration of energy systems, life support systems, artificial greenhouses, industrial systems, etc.)

The question of selecting the individuals who will go to these shelters thus becomes paramount. The most important criterion is to maximise the chances of survival and rebirth of Humanity, which could be incompatible with other essential criteria, such as saving the greatest number, which could be shocking from an ethical standpoint.

Let us consider the objectives for this "chosen" population. This population must have the physical and psychological aptitudes and skills/qualifications necessary to survive in a shelter for a decade or more, and then to live outside the shelter in a very different environment. Then, this population will have to ensure the renewal of Humanity.

What does that mean for the selection process? First, the number and proportion of each gender. According to the study by Marin and Beluffi [15], 98 persons is sufficient for the criterion of genetic variability. One possible option is to choose a largely female population. Indeed, sperm banks today allow to keep male gametes to be kept for decades. Science also makes it possible to preserve female gametes, but it is always necessary that these be grafted to a woman before being able to give birth. The rebirth of the human species would therefore be facilitated if we had a significant proportion of

women. However, according to Marin and Beluffi a balance between the two sexes would not be penalising. It would even be preferable if we consider that the two-parent family is the most appropriate context for the development of the child [15]. Second, the age of the population. We need a population that is still fertile around 15 years after impact, while at the same time maximising the working population. This implies relatively young individuals and a relatively balanced age pyramid with young children, which is also proposed by Marin and Beluffi.

Let us now consider the skills and competencies that members of this population will need to possess. Like astronauts, they will have to live in a confined space for a long time. In addition, there is the psychological pressure of being a survivor. This requires special physical and psychological resistance skills. One way to select these members would be to have them take tests similar to those that future astronauts must pass. This population will also have to manage in a completely autonomous way the life in the shelter, then out of the shelter. This involves a large number of diverse technical tasks and highly skilled workers in a large number of areas. Considering a list of needs and skills, a recent study suggests a minimum number of people of 110 for survival on Mars [22]. This number must certainly be much larger in the present case, of the order of a thousand, on the one hand to maximise the chances of survival, and on the other hand to preserve a level of life and comfort superior to that of survival in degraded mode. Moreover, from a social point of view, Dunbar's number indicates that above 100 to 150 people, mutual trust and communication are no longer sufficient to ensure the functioning of the group [6]. An appropriate organisation of life and tasks, as well as a system of justice and maintenance of order are thus necessary. Whatever political organisation is adopted within the shelter, there will be a need for rulers, managers, magistrates and security officers.

3.3 Key technical choices to ensure survival

Two domains are considered here, food and energy production. Concerning food, many options exist. Two solutions are considered here to ensure survival. The first one is insects farming [20]. Unlike conventional farm animals, insects have the great advantage of being very low in resource consumption. In addition, food recycling is possible, as insects can be cultivated using organic waste. They also represent an economical production in terms of working space, as it is possible to

farm them horizontally as well as vertically. Low in fat, high in protein and rich in micronutrients: the health benefits of insects are now confirmed. The second solution is hydroponics, which allows growing a large number of plants without ground [12]. The nutrients necessary for the growth of the crops are directly injected into the water, which is subsequently filtered to purify it from the waste products released by the plants. This technique has many advantages because it allows a significant saving of water thanks to its closed circuit system. It also allows to realise vertical cultures, which take less space and which consequently allow a more intensive production of food than a culture in traditional ground for the same surface. Hydroponics has another major advantage: it is a technique that can be combined in symbiosis with other crops, such as bacteria or fish [19]. In the latter, called aquaponics, the waste products of the fish farm are the nutrients for the plants, while the plants filter the water from the fish by feeding on it. This beneficial cycle would be an asset for the surviving populations. The disadvantage of hydroponics is the need for complex equipment to precisely control water quality and to produce perfectly dosed nutrient solutions, which requires additional industrial capacity. Whatever the preferred option for growing plants, an important issue is the enormous amount of energy that is required for artificial lighting [28].

