REVIEW

Biological mass extinctions on planet Earth

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Abstract

Both gradual and catastrophic events have been involved on the mass extinction events on the planet Earth. Although the greatest mass extinction with currently identified fossil remains was the Great Dying, the greatest of all mass extinctions on planet Earth should have been the Great Oxygenation Event (GOE), assuming that no life was present at the time of the Moon formation. In general, and excluding the unique GOE, the climate changes have been the most common causes of mass extinctions on Earth. A comet or large meteorite may cause mass extinctions not only on land, but also on the oceans. Indeed, a bolide of a few kilometers in diameter may release as much energy as several million nuclear bombs. On the other hand, localized oceanic extinctions may arise from special events like the quasi-periodic climate pattern known as "El Niño" Southern Oscillation (ENSO). Such events may have also a significant impact on terrestrial ecosystems, causing extinctions of plants and animals. Up to five major mass extinctions have been recorded in the last 540 million years, killing an average of 50% or more of all living species at the time of the event. The fossil record suggests that mass extinctions on the planet Earth occur about every 26 million years. This is a very serious matter indeed, because if such hypothesis holds true, it is just a matter of time before the Earth is hit by a huge bolide with catastrophic consequences. It is revealing to note that 99% of all species that ever lived on planet Earth are now extinct. That includes all our hominid ancestors. Besides other considerations and factors, the human activity is significantly disrupting the planet Earth ecosystems. It should be also taken into account that now –for the first time–, the human activity can also cause mass extinctions. In fact, the current rate of species extinctions is shocking; estimated at about 10,000 times the past average as deduced from the fossil record. The conclusion is clear and definitive: our only chance to survive is to colonize the cosmos. On the other hand, we must take care of many possible causes of extinction, but particularly on those derived from the synergistic effects of human activities, in order to take action to prevent the global contamination and warming of the planet Earth. In a practical way, halting and reversing such trends requires significant changes not only in industries in general, but also in human behavior in particular (food wastefulness, unnecessary travel and pleasure tourism, fashion squandering, etc), in order to effectively reduce both the contamination and the emissions of the greenhouse gases. Obviously, that requires a global economic and marketing change. A pacific revolution involving a global social and political agreement is needed. It should be also clear that each and every one of us has the responsibility to take care of our planet Earth.

Key words: Big Bang theory, asteroids, comets, Homo sapiens sapiens, dinosaurs, Doomsday Argument.

Resumen

Tanto acontecimientos graduales como catastróficos han estado implicados a las extinciones masivas en el planeta Tierra. A pesar de que la mayor extinción masiva, según restos fósiles identificados actualmente, fue la Gran Mortandad (del inglés, “Great Dying”), la mayor de todas las extinciones masivas en el planeta Tierra debió haber sido la Gran Oxidación (del inglés, “Great Oxygenation”); también llamada crisis del oxígeno, revolución del oxígeno o catástrofe del oxígeno (suponiendo la no existencia de vida en el momento de la formación de la Luna). En general y excluyendo el suceso de la Gran Oxidación, los cambios climáticos han sido las causas más comunes de extinciones masivas en la Tierra. Un cometa o un gran meteorito pueden causar extinciones masivas, no sólo en la tierra, sino también en los océanos. De hecho, un aerolito de unos pocos kilómetros de diámetro puede liberar tanta energía como varios millones de bombas nucleares. Por otro lado, las extinciones oceánicas localizadas pueden derivarse de sucesos especiales como el patrón climático cuasiperiódico conocido como la Oscilación del Sur de “El Niño” (del inglés, “‘El Niño’ Southern Oscillation”; ENOS). Estos eventos pueden tener también un impacto significativo en los ecosistemas terrestres, causando la extinción de plantas y animales. Hasta cinco importantes extinciones masivas han sido registradas en los últimos 540 millones años, aniquilando a un promedio del 50% o más de todas las especies vivientes en el momento del evento. El registro fósil sugiere que las extinciones masivas en el planeta Tierra se producen aproximadamente cada 26 millones de años. Se trata, ciertamente, de un asunto muy grave, porque de ser cierta esa hipótesis, es simplemente una cuestión de tiempo que la Tierra pueda ser alcanzada por un enorme aerolito que generaría consecuencias catastróficas. Es interesante tener en cuenta que el 99% de todas las especies que alguna vez vivieron en el planeta Tierra están ahora extintas. Esto incluye a todos nuestros antepasados homínidos. Además de otras consideraciones y factores, la actividad humana está interfiriendo considerablemente en los ecosistemas del planeta Tierra. Debe tenerse también en cuenta que ahora –por primera vez–, la actividad humana puede también causar extinciones masivas. De hecho, la tasa actual de extinción de especies es alarmante; estimada en alrededor de 10.000 veces la media con respecto al pasado, como se deduce del registro fósil. La conclusión es clara y definitiva: nuestra única posibilidad de sobrevivir es colonizar el cosmos. Por otra parte, debemos preocuparnos por muchas posibles causas de extinción, pero sobre todo por aquellas derivadas de los efectos sinérgicos de las actividades humanas, a fin de tomar medidas para prevenir la contaminación y calentamiento global del planeta Tierra. De un modo práctico, detener y revertir esas tendencias requiere importantes cambios no sólo en las industrias en general, sino también en el comportamiento humano en particular (despilfarro de comida, viajes superfluos turismo de placer, derroche en moda, etc.), a fin de reducir eficazmente la contaminación y las emisiones de los gases de efecto invernadero. Indiscutiblemente, esto requiere un cambio global a nivel económico y comercial. Se necesita una revolución pacífica que implique un acuerdo global a nivel social y político. Es también evidente que todos y cada uno de nosotros tenemos la responsabilidad de cuidar de nuestro planeta Tierra.

