Extremophiles

In this class we will focus on one of the coolest developments in biology over the last 2-3 decades: the discovery of many *extremophiles* in different environments. Loosely, we can define extremophiles as organisms that live and indeed thrive in realms that would be quickly fatal to us. Yes, it's a rather human-centered way of looking at things; we'll discuss at the end whether this is reasonable.

We will begin by discussing some of the specific bizarre conditions in which we find life. For this, a good reference is http://www.nhm.ac.uk/research-curation/projects/euk-extreme/. We will then indulge in some wild speculation about what this might mean for life on Mars, and conclude by discussing whether we've been at all reasonable in our categorization: for example, could it be that on some other planet the dominant intelligent lifeform(s) are used to a high-temperature, high-salt environment and would consider a pleasant fall day in Maryland to be extreme?

One last thing before we think about specifics: on occasion we will draw distinctions between organisms that can *tolerate* an extreme environment and organisms that *require* an extreme environment in order to grow and reproduce. The latter category are called "obligate" extremophiles, because they are obliged to be in a certain extreme realm. For example, an obligate thermophile ("heat-lover") requires high temperatures.

Oxygen-free environments

For much, perhaps most, of the history of life on earth, this was the rule rather than the exception. Molecular oxygen is highly reactive, and it is maintained in our atmosphere because it is a waste product of photosynthesis (fortunately for us). However, in maybe the first two billion years of life here, there weren't enough photosynthetic bacteria to produce much of a concentration. As a result, most life had to use something else. Indeed, the life at the time would have found oxygen to be a deadly poison, so this is an early example of air pollution!

Currently, some bacteria and archea use other elements (e.g., nitrogen or sulfur) as the main source of their energy. This can for example occur near deep oceanic volcanic vents, which are also places where many other extreme things occur (see below). However, the "fixing" (usage) of nitrogen or sulfur is not as efficient at producing energy as the use of oxygen. In general, it appears that the majority of organisms in an environment tend to rely on the highest-efficiency basic pathway for energy. Other organisms can exist at the same time, though, as different pathways open up. You may remember, for example, that in some of the Lenski-like experiments with the bacterium E. coli, in a few different cases new species of E. coli appeared that ate acetate, which was a waste product of the glucose consumption that was the norm for other species.

High temperatures

For the following discussion it is useful to remember that a very hot summer day in Maryland might reach 40°C. How comfortable do you feel outside in such an environment?

The most extreme of the extreme are the "hyperthermophiles" (hey, scientists like the biggest and best too), which can *require* temperatures of at least 90°C to survive! These are, to put it mildly, obligate thermophiles. One particular type, called Strain 121, managed to double its population over 24 hours in a 121°C environment. Recall that 100°C is the boiling point of water at normal pressures.

Where the heck would you find such environments naturally? The answer is hydrothermal vents at the bottom of the ocean. Such high pressures allow water to remain liquid at higher temperatures than normal. The temperatures can be even much higher than these already high values. It is not clear what the fundamental limit is for such organisms. Our friend Strain 121 wasn't able to reproduce at 130°C, but it survived. DNA and some other critical molecules start breaking down above 150°C, so that might seem to be a limit. However, at higher temperatures, could it be that other molecules would take over the roles of DNA etc.?

For whatever reason, most hyperthermophiles are archea, although some bacteria can thrive at high temperatures as well.

By the way, thermophiles provide an outstanding example of how basic research can lead to absolutely unanticipated practical benefits. One such organism, the bacterium *Thermus aquaticus*, has a heat-resistant enzyme that is critical in the polymerase chain reaction (PCR). PCR is now indispensible in forensics and the diagnosis and detection of hereditary and infectious diseases. No one went searching for heat-resistant organisms with PCR in mind.

Low temperatures

These are the cryophiles, or psychrophiles (I prefer the former term; psychrophiles sound like mental cases to me!).

Some organisms can survive and grow at temperatures even below 0°C, where pure water freezes. Salt water doesn't, though, and even in ice there can be small portions of liquid water. This doesn't solve the difficulties of the organism, though. You and I would die rapidly if we were immersed in water of temperature < 5°C for any length of time. In our case this is because we would drop below our preferred body temperature, but there are more fundamental problems. For example, if the water inside an organism freezes, that at least renders it inert and can kill it. The membranes themselves can also stiffen.