Concerning energy production, an interesting solution is the use of geothermal sources. The use of geothermal energy is feasible to supply electricity to an underground base [21], but the feasibility must be checked. The sustainable exploitation of a geothermal source implies an energy extraction rate limited to the heat flow feeding the resource. Overexploitation of the site may result in the depletion of the geothermal source for a certain period of time according to Rybach *et al.* Unlike other renewable energies, deep geothermal energy has the advantage of not depending on unpredictable weather conditions. It is therefore a quasi-continuous energy source. It is only interrupted during maintenance operations on the geothermal plant or the distribution network. This solution remains in mercy of the external conditions caused by the asteroid.

3.4 Ecosystem preservation and recovery

The damage caused by the meteorite will strongly impact the ecosystems. In order to preserve biodiversity and to be able to revive it artificially, it seems essential to safeguard this biodiversity in a certain way. For us, the best solution to meet this challenge is cryopreservation [14].

Since the publication of Lee *et al* three decades ago [13], an increasing number of insect species have been successfully cryopreserved. We are now able to store insect larvae or eggs indefinitely, which can help preserve valuable genetic resources. Cryopreservation protocols have also been developed and utilised for practical applications [14]. These methods could be a solution to preserve insects that have an important role in ecosystems, such as pollinators. As mentioned by Almiñana, mammals can be conserved in the same way [1]. Embryo cryopreservation is now a viable method for the long-term storage of valuable genetic resources. Regarding plants, a simple solution would be to keep the seeds safe. It would then be necessary to set up projects such as the Svalbard Global Seed Vault in order to safeguard a maximum of plant species [8].

A living species is part of a complete system. If it is inserted in the wrong ecosystem, it may not survive, or it may disrupt it. To save a species, it is therefore preferable to also save its entire ecosystem. That is why, the sites must be predisposed before reintegrating living species into the environment once conditions permit. The plants and other elements necessary for their survival must already be present. Thus, by saving different species we could rebuild an ecosystem similar to the original one.

The development of different cryopreservation banks around the world would secure the preservation of biodiversity, and eventually revive some dead ecosystems.

However, cryopreservation protocols are specific to each type of species and embryo, just like for plants and insects. This is why this approach is difficult to implement. Even if it would represent a hope for the safeguarding of certain species that could not survive the catastrophe, several limits are posed. For example, for the cryopreservation and recovery phases, a rigorous protocol must also be followed as explained in [14]. Other limitations for long-term storage of cryopreserved embryos will be the cost for the astronomical amount of liquid nitrogen required for the cryopreservation process, as well as the storage space and equipment associated with the liquid nitrogen demand [1]

This shows that the feasibility of setting up backup banks of different species around the world is feasible, but that there are some limitations. It would then be necessary to prioritise the survival of species according to their capacity to quickly revive ecosystems with a redevelopment of biodiversity. This would require a preliminary study to be conducted during the disaster preparedness phase.

3.5 Humanity heritage

Depending on the category of the object, different options exist to preserve it from total destruction.

- **Monuments**

The universal heritage represents today 812 monuments. In order to keep a trace of all important monuments, there is the possibility of reconstituting them in three dimensions. For instance, for Notre Dame (Paris cathedral), several billion points have been recorded for a detailed 3D reconstruction of the monument. However, a possible technological difficulty is to preserve the data during a long period of time (possibly decades or even centuries). Photographs are much less accurate but can last much longer.

- **Books, written documents, paintings**

A possible option is to store all information numerically. However, once again, the slow degradation of the storing devices might be an issue. A complementary option is to build specific shelters for the storage of these objects, which do not require life support systems. They could be recovered centuries after the cataclysm if necessary, if someone survives.

- **Sculptures and other 3D objects**

3D models of sculptures and other 3D objects that can be found in museums (for instance prehistoric objects) can be stored numerically. Like books, provided that they are easily transportable, they can be saved in dedicated shelters without life support.

- **Music**

It seems relevant to bring musical instruments in each shelter, so that each individual can play his favourite song or music and participate in the transmission of a cultural heritage. For the storage of songs and music, it is possible to store the sounds on dedicated devices for an exact reproduction and at the same time to store in documents all relevant information to be able to play them again.