Palabras clave: teoría del la Gran Explosión (Big Bang), asteroides, cometas, Homo sapiens sapiens, dinosaurios, Argumento del Juicio Final (Doomsday Argument).

Introduction

According to the Big Bang theory, the known Universe was created about 13.7 milliard years ago (Komatsu et al, 2009; Menegoni et al, 2009), giving rise to the Earth about 4.54 milliard years ago (Dalrymple, 1991). Life started on Earth approximately a milliard years after that: about 3.5 milliard years ago (Wilde et al, 2001; Schopf et al, 2002). During the Earth biological evolution, different biological mass extinction events have taken place, triggered by different causes, including abiotic (eg., climate) and biotic (eg., diseases) factors. Sometimes, the abiotic factors may trigger biotic ones, like the lack of food after a severe drought.

The mass extinction events wipe out many species, but at the same time they usually represent a major regenerative force, providing new and unique opportunities for the adaptation and subsequent explosive evolution and diversification of the surviving clades. Thus, such events have shaped the life on the Earth, determining the catalog of biological entities at each particular time in the biological evolution of the planet. In fact, if no mass extinctions had taken place, the life on Earth would be surprisingly different, without most of the current species, including the modern humans, which are a subspecies of *Homo sapiens* (*Homo sapiens sapiens*). For instance, the only living beings on planet Earth could be anaerobic with all the energetic limitations involved. Likewise, the evolution and dominance of mammals required the extinction of dinosaurs, as described below. Otherwise, the planet Earth would still be dominated by roaming dinosaurs, and some of them, like the *Stenonychosaurus inequalis* might have eventually evolved into intelligent dinosauroid reptiles, being quite different from humans (Russell and Séguin, 1982).

Both gradual and catastrophic events have been involved on the mass extinction events on the planet Earth. The former ones may include, for instance, a reduction of the oxygen concentration, climate changes generating aridity, shifts in ocean current circulations and changes in sea levels. The catastrophic ones may include bolide impacts (like the ones involving asteroids and comets), increased volcanism (including acid rain, etc) and the release of methane clathrate (also known as methane hydrate, hydromethane, methane ice or “fire ice”) from sea and ocean floors (Tanner et al, 2004).