These organisms have evolved membranes that are chemically resistant to such stiffening, as well as organic “antifreezes”. Pretty impressive. It does appear that growth and reproduction still requires liquid water. However, bacteria and archea can attain stasis in very low temperatures, and be revived later. Laboratories take advantage of this and store some samples at extremely low temperatures. In science fiction we sometimes encounter cases in which humans are supposed to be frozen in stasis in a similar way (e.g., as a way to travel between stars without experiencing hundreds of years). There are some cool bits of research being done on ways to freeze without damage, but it is at best a technique for the far future.

Very acidic or alkaline

For this, recall that a neutral medium (e.g., distilled water) has a pH of 7.0, that acidic mediums have pH<7, and that alkaline mediums have pH>7. Our blood is very slightly basic (pH=7.4), Lemon juice has a pH of about 2.0; battery acid has pH=1.0. Lye (used in detergents) has pH=13.0. You would take damage if you swam around in lye or battery acid, but would probably be okay for at least a little while in lemon juice. However, you'd prefer swimming in water, and if you decided to drink nothing but lemon juice you'd regret it after a while!

Acidophiles (lovers of acid) are defined as organisms that grow optimally at pH<2. The most extreme known example is an archaean called *Picrophilus*, which has been seen to grow at a pH of 0, i.e., the same acidity as undiluted hydrochloric acid(!!).

Most acidophiles “cheat” by developing ways to pump out extra protons from their intracellular space, meaning that they can use “normal” proteins. Some, however, have evolved proteins that are stable in very acid environments. This is an example of how evolution often allows exploration of many different solutions to the same basic problem.

Alkaliphiles (lovers of alkalines) are similarly defined as organisms that grow best in environments with pH greater than 9. There appears to have been less exploration of such organisms, but as with acidophiles it seems that most of these (and they're all microbes, of course) maintain a nearly neutral intracellular environment, in this case by pumping in protons.

Very salty

We can basically define these as organisms that require a salt concentration at least five times that of the ocean. That means they can be found in places such as the Great Salt Lake, the Dead Sea, and various much smaller evaporation ponds.

As with the acid and alkali lovers, the key to their survival appears to be maintaining a cellular environment that is relatively free of salt, by pumping out salt vigorously. Of course, that means that in a normal environment these would expire.

It has been suggested that liquid water on Mars will be very salty, due to the low temperatures and pressures, so if there is life on Mars it is possible that it resembles our salt-lovers!

Living in deep rock cracks

In a fairly recent surprise, researchers have discovered enormous numbers of small life-forms very deep in rock, up to several kilometers below the surface (some a few km below the bottom of the ocean.). The total mass of all of these creatures could be significantly in excess of the mass of all life previously known(!!!). Such organisms feed on iron, potassium, or sulfur, or in some cases on each other. This therefore forms a biome, and as proof that some biologists have a sense of humor, it has been called a Subsurface Lithotrophic Microbial Ecosystem, or SLiME for short :). These things live very slowly, possibly reproducing as seldom as once per hundred years. They spend most of their energy repairing things like cosmic ray damage.

As with most extremophiles, the true limits of rock-lovers are not known yet. It is suspected that the main limiting factor is temperature. That is, if the temperature rises above, say, 150°C, liquid water won't exist or DNA will become denatured. That would limit the depth to which these organisms could exist; not much more than a few km down.

It occurs to me that this can lead to wild but interesting speculation. Think about Mars, which is a smaller planet than Earth and thus cooled faster and has a much thicker crust. Suppose that rock-loving microbes live on Mars, and that they have the same upper limit to temperature that ours do. Then it seems possible that the *current living biomass* on Mars could be greater than it is on Earth! We're still a fairly hot planet, meaning that our crust is thin and the temperature increases quickly with depth. On Mars, therefore, the total volume available to rock-lovers might be a lot greater than it is on Earth. Of course, to test this would require pretty substantial drilling on Mars, and that is decades away.

An Extreme Ecosystem: Undersea Thermal Vents

From the discussion above you might draw the conclusion that most extremophiles on Earth are single-celled, and you'd be right. Why, then, should we care?

One reason is that *any* life outside Earth would be big news. The existence of extremophiles tells us that the range of acceptable environments is vastly greater than what we personally can tolerate. Essentially, anywhere on Earth that has liquid water appears to have life evolved to make what it can of the specifics.