3.6 Final preparation

One week before the impact, the organisation and evacuation of some populations to shelters would begin. Some states would have failed to contain their population and would suffer a civil war or would have been reorganised into several communities. The most likely organisation within the shelters is a pyramidal hierarchy. Opinion differences among populations could indeed cause the loss of control of the shelter and a military regime could be appropriate.

4. Scenario 1

4.1 Scenario definition

This scenario is proposed to assess the survival of human species in a very hostile environment, mainly at the climatic level. An asteroid 50 km in diameter would crash into East Asia. It would be of type C and would consist of porous rocks with a density of 1.3. The asteroid would collide with Earth at a speed of 20 km / s and an angle of 45 degrees. The kinetic energy would be $4.07 \times 10^9 MT$. The crater created by the impact would have a diameter of 360 km, and a depth of 1.74 km [4].

4.2 Day of impact

Just after the impact, a devastating shock wave would cross half the globe. This would cause significant damages, but it would not pose a threat on a global scale. At the time of impact, lots of ejecta would be sent back into space and then would re-enter the atmosphere. This ejecta would be heated to incandescence (+ 500 ° C). They are called the “shooting stars” by Toon et al. [26]. In addition, 0.1% of the ejecta would be pulverised (30% of the mass of the impactor). It would be sub-micrometer in size, be taken in the rise of the plume and then diffused globally around the globe, following ballistic trajectories. The soot and ash generated by such fires would envelop the Earth in less than an hour [16]. The light level would then drop quickly to too low a level for photosynthesis and human vision. People still living on the surface without protection would not survive a long time even if located at the opposite side of the Earth because of the shooting stars and fires. Because of the very random phenomenon of the fallout of shooting stars and the size of these, some shelters would be strongly impacted and their population collapsed.

4.3 First week

The first week of survival is essential. Indeed, the survivors would be aware of the consequences of the impact, which can lead to significant trauma. The uncertainty of the situation and the lack of control will also accentuate the stress of survivors. Some of them could be plunged into confusion and could no longer make sound judgments and make appropriate decisions. Depression would also affect survivors. Discouragement and the impression that nothing makes sense could cause a physical and mental exhaustion of survivors. This first week of survival is therefore an essential phase. Even if all the infrastructures put in place to allow the survival of the population have been tested, the risk of malfunction is not zero, which can cause stress on

managers or technicians of the shelter. In addition, this week will allow the viability of the political organisation of shelters to be tested. Some shelters will face unexpected behaviour from the population, such as refusals to respect established rules. Depending on the type of political regime, we can imagine more or less harsh sanctions to maintain an effective organisation. This week spent in the shelter will also cause the creation of small groups. These groups can be formed in particular according to social class or the function entrusted to the shelter. The size of these groups may have a weight in the future for the decisions made in the shelter.

Regarding the situation on the surface, the surface of the globe is facing terrible fires caused by shooting stars [18]. The light level is lower than the minimum required for photosynthesis and human vision. All populations that did not take refuge in shelters do not survive. Despite the fires and an increase of temperatures at the beginning, at the end of the week, the average temperature has finally dropped to 8K. The biggest cooling would take place in the northern hemisphere, with areas cooled from 0 to 10° C.

4.4 First month

A period of two weeks spent in a shelter is often sufficient to cause major psychological consequences in the population such as irritability and depression. These behaviours can lead to aggressive behaviour, and withdrawal into oneself.

There are conflicts between certain groups of people within the shelters. These conflicts can interfere with the proper functioning of the shelter, which is why they are managed quickly by the leaders. But it is possible that these conflicts will turn into riots or even overthrow of the organisation and the power established in the shelter. Those reversals can sometimes be detrimental to the survival of residents if infrastructures are impacted by conflicts. In other shelters that do not experience riots, one can imagine the appearance of new social classes according to their place in the shelter. Technicians having a very important place for the survival of the shelter can, for example, be part of the upper social classes of the shelter. Survivors who participate in the proper functioning shelter might therefore be better rewarded than other survivors. It depends obviously on the type of organisational regime established initially, and would not be applied in all shelters. We can also show optimism with very docile and reliable populations, contenting themselves with the first floor of the pyramid of Maslow.