The Solar System formed about 4.568 milliard years ago, containing the sun, planets and other astronomical objects bound to each other by gravity. The bolide impacts were more frequent in the younger planet Earth, since the number of such bodies in the Solar System is being reduced with time, simply because they eventually impact on planets or satellites (or collide between themselves), and thus get out of orbit. In the beginning, the impacts could have included huge bolides of hundreds of kilometers in diameter. An impact of such large bodies could have devastating effects, vaporizing all the oceans. Obviously, such impacts could represent the greatest biological mass extinctions on planet Earth, yet the research of such area seems unreachable today and probably for ever. In any case, it is obvious that the life on Earth could only evolve to the present day after such bombardment ceased.

The formation of the Moon has been a mystery for a long time. Among the initial huge impacts is one that is considered the greatest one ever over the Earth (at least, the greatest hypothesized one). Indeed, it was so powerful that it formed the Moon satellite out of the impact. Thus, the Giant Impact hypothesis proposes that the stability of the planetoid Theia orbit was affected due to its growing mass (having about the size of the planet Mars), departing from its stable location and subsequently colliding with the Earth proto-planet about 4.48 milliard years ago (about 120 million years after the formation of the Solar System) (Belbruno and Gott, 2005; Halliday, 2008).

The greatest biological mass extinctions

Some authors consider five big mass extinction events on planet Earth: Ordovician-Silurian (440 to 450 million years ago), Late Devonian (364 million years ago), Permian-Triassic (251.4 million years ago), Triassic-Jurassic (199.6 million years ago) and Cretaceous-Tertiary (65.5 million years ago) (Raup and Sepkoski, 1982). Additionally, it is generally assumed that the largest biological mass extinction event on the planet Earth occurred during the Permian-Triassic period (251.4 million years ago) (P-Tr extinction event), wiping out most living vertebrate species (96% marine and 70% terrestrial), and an average of 90% of all species. As a proof of its severity, it is the only known mass extinction of insects (Bowring et al, 1998; Jin et al, 2000; Benton, 2005). In fact, the life on the planet Earth took 30 million years to recover (Sahney and Benton, 2008). That is why it has been called the Great Dying (Barry, 2002) and “the mother” of all mass extinctions (Erwin, 1983).

Yet, there was a much significant extinction event on the planet Earth 2.4 milliard years ago, that destroyed almost all living species at that time. It occurred when free oxygen (O_2) produced by photosynthetic bacteria (cyanobacteria) transformed the original reducing atmosphere into an oxidizing one, being lethal for virtually all the rest of living creatures (being anaerobic at that time). Such catastrophe is called the Great Oxygenation Event (GOE), also known as the oxygen holocaust, oxygen catastrophe, oxygen crisis, and the great oxidation. Indeed, the oxygen –or more properly, the Reactive Oxygen Species (ROS) derived from it– are toxic to any biological entity, including aerobic ones. The ROS include oxygen ions (with unpaired valence shell electrons) and peroxides (powerful oxidizers, and usually quite unstable), therefore being all very chemically reactive. The ROS can generate oxidative stress, that may result in significant damage to cell molecules, with significant deleterious effects (mutations, cancer, cell and tissue degeneration, aging, etc). On the bright side, the aerobic metabolism is much more efficient than the anaerobic one, thus being an Evolutionarily Stable Strategy (ESS) exploited by most living cells, albeit with the associated dangers indicate before. Indeed, the anaerobic metabolism (via fermentations) only generates two Adenosine-5'-TriphosPhate (ATP)/glucose, whereas the aerobic one (via the Kreb's cycle) yields 36 (prokaryotes) or 38 (eukaryotes) ATP/glucose (almost 20 times more!).

On the other hand, the released oxygen could combine with the methane (a greenhouse gas, being remains of the previous anaerobic Earth) in the atmosphere, possibly triggering the longest "Snowball Earth" episode (Huronian glaciation), in which the Earth surface became entirely (or nearly) frozen in the Paleoproterozoic era; in particular, during the Siderian and Rhyacian periods (from 2.4 to 2.1 milliard years ago) (Kopp et al, 2005). Another Snowball Earth episode took place 650 million years ago. Interestingly, such later event seems to have triggered the evolution of multi-cellular organisms and the huge generation of amazing new life forms during the Cambrian explosion event (Smith, 2009). Thus, although the greatest mass extinction with currently identified fossil remains was the Great Dying, the greatest of all mass extinctions on planet Earth should have been the Great Oxygenation (assuming that no life was present at the time of the Moon formation).

