Mass Extinctions

In this lecture we will discuss mass extinctions, which can provide insight about the possible survival of life (maybe even intelligent life). We will discover that in addition to destroying life, mass extinctions can also open up the door for new life to emerge, and indeed there is evidence in several cases that this has had a major impact. We'll start with a few definitions and context, and will then talk about some specific extinctions starting with the famous K-T extinction that did in the non-avian dinosaurs. We will then think about mechanisms for such extinction, and find that at least a couple of different suggested types have astrophysical origins.

Definitions: taxonomic classes

We'll need these to most properly appreciate how massive the mass extinctions are. We've talked about different divisions of life, and have indicated that at a basic level life can be divided into *domains*: bacteria, archaea, and eukaryotes (we belong to the last of these). However, historically people have focused mainly on eukaryotes (plants, animals, fungi, protists), and have devised a taxonomic scheme for those members. From the most general to the most specific (pun intended), we have **kingdom**, **phylum**, **class**, **order**, **family**, **genus**, and **species**. To give examples of each in order, humans are

- Kingdom: animals (alternatives: plants, fungi, etc.)
- Phylum: chordata, subphylum vertebrates (i.e., we have backbones; alternatives include mollusks, arthropods [insects, spiders, etc.], and many others)
- Class: mammals (alternatives are birds, fish, reptiles, and amphibians)
- Order: primates (many alternatives: bats, rodents, etc.)
- Family: hominids (alternatives: lemurs, tarsiers, monkeys, ...)
- Genus: homo (alternatives: chimpanzees, gorillas, orangutans, some extinct genera)
- Species: sapiens (homo sapiens means "wise man", which in some cases is debatable!)

We gave the species definition earlier: two individuals are members of the same species if (assuming one male and one female!) they can in principle produce viable offspring, i.e., offspring who have offspring. The more general definitions are less clear, but basically a genus is a group of related species, a family is a group of related genera (plural of "genus"), and so on.

The relation to mass extinctions is that for a species to go extinct means you have no remaining members of just that species. For example, passenger pigeons are extinct. To make a genus go extinct requires that all species in that genus go extinct. To make a family go extinct requires that all genera in that family go extinct. For example, for hominids to go extinct requires that not just all humans, but also all chimpanzees, gorillas, and orangutans go extinct. Hominids don't include many species, but some (e.g., some beetle families) can have thousands. Therefore, as we discuss mass extinctions, you should keep in mind that family extinction is pretty impressive!

What is a mass extinction?

As you might expect, for ever major (or "mass") extinction, there are many minor extinctions. In fact, practically every species that has ever walked the earth is now extinct. This, however, does not necessarily require violence; it could be that gradual evolution simply means that an old species gives way to new. What we're looking for is a sharp decrease in species number in a short time (more on what "short" means below). With this in mind, people often talk about the "big five" extinction events over the last 540 million years, i.e., over the time that we have had diverse large life. A definition for the big five is that in each case it appears that more than 50% of animal species became extinct. In the biggest mass extinction in history, the Permian extinction, it is estimated that 53% of marine *families* went extinct! Yow.

But what does this mean in practice? It means that below rocks at a certain level (hence before a certain time) one sees fossils of many individuals that are not present above those rocks (after that time). Note, though, that incompleteness of the fossil record can easily mean that this "sharp" distinction might really mean a period of a few million years, especially very early on. It is therefore good to keep in mind that a mass extinction does *not* have to mean a single catastrophic event that nuked every member of lots of species in a fraction of a second! It could be a change that appeared gradual at the time. This ambiguity is the source of much disagreement about the causes of particular extinctions.

Effects of mass extinctions

When we go through a few individual mass extinctions, it is useful to remember that in addition to destroying life, they can also renew life. Obviously a 100% extinction is purely destructive. However, we haven't had any of those in the last 3.8 billion years. Partial extinctions are very different in this respect. For example, the extinction of the dinosaurs allowed the rise of the mammals, and we all have reason to be thankful for that!