One can imagine that from one month on, scientists study the state of the surface using sensors or remotely controlled robots to take readings in different places. These readings make it possible to study the composition of the air, debris and to deduce more precisely the dates from which it will be possible to make the first outings. Findings in this regard could be transmitted by means of telecommunication set up between the shelters.

During this period of extreme confinement underground, communities will try to find a life cycle more or less similar to their life cycle before the disaster. Establishing routines helps reducing stress and depression, it is therefore normal to wish to find a stable cycle allowing to rest on the temporal elements

Temporary education systems can be set up to allow children to continue learning despite difficult conditions. Art, entertainment and sport must also have an important place in the lives of long-term survivors.

Depending on the resources available to communities and shelters, health can also be set up to meet the needs of survivors. Survivors may experience health issues or psychological problems. It is therefore important to have doctors and psychologists. We may also consider the involvement of complementary care or health specialists such as nurses, dentists, dermatologists, etc. Regarding the external situation, the fires are no longer active, but the level of light is still very low. A simulation of the evolution of dust clouds in the stratosphere by Pollack et al showed that the drop of light intensity below the level necessary for photosynthesis cannot exceed one year [8].

4.5 Six months after impact

After 6 months, only the communities living in shelters with a stable organisation survive. A routine is probably installed within the shelter to maintain a life cycle close to a classic life cycle. However, it is quite possible that some unstable communities managed to survive, despite more difficult conditions.

There are several reasons for the disappearance of some communities.

Firstly, it is psychologically difficult to remain locked up underground for several months. One can therefore assume that riots would be the main cause of destruction of some communities. These riots may impact the infrastructure, organisation or facilities that allow the shelter to function properly. These riots may lead some individuals to sabotage facilities, causing the disappearance of the community that depended on the shelter.

Secondly, there is the element of randomness that can affect the survivors. Malfunctions can occur in ventilation systems, water treatment systems or electricity production. If these malfunctions are significant and it is not feasible to make a repair, these communities can disappear.

Randomness can also intervene in the appearance of disease within the communities. It is difficult to assess the source of these potential diseases, which may be due to the food, the ventilation system, etc. Depending on the severity of the diseases, great damage can be caused within the communities, even to the point of causing the end of them. Another element of randomness is the incorrect prediction of the situation by scientists. It is quite possible that scientific research into the survival of humanity after a meteorite impact has not covered a major issue. It is also possible that some communities were relying on the presence of resources that unexpectedly disappeared as a result of the long-term damage of the impact. For example, simulations by Covey show that precipitation decreases by 90% for several months [5]. This effect dissipates, allowing the recovery of half of the average precipitation rate (before impact) at the end of the first year after impact. This would cause a global drought. This drought could negatively impact some communities that relied on water recovery from the surface. All these random parameters are part of the risks that survivors must consider.

After 6 months, light begins to return to the surface and humans can finally discern elements [5]. However, this light remains superficial because it corresponds to the light emitted at night by a full moon. Photosynthesis is still not possible. Hope returns to the survivors because the first outings on the surface are carried out by scientists. These trips allow them to make an inventory of the current situation, and to foresee the possibilities concerning an extraction of the population towards the surface.

4.6 One year after impact

According to Pollack, the period during which the temperature is below 0°C corresponds roughly to twice the period without light [18]. We can therefore assume here that the global terrestrial temperatures will start to exceed 0°C after one year. Moreover, the level of light would reach a sufficient level to allow photosynthesis. allow photosynthesis.

The temperature is still too low in the northern hemisphere to consider cultivating the land. However, in the southern hemisphere, the level of luminosity being

sufficient for photosynthesis, we can suppose that certain communities are beginning to establish crops (in small proportions) around the shelters. However, the yield would probably not be sufficient to consider feeding the entire shelter. Hydroponics or perhaps edible insects would therefore remain the main source of food [12,20].