Additionally, diseases caused by living entities including viroids, virusoids, viruses and cells (prokaryotes like bacteria, as well as eukaryotes, including unicellular and pluricellular organisms), as well as over-parasitism and over-predation events, may have also caused extinctions. Yet their impacts are usually reduced, due to their intrinsic biological nature, thus usually allowing the development of resistance, affecting a reduced number of individuals or species.

Terrestrial and oceanic mass extinctions

In general, and excluding the unique GOE, the climate changes have been the most common causes of mass extinctions on Earth. In fact, any drastic climate change (fast or slow) is likely to produce mass extinctions. In the first case, many species will just abruptly disappear, only surviving the ones capable to withstand the new conditions (which, in fact, may feed on the dying ones for some time. In the latter case, some species may disappear, whereas others will evolve, being replaced by new ones, better adapted to the new conditions. As previously indicated, these events have offered new opportunities for the development of new species, effectively shaping the catalog of life on the planet Earth to our days.

The climate changes may be caused by different factors, including volcanoes and the crashing of massive meteorites or comets over the planet Earth. Such factors are most likely to affect the land ecosystems, where temperature changes can be more intense. The excessive rainfall and –most significantly– the lack of rain are also factors that may be involved in mass extinctions on land ecosystems, yet have no effect on marine ecosystems, except for small interior aquatic ecosystems that could be also drastically affected in the case of severe droughts periods.

Localized oceanic extinctions may arise from special events like the quasi-periodic climate pattern known as “El Niño” Southern Oscillation (ENSO). Such events may have also a significant impact on terrestrial ecosystems, causing extinctions of plants and animals (Harrison, 2000). Yet, oceanic mass extinctions usually require special events drastically disrupting the food chain (Jackson, 2008). Such events are usually much more general than the ones required to cause mass extinctions on land, since the homeostasis in aquatic environments in general and oceanic ones in particular is very high as compared to the terrestrial ones. Such drastic extinction events may include the solar light blocking by intense volcanic activity and –most likely– by large extraterrestrial bolide impacts. The former may trigger extinction events over millions of years, whereas the latter would take effect over just thousands of years.

As previously indicated, up to five major mass extinctions have been recorded in the last 540 million years, killing an average of 50% or more of all living species at the time of the event. Yet, only for the last one (the Cretaceous-Tertiary; K-T extinction event) there is definitive evidence of impacts leading to mass extinctions. That is also the most popular one, which took place 65 million years ago, killing most dinosaurs, as indicated below. Nevertheless, if an extraterrestrial bolide impacts in the ocean, the scenario may be different with regard to the sedimentary evidences left. Such could have been the case for the P-Tr extinction event. It should be taken into account that at the late Permian there was a single super-continent (Pangaea), as well as a single super-ocean (Panthalassa).

Bolide-related mass extinctions

A comet or large meteorite may cause mass extinctions not only on land, but also on the oceans. Indeed, a bolide of a few kilometers in diameter may release as much energy as several million nuclear bombs. The scenario may be as follows:

1. The large bolide impacts the Earth, creating a huge crater, like the case of the Chicxulub crater (180 km in diameter) at the Yucatán Peninsula (Mexico). The impact will cause earthquakes and tsunamis, with great devastating effects,

depending on the bolide size and on the place of impact (land, ocean, etc). Interestingly, the Chicxulub crater has been linked to the extinction of most dinosaurs, as indicated below. Other craters around the world have been dated to approximately the same age (Silverpit crater in the United Kingdom, Boltysh crater in Ukraine and Shiva crater in the Indian Ocean). It seems therefore plausible that such impacts could be due to a comet disruption, similar to the collision of the "Shoemaker-Levy 9" comet (formally designated D/1993 F2 and nicknamed "String of Pearls" due to its appearance) with Jupiter in 1994 (Boehnhardt, 2004).

2. The bolide will cause also an increase in temperature, transforming the kinetic energy into thermal one, with devastating effects.