Let's think of some particular mass extinctions now. We'll start with the most famous, because it did in the dinosaurs. It is also a good story about creative thinking and the triumph of a scientific idea against initial skepticism.

The K-T extinction

All of us have been to museums where we get to marvel at the size of dinosaur bones and become thrilled by imagining a T. Rex pursuing us. It is possible that in earlier stages of human history these bones led to legends of dragons and giants. In their many manifestations, dinosaurs ruled the land for about 160 million years. But then, suddenly, they disappeared 65 million years ago. What happened?

Far back in the last millennium when I was growing up, people didn't really have a good idea about what had occurred. One idea I remember that was presented in a kids' book now sounds pretty ridiculous to me. They said the dinosaurs died off because mammals were small and quick and were able to run around eating the eggs of dinosaurs until they succumbed. Now, the problem with that is that mammals arose at about the same time as dinosaurs, around 220 million years ago, so the mammals had been night-dwelling rat-sized things for 160 million years. What the heck were they waiting for??

Other ideas included intense volcanic activity or climate change, but nothing was really convincing. Into this milieu came an unlikely combination of a physicist and geologist.

It helped that they were related: the father was Luis Alvarez, a Nobel Prize winning physicist. The son was Walter Alvarez, a geologist. In 1980 they discovered that all over the world, the rocks that marked the event (at the boundary between the Cretaceous and Tertiary, thus the K-T boundary) were rich in the element iridium by a factor of hundreds over normal rocks. Iridium is really dense (in fact, it's the second-densest element), so it is rare in the Earth's crust because it sank quickly. However, it is common in asteroids. Their hypothesis was therefore that an asteroid possibly 10 kilometers in diameter hit the Earth, knocking up debris and shielding the sun as well as starting massive fires from the impact. Such an impact would release energy equivalent to about two million times the largest H-bomb ever exploded.

This is an extremely interesting idea, but it received a cool reception from most geologists. The reason was (and still is to an extent) cultural. Starting with the work of Lyell and Hutton in the early 1800s, geologists had become accustomed to the doctorine of *gradualism*. Basically, almost everything in geology happens over long periods of time. The Grand Canyon was produced by extended action of the Colorado river, over millions of years, rather than by a catastrophic event. The Himalayas, impressive though they are, are being pushed up by the many millions of years old ongoing collision of the Indian subcontinent with Asia.

However, here was a physicist (albeit paired with a geologist) claiming that a single catastrophic event had killed off not just the dinosaurs (other than those that evolved into birds) but also 18% of land vertebrate families. Besides, some geologists thought that they already had a good explanation: a huge surge in volcanic eruptions that produced the Deccan Traps in India. The idea was that these eruptions generated nasty gases that caused the extinctions. At times, the opposition to the Alvarez hypothesis got very intense.

As a side comment, I find it interesting that many geologists reacted so strongly. By

1960 it was known, for example, that Meteor Crater in Arizona was produced by a meteorite impact, so it was accepted (maybe grudgingly!) that impacts happened. Perhaps there was a major psychological barrier to thinking that such impacts could have world-wide effects; the one that made Meteor Crater was too small to do much to anything more than a few kilometers away.

However, the nature of science means that if a novel hypothesis is presented, one looks for additional evidence to confirm or disprove it. Some such evidence existed at the time the Alvarezes presented their ideas. For example, a giant impact will melt the rock it hits, and then the melted rock re-forms into things like shocked quartz and glass spherules. These were also found.

The clincher for most people, though, was that in the 1990s a series of studies suggested that the actual impact crater had been identified. Note that this was not easy: erosion processes mean that craters are rapidly smoothed over, and 65 million years is a long time. The candidate, which was dated to the right time and which has many indications of impact, is in the northern part of the Yucatan peninsula in eastern Mexico. It is called the Chicxulub crater, and it has the right size to have done the job. Further evidence that this was the crater is that there is evidence for major splashing on the southern coast of Texas.

There is still some dispute about whether the impact was the *only* factor causing the extinction, or simply one of several. Those volcanic eruptions in India didn't go away, for example. It is possible that the impact helped initiate the eruptions, e.g., by weakening the crust. Note, though, that the impact did have a significant effect, so here we have a clear example of an extinction caused at least in part by astronomical messengers of doom!