These outings allow some communities to plan a return to the surface. It is indeed important to study the feasibility of establishing an outdoor base.

For that, it is necessary to study several parameters such as the ground or the weather conditions. These external bases must however remain close to the shelters to allow access to drinking water, a viable food source, and enough to shelter the population from the external conditions which are still difficult.

4.7 Five years after impact

Five years after the impact, the communities that have survived so far have established camps outside the shelters. Although the shelters remain heavily used, outdoor housing is emerging. "Cities" are beginning to develop around the shelters. Survivors have even been able to meet other peers from relatively close shelters. These shelters provide for the needs of the inhabitants such as food, waste disposal, etc. The materials in the shelters are also used outside to rebuild homes, tools, etc.

Humanity is thus summarised in several agglomerations of shelters, communities scattered over the part of the globe that was not directly affected by the impact, where the shelters were present.

4.8 Twenty years after impact

Twenty years after the impact, the society is in the process of reconstruction. It is not at all comparable to the society before the impact. Agriculture has been stabilised, which allows the survivors to meet their needs. A re-implantation of certain animal species has begun as well as the planting of seeds from the Svalbard world seed reserve. This allows people to start rebuilding self-regulating ecosystems as it could be the case before impact.

The large shelter agglomerations constitute large development poles which can be similar to states as we know them today.

However, the territories of East Asia are still heavily impacted by the disaster. The devastating effects of the impact are still felt in the climate and the total disappearance of any ecosystem. Some populations are

coming to resettle on the extremities of these territories, but the impact zone remains completely deserted. As a reminder, the diameter of the crater created is 360 km.

4.9 Discussion

Finally, in this scenario, humanity has managed to survive the catastrophe. However, this survival comes mostly from the human preparation before the impact. Without the establishment of shelters with all the means to provide for human needs, humanity could not have survived such a catastrophe. Furthermore, we have not found reliable information concerning the breathability of the air, which does not allow us to take into account this very important element. Finally, most of the choices are based on hypotheses or even speculations. This interdisciplinary field of research is so vast that the study of a particular part such as the facilities present in the shelters could constitute a complete research project on its own. We have therefore had to base our study on elements that are sometimes incomplete, which can impact the veracity of the scenario.

5. Scenario 2

5.1 Scenario definition

In this scenario, there is the fall of a hypothetical 100 km diameter asteroid in the middle of the Pacific Ocean. The meteorite collides with the Earth at a speed of 20 km/s and an angle of 45 degrees. The kinetic energy of the meteorite is 7.57×10^{10} MT, that is more than ten times the energy of the asteroid of the first scenario [4].

5.2 One week before impact

Ten years have passed since the news of the future impact. One can imagine that on a population scale, the reaction would not be so different than if the meteorite was "only" 50 km in diameter. There have been several mass exoduses, notably from the Asian (Japan, China, etc.) and American (California, Mexico, etc.) coasts. Although the planned area of destruction covers a larger area, these regions, very dynamic in globalisation, have become very unstable. The host geographical areas, Europe, Africa, Central Asia, also having to think about their own population, have been put under great tension. Inevitably, many civil wars broke out. States have also fallen, either because of the hysteria of the population, or because of the covetousness of resources or advantageous territories in view of the catastrophe. In the midst of this apparent chaos, a majority of the population will have remained astonished, stunned. It is

a population that will have tried to maintain its daily life by covering its eyes, not particularly active for its survival. The threat seems too great, and the hopes of escape from the Earth or of destruction/avoidance of the asteroid have been extinguished since the first year.

During these 10 years, the few states, very militarised, which will not have succumbed have put in place authoritarian regimes, and will have prepared post-impact plans to follow. It is also the case of private communities with strong power (economic, political, etc.) which will have organised themselves independently of the states, according to their means. The first ones then had the necessity to set up a plan of sorting the population according to corruption, genetic heritage and capacities for the times to come. This sorting has still caused serious civil wars. This is not the case for the private communities which are already a limited number (of the order of several thousands), and which thus set up their solutions for all their population. The shock arrives in a week, and the selected populations are moved to the shelters, with all the equipment and food not yet installed. These populations, which will be hastily estimated at only a few million people, are subjected to enormous psychological and moral pressure, but this is small compared to the rest of the Earth. Indeed, the forgotten of survival, condemned by all the forecasts, oscillate between collective suicides, total chaos (unleashing of violence), and mute ataraxic for the resigned.