3. The bolide may create huge dust clouds, made of both bolide and Earth material. In fact, it is possible to track the history of the largest bolide impacts on Earth because they may leave an evidence of extra-terrestrial material on the geological strata (e.g., elements that are rare on Earth, yet abundant on bolides, like iridium). Other evidences may also point to bolide impacts, mainly when linked to mass extinctions at the same time. Such is the case of the high concentrations of shocked quartz, Ni, Cr, As, V, and Co anomalies, large negative carbon isotope shifts and microspherules and microcrysts corresponding to the mid-Devonian (380 million years ago), as found in the Anti Atlas desert (Morocco). Indeed, such evidences have been related to the extinction of 40% of marine animal genera at such time (Ellwood et al, 2003).

4. The dust clouds will cover the full planet Earth (or nearly), with the help of the atmospheric pressure differences and thus the corresponding winds, effectively blocking most of the solar light in most locations for months and even years.

5. Such scenario may cause a drastic drop of dozens of Celsius degrees on the average temperature on planet Earth, which is specially lethal on land ecosystems. As a consequence, many species will disappear. Such effect is less drastic on the ocean, due to its huge amount of water, its high heat capacity (C) and corresponding homeostatic effect. The previous sharp increase and –mainly– the subsequent drastic and significant drop in the planet Earth average temperature can kill many land species; mainly those not protected against such thermal aggressions. As an example, the dinosaurs were almost completely wiped out from planet Earth at the end of the Cretaceous period, as previously indicated. They included different animals that dominated the Earth for over 160 million years, from the late Triassic period (about 230 million years ago). Among them were a group of feathered dinosaurs that evolved from theropod dinosaurs during the Jurassic period (199.6 to 145.5 million years ago). The feathers are a fantastic technological achievement of nature, since they are light, yet strong, being also flexible or rigid, as needed. And most importantly, they are fantastic thermal insulators from both high and –mainly– low temperatures. Indeed, they protected the feathered dinosaurs, being the only group of dinosaurs that could survive such mass extinction event, giving rise of the current birds (Zhou, 2004).

6. The continued blockage of the sun light causes photosynthetic organisms to stop such process and eventually dye. Such effect is relevant on both land and ocean ecosystems. Thus, plants die on land, but photosynthetic plankton (photoplankton) also perish on the ocean surface.

7. As a consequence, the food chain is suddenly and drastically disrupted. Animals feeding from the photosynthetic organisms also perish from starvation, both on land and the oceans (eg., zooplankton).

8. The lack of food is transmitted to all links/stages of the food chain/pyramid. A huge mass extinction takes place in days, weeks and months. Many species are wiped out from terrestrial and aquatic ecosystems.

9. Eventually, the gravity acceleration and other factors like the rain will clear the atmosphere, allowing a progressive deposition of the dust particles. Eventually, the sun light reaches the planet Earth surface again, months or years after the bolide impact.

10. Living beings will recover slowly, including plants from seeds (some seeds may remain germinative for decades), animals from eggs (eg., insects) and other surviving animals (hibernation, etc).

11. A brand new Earth is born, offering new opportunities to survivors to re-colonize both terrestrial and aquatic ecosystems.

12. New species will evolve from survivors, effectively replacing the disappeared ones, albeit at a slow pace. As an example previously described, the life on the planet Earth took 30 million years to recover from the Permian-Triassic extinction event (Sahney and Benton, 2008).

Mass extinction periodicity and anthropocentric considerations

The fossil record suggests that mass extinctions on the planet Earth occur about every 26 million years (Raup and Sepkoski, 1984). Such periodicity could be triggered by a hypothetical dwarf star or brown dwarf (known as Nemesis), orbiting the Sun at a distance of about 50,000 to 100,000 Astronomical Units (AU; 149,597,870.7 kilometers; approximately the mean Earth-Sun distance or about 1 to 2 light-years). Such companion red star to the Sun could periodically disrupt the comet orbits in the Oort cloud, and thus increasing the number of comets that reach the inner solar system, effectively increasing their probability to collide with the planet Earth (Davis et al, 1984; Whitmire and Jackson, 1984).