The Permian extinction

No extinct animals are sexier than dinosaurs, so unfortunately a lot of the other mass extinctions get short shrift. However, there was one extinction that was far more extensive than the K-T one: the Permian extinction.

This extinction did in 53% of all marine *families*, and probably about 95% of all marine *species*. It even produced a mass extinction of insects, which is pretty tough, as anyone who has tried to kill insects knows! It happened 250 million years ago, and might have opened the way for dinosaurs to evolve. The duration of the event is difficult to determine, and seems to range from maybe tens of thousands of years up to possibly millions, depending on the species.

What caused this extinction? It's not clear. Some people think that another major impact or possibly impacts are to blame. Some think it was massive volcanic eruptions. Others blame a relatively gradual change in sea level or reduction in atmospheric oxygen. This will be much more difficult to track down, given that it was far earlier than the K-

T extinction and therefore evidence is tougher to obtain. This is, in any case, the most dramatic mass extinction in the history of the Earth.

The precambrian extinction

The first great extinction of which we have any record occurred about 650 million years ago. This was a time when no animals existed that had hard parts that were easily fossilized, so we don't have great information about this event and have to resort to speculation about its cause and subsequent effects. We bring it up, however, because some of that speculation has potential bearing on life elsewhere.

The first point is that there is evidence of global glaciation at around this time. In fact, some people think that it was severe enough to have been a "Snowball Earth" episode. The idea is that if ice covers enough of the Earth, then more light reflects off the planet (since it's now mainly white!) and that this will run away to lower temperatures and more ice. Perhaps the whole planet would then be covered. Would this end life as we know it?

Nope. Suppose that the whole world were sealed in ice a mile deep. Deep in the Earth, there would still be radioactive elements decaying, and thus releasing energy. The thick ice layer would act as a cap to this energy, but not forever. Just as trying to cap a boiling pot just delays the eventual explosion, the idea is that the released energy would build up until eventually the ice melted. This type of occurrence suggests that life might be pretty robust once it gets going.

The second point is that this particular extinction event is credited by some with making the ecological niche that was filled by large animals and that led to the explosion of lifeforms over the last six hundred million years plus. In fact, it could be that an occasional mass extinction plays a key role in allowing life to diversify.

Perspectives: could all life go extinct?

Sure, if something really spectacular occurred. For example, if another star passed close by through our solar system, the Earth would likely be kicked deep into space where it would freeze. Some bacteria might not be technically dead (more like in stasis), but nothing would be active. The odds of this, though, are so small that this scenario is irrelevant.

What about asteroid impacts? Remember that in the early days of the solar system large impacts were common, such as the one that kicked up the debris that made our Moon. As time has gone on, though, impacts are rarer and less severe, although they still happen. In fact, in 1994 we got to see a comet, Shoemaker-Levy 9, be torn apart by Jupiter's gravity and have its pieces slam into Jupiter. However, even impacts of that size or the K-T impact wouldn't come close to eliminating *all* life on Earth.

What about killing off just humans? This would be easier, given that we occupy a smaller number of ecological niches. There have even been suggestions that we might do it ourselves, e.g., by a global nuclear war or by sufficient destruction of the environment. In fact, some people think that the current rate at which species are going extinct due to human activity (e.g., clearing of rainforests) qualifies our current epoch as a mass extinction. That may be, but I don't personally envision us killing ourselves off entirely. I *do* think that there are horrifying scenarios in which billions of people die off due to war or disease, but hopefully we can avoid these by prudent politics and resource management.

The net result of all this is that although life on Earth has taken a number of serious hits, it has always rebounded in the historical record. It is possible that life started up four billion years ago and then the planet was completely sterilized by a major impact, but since most of the debris has been cleaned up this has no longer posed a significant threat. With that in mind, taking the long view mass extinctions seem to conform to Thomas Jefferson's quote: a little rebellion, now and then, is a good thing!