We believe that the most likely organisation within the shelters is a pyramidal hierarchy. Indeed, the decisions to be taken imply a high level of knowledge of the situation and of the possible evolutions of the surface state. Differences of opinion within the populations could then cause the loss of control of the shelter. It is also possible that democratic regimes could be established, especially in private communities. However, these regimes would likely be more unstable due to the psychological evolution of the survivors.

Some shelter functions will be assigned to certain survivors to ensure the smooth running of the shelter. This could be, for example, technicians, scientists, or law enforcement personnel. For the sake of efficiency, most of the people accepted in shelters should be active. Some less specific functions such as maintaining hygiene or distributing food can be listed.

5.3 Day of impact

The final crater created by the impact has a diameter of about 1000 km, and a depth of 2.5 km [4]. Note that the crater at impact reaches a depth of 180 km. Thus, the

atmosphere comes into contact with the asthenosphere. On half of the globe, all the infrastructures are destroyed by the shock wave. However, it takes 16 hours to reach the opposite point of the globe, with gusts of 150 km/h. In only 1 hour, an earthquake of magnitude 11,9 shakes this opposite point. Nothing was designed to support such an earthquake, almost 100 times stronger than the most powerful earthquake recorded. It is very likely that many shelters will not withstand the earthquake, dooming their populations.

During the impact, many debris are sent into space and then re-enter the atmosphere (shooting stars). In addition, 0.1% of the sprayed ejecta (30% of the impactor mass), of sub-micrometer size is caught in the rising plume and is diffused globally around the globe in a ballistic manner. Soot and ash generated by shooting star fires will add to the debris floating in the air resulting in an envelopment of the Earth in less than an hour. The sub-micrometer dust and soot repel light rays into space, but the soot will also absorb sunlight. The light level will then drop rapidly to a level too low for the photosynthesis mechanism and human vision. Added to this is the staggering amount of water vapor, on the order of 100 GigaTons, rising into the atmosphere [16]. The coastlines of the Pacific Ocean are affected by titanic tsunamis, on the order of 100 metres. A mass of water over the entire depth of the ocean has been displaced. The water movement is global, and coastlines throughout the Pacific will be razed.

People still living on the surface without protection will not survive in the long term even if they are on the opposite side of the globe from the point of impact due to shooting stars and fires [26]. Because of the very random phenomenon of the shooting stars' fallout and their size (in fact like small meteorites), some shelters are strongly impacted and the sheltered population is doomed not to survive.

It should also be noted that despite the size of the asteroid, the astronomical constants of the Earth, i.e. the length of the day, the Earth's mass or the Earth's orbit, will not be impacted or hardly impacted at all [4]. Thus, at the end of this first day, it is predictable that most of humanity outside of a shelter will be killed (about 99%). The only potentially earthquake-resistant subsurface shelters will not be numerous, perhaps half or a third of the sheltered population.

5.4 One week after impact

During the first week, catastrophic events follow one another. Fire hurricanes have broken out in all the major forests of the world and continue to wreak havoc, still

releasing huge amounts of ash and water vapor [16]. Moreover, the impact has unbalanced the earth's crust, awakening volcanoes and supervolcanoes (e.g., Yellowstone) or causing new earthquakes, especially in sensitive areas such as the San Andreas Fault in California. These disasters in turn bring their share of damage and consequences, such as new tsunamis or the addition of dust and volcanic ash in the atmosphere. And this is true for the whole world.

During the first few weeks, the energy released by the impact, the fiery hurricanes, and the suspended water vapor cause the temperature of the atmosphere to remain above 500°C [5]. It is unclear if there are areas that are less affected by this temperature rise, but they would be exceptional. The ocean and coastlines are no exception, as the water is boiling everywhere. Thus, life on the surface was virtually annihilated and only animals living in the deep ocean may survive.