This is a very serious matter indeed, because if such hypothesis holds true, it is just a matter of time before the Earth is hit by a huge bolide with catastrophic consequences (unless, of course nuclear weapons are fired against it, modifying its path to the planet Earth). But the extinction by extraterrestrial bolide impacts is not the only possible cause for human extinction. An interesting informative review points out to 20 possible causes, including natural disasters (eg., asteroid impact), human-triggered cataclysms (eg., global warming), willful self-destruction (eg., global war), and greater forces directed against us (eg., alien invasion) (Powell and Martindale, 2000).

It is revealing to note that 99% of all species that ever lived on planet Earth are now extinct. That includes all our hominid ancestors. With the exception of *Homo sapiens sapiens*, all other human subspecies have become extinct, including *Homo sapiens idaltu* (meaning "elder wise human"; extinct almost 160,000 years ago) and *Homo sapiens neanderthalensis* (also known as *Homo neanderthalensis*; extinct 30,000 years ago). *Homo sapiens sapiens* and *Homo sapiens neanderthalensis* diverged about half a million years ago (Green et al, 2006). The first fossil records of anatomically modern humans were found in Africa, dated about 195,000 years ago, with an estimated divergence from the common ancestor of all modern human populations of about 200,000 years ago (Alemseged et al, 2002).

Besides other considerations and factors, the human activity is significantly disrupting the planet Earth ecosystems. It should be also taken into account that now, for the first time, the human activity can also cause mass extinctions. Not only because of biological and –mainly– nuclear weapons, but also –and most significantly–, due to contamination, alteration and destruction of natural ecosystems. The aquatic ecosystems are specially sensitive to such contamination, which may be first detected on the atmosphere and the fresh water (rivers, lakes, aquifers, etc), but eventually ends up in the seas and oceans, with unknown ecological and evolutionary consequences. In fact, it is no longer safe to eat sea products as it used to be (Domingo et al, 2007). Also, the human activity may cause or contribute to the observed global warming, which may have catastrophic consequences on the life of the planet Earth. As an example, the increase in temperature may also affect the sexual reproduction of plants (Hedhly et al, 2009), which in turn may have significant effects on animals feeding from them.

In fact, the current rate of species extinctions is shocking; estimated at about 10,000 times the past average as deduced from the fossil record. We must not forget that we are also a living species on the planet Earth. The statistical probabilities of current human extinction have been studied by means of the "Doomsday Argument" (DA), also known as the Carter catastrophe (Carter and McCrea, 1983; Gott, 1994; Leslie, 1998). In plain English, assuming that the current living humans are in a random place at the full human history timeline, chances are that we are indeed about halfway through it.

In any case, the days of the Earth as a living planet are numbered. The Solar System was formed 4.568 milliard years ago due to the gravitational collapse of a small part of a giant molecular cloud (Bouvier and Wadhwa, 2010). In about five milliard years more, the Sun will cool and expand becoming a red giant, leaving behind a stellar corpse known as a white dwarf. The Solar System planets will be destroyed and ejected into the outer space (Dyson, 1979). It is obvious that the humans must do something about it to escape such astronomical fate.

The conclusion is clear and definitive: our only chance to survive is to colonize the cosmos. Indeed, that has been recently proposed by the academic celebrity Stephen William Hawking (Roger, 2001; Dermont, 2010). On the other hand, we must take care of many possible causes of extinction, but particularly on those derived from the synergistic effects of human activities to prevent the global contamination and warming of the planet Earth. Drastic measures should be taken now, because tomorrow may be too late. It should be noted that the rates of change may be faster than expected and nonlinear. Besides, the chances of survival are lower for plants and animals and higher for more metabolically flexible organisms like microorganisms and algae, which could change the ecosystems equilibriums for ever. In a practical way, halting and reversing such trends requires significant changes not only in industries in general (Jackson, 2008), but also in human behavior in general (food waste, unnecessary travel and pleasure tourism, fashion squandering, etc), in order to effectively reduce both the contamination and the emissions of the greenhouse gases. Obviously, that requires a global economic and marketing change. A pacific revolution involving a global social and political agreement is needed. It should be also clear that all of us have the responsibility to take care of our planet Earth. As the singer Michael Jackson said in the song “Man in the Mirror”, “if you wanna make the world a better place, take a look at yourself, and then make a change”.

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