In the shelters, the cooling and air filtering systems must be optimally efficient to maintain livable conditions, and technical problems due to the extreme conditions may already occur. At this point, we may only be talking about a hundred thousand survivors spread across the globe.

5.5 The first month

As far as life in the remaining shelters is concerned, it does not diverge so far from the case of a smaller impact (50 km diameter scenario). Indeed, as long as the shelter is functioning, the external conditions do not impact the internal conditions, at least for now.

Conflicts between certain groups of people within shelters are emerging. These conflicts can be detrimental to the smooth running of the shelter, so they are dealt with quickly by the leadership. But it is possible for these conflicts to turn into riots that could overthrow the organisation and power established in the shelter. These overthrows can sometimes be detrimental to the survival of the inhabitants if the infrastructure is impacted.

In other shelters that do not experience riots, one can imagine the emergence of new social classes depending on their place in the shelter. Technicians with a very important place in the survival of the shelter may, for example, be part of the upper social classes of the shelter. Survivors who are involved in the smooth running of the shelter might therefore be better rewarded than other survivors. This obviously depends on the type of organisational regime initially established, and would not be true in all shelters. One can also be optimistic with populations that are very docile and

reliable, settling for the second floor of Maslow's pyramid.

During this period of extreme confinement, communities will try to return to a life cycle more or less similar to their life cycle before the disaster. Establishing a routine decreases stress and depression. Temporary education systems can be put in place to allow children to continue learning despite difficult conditions. Those of working age may be able to make themselves useful in shelter maintenance, food distribution, or other essential function that allows the shelter to function properly. Art, entertainment, and sports should also have an important place in the lives of survivors in the long run. To allow survivors to think about something other than the disaster, sports or several forms of art may be considered. This would likely be beneficial in curing the depression of some survivors.

Depending on the resources available to communities and shelters, health systems may also be developed to provide for the needs of survivors.

Regarding the outside, the temperature remains well above 100°C, continuing to kill everything that can be killed [16]. Volcanic eruptions have apparently calmed down, and fewer and fewer earthquakes are shaking the Earth. The atmosphere is still largely unbreathable, due to the fine particles in suspension. The weather conditions are totally unpredictable during this period. Thus, going outside is almost impossible and of little interest. Concerning life on the surface of the earth, there is not much left.

5.6 Six months after impact

Again, the sheltered life is quite similar to that in the "50 km" scenario. However, the even harsher outdoor conditions (including higher temperatures) will have tended to bring more life support systems to their knees. Thus, the number of remaining shelters gets smaller and smaller.

At the end of six months, only the communities with shelter and relatively stable organisation have survived. A routine is probably established within the shelter to maintain a life cycle close to a conventional life cycle.

There are several reasons that may be the cause of the collapse of some communities. Firstly, it is psychologically difficult to remain locked up underground for several months without any perspective and room for improvement. Therefore, we can assume that riots would be the main cause of destruction of some communities. These riots may impact the infrastructure, organisation, or facilities that allow the shelter to function properly. These riots may

lead some individuals to sabotage facilities, which may cause significant irreparable damage, causing the disappearance of the community that depended on the shelter.

Secondly, inappropriate preparation and the element of randomness can affect the survivors. Malfunctions can occur in many life support systems and it is doubtful that there would be enough resources and the necessary industrial tools to repair everything.

Randomness may also be involved in the occurrence of disease within communities. It is difficult to assess the source of these potential diseases, which may be due to malnutrition, the presence of toxic molecules in the air, etc. Depending on the severity of the diseases, the communities could slowly but surely collapse.

Another important issue is the difficulty to predict what are all the resources, tools and industrial processes that are needed for survival. The lack of a single important resource could lead to the collapse of the community. It could be for example water. As a severe drought is expected on the surface, some communities that relied on water recovery from the surface or from a small underground reservoir would die. All these random parameters are part of the risks that survivors must consider.

Although the external luminosity goes up a little, the temperature remains above 100°C. The water is still boiling and the first hundred meters of the oceans would be too hot for species living in the deep ocean. In fact, at this stage, the outside is unliveable. The only elements allowing the survival of the remaining tens of thousands of people are inside the shelters.

5.7 One year after impact

It is around this period that we will witness a reversal of the phenomenon. For almost a year, the Earth was overheated. Indeed, it has been a year since solar energy was almost completely absorbed by the pile of ash, dust, and water vapor in the atmosphere. And a large part of these elements has not yet fallen back to the ground. Thus, the planet will see a slow decrease in its average temperature compared to normal. However, it is also possible that the volcanic activity remains very high and continue to fill the atmosphere with dust and to heat up the surface.

5.8 Five or ten years after impact

The duration of the overheated period is not clear. It could be five to ten years, perhaps more. At some point, however, the winter impact should settle down durably.

The life annihilated by the post-impact period cannot restart under these conditions. The climatic and meteorological conditions hardly allow expeditions outside the shelters, which for the most part have already reached their limits and seen their population die out.

As for the mental state of the survivors, it is difficult to determine, between resignation, hope, questioning, fear, frustration etc. It is likely that the population of numerous remaining shelters has fallen below the threshold of healthy reproducibility. And the perspectives are bad.

5.9 Decades after impact

After ten years or perhaps decades, terrestrial temperatures will drop down and become liveable for simple organisms and plants in some places on Earth. However, even if some people were still alive in well-organised shelters, there is no guarantee that these places would be safe and full of useful resources for living. There are numerous reasons to believe that nobody would survive [10,22]:

- Environmental issues

New volcanoes and tsunamis could destroy the remaining shelters. The atmosphere could also become unbreathable due to the presence of toxic gases. Acid rains could be dangerous to all terrestrial life forms.

- Insufficient resources

For survival, huge amounts of water are needed, to grow plants and for many other usages. As 100% recycling is not possible, many shelters might collapse due to a lack of this resource if their reservoir is limited. Similar issues exist for repairing capabilities.

- Insufficient energy

Lots of energy is needed, especially in the form of electricity, for the photosynthesis of plants using artificial lighting, and also for many complex systems (life support, pumps), and industrial processes.

- Insufficient human resources

There is an issue with the genetic variability and also with the needs to implement all human activities required for survival (maintenance of life support, agriculture, industry, growing babies, etc.) [15,22].

- Anarchy

A strong and effective organisation is required to obtain a synergy of all human activities and avoid riots and wars among the different communities.

- Insufficient adaptation capacities

Without experience, the communities will have to face many unexpected problems without appropriate tools and solutions.

For all these reasons, the total annihilation of humanity cannot be demonstrated, but the long term survival capability seems very weak. Regarding living organisms in general, they will resume from the ocean floor, or close to hydrothermal vents but the settlement of the surface will probably last centuries.

6. Conclusions

The collision of a gigantic asteroid or comet with the Earth has lasting planetary effects that threaten life and humanity. According to our study, an asteroid of 50 km in diameter would not be enough to cause human extinction, but an asteroid of 100 km in diameter would. Survival is only possible for a small number of people placed in shelters isolated from the outside world, with significant resources, important energy, agricultural and industrial production capacities and an adapted social and societal organisation. Depending on the energy of the collision, outdoor living conditions could be unbearable for a long period of time and forced isolation could last from a few years to several tens or hundreds of years. In light of the scenarios studied, even if many shelters were built, there are a large number of factors leading, slowly but surely, to a degradation of living conditions and, if the duration of isolation exceeds a few years, to human extinction. In this perspective, the colonisation of new planets (e.g., the Moon or Mars) appears to be a way to ensure the sustainability of the human species and of life in general. The feasibility of colonisation remains to be demonstrated, but since complete autonomy is not required during the first years of development of such a colony, it is certainly easier to settle a new planet than to survive in autarky for decades confined to an earthly shelter [25, 28]. In spite of the efforts made in this work, these scenarios remain nevertheless the result of several choices made in the analysis and of several assumptions.

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