However, even if we are only interested in more complicated multicellular organisms, we can point to a remarkable environment that has many species including some that are pretty large. These are found near undersea thermal vents. We presume that the base of the food chain is still achaea or bacteria, but there are also giant tubular creatures. Even more bizarrely, there are *photosynthetic* organisms. Why is this bizarre? Because these vents are many kilometers below the ocean surface, and absolutely no sunlight can reach down that far. However, these vents are volcanic and involve hot rock that glows red. That pitiful little amount of light is nonetheless an energy source, and some organisms have evolved to take advantage of them! You can look for videos on "black smokers" to see some of these vents and their ecosystems.

This is especially relevant for Jupiter's moon Europa, which is considered to be one of the best other candidates for life in our Solar System. As we will discuss in detail in a future class, Europa is being squeezed enough by Jupiter's gravity that it is much hotter than it would be normally. In particular, there is evidence from the cracking of Europa's ice that there is a large ocean on the moon. It is speculated by some that there are hydrothermal vents at the base of Europa's ocean, which could mean that life might exist there as well. It's likely to be quite a while before we find out.

What might extremophiles mean about life in the universe?

Let us now return to the overall topic of this class. What does the existence of extremophiles mean about life elsewhere?

From the standpoint of having any life at all, I think they suggest that life can appear in more niches than we had realized a few decades ago. For example, photosynthesis is apparently not necessary for life. This could mean that there is some planet slightly larger than Earth but farther from its host star that could have life similar to what we see in undersea vents. One could also imagine cloud-bound planets that nonetheless have a thriving ecosystem.

On the other hand, although discovery of microbial life elsewhere would be really exciting, what most of us would really like is if there were complex, even intelligent, life on other planets. From that standpoint, we notice that almost all extremophiles are rather simple organisms. Can we draw any special conclusions from this? Note, for example, that most of the volume of Earth that supports life at all could be said to host extremophiles: deep rock and deep sea, for instance. Does this mean that extreme conditions are not conducive to the development of complex life?

My feeling is that we still don't know enough to make such statements. It could be, for example, that the reason that extremophiles haven't made it to the big time (meaning large complex organisms) is that animals and plants of less extreme nature have already occupied those evolutionary niches. Maybe on a planet that had nothing but extremes, the ecosystems would still have flourished.

What we can say is that anywhere there is an energy source and liquid water on Earth, there appears to be life. Could this extend to other environments, e.g., the atmospheres of

Jupiter and Saturn, where there is substantial energy still being produced as the planets contract? I don't know.

One thing that is interesting is that all life on Earth is carbon-based. Carbon does have very flexible chemistry, so it is a natural, but are there other options? One element pointed to by many people is silicon, which is just below carbon in the periodic table and thus has similar properties for its electrons. However, although there is vastly more silicon than carbon on the Earth, including on the Earth's surface (think of all that sand!), no silicon-based life has been identified. That might point to a limitation of life, but it is also conceivable that in very different circumstances (e.g., much hotter planets) silicon might come to the fore. What I've read about silicon, though, suggests to me that the variety and complexity of molecules it can form is very restricted, suggesting that it probably can't do the job.

Mass Extinctions

We will now 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.

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 (see our fourth supplement for definitions of taxonomic terms such as "family")! 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!

The K-T extinction (for Cretaceous-Tertiary after the geological times; apparently this has been renamed the Cretaceous-Paleogene extinction) is the most famous one because it took out the non-avian dinosaurs, about 66 million years ago. It also took out about 3/4 of all plant and animal species on Earth. The general consensus is that this happened because of an asteroid impact, but there might have been other effects within the critical million years (such as the huge rate of volcanic explosions that created the Deccan Traps in India). However, this isn't the only mass extinction in Earth's history. It isn't even the most extensive one. That title belongs to the Permian extinction of about 250 million years ago, which did in 53% of all marine *families*, and probably about 95% of all marine *species* (!!!). This happened much longer ago than the K-T/K-Pg extinction, so as you'd expect the causes are not as well understood. Candidates include another major impact, or more volcanos, or the formation of Pangaea (which removed coastal areas, which are locations of great evolutionary innovation due to their status as boundary regions). Yet another mass extiction happened about 650 million years ago. This "precambrian" extinction seems to have happened because the whole Earth got wrapped in a deep layer of ice and snow(!), which was naturally not good for the health of the organisms then.

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 I hope 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!

The Habitable Zone

When considering where life may exist, we have relied again and again on what we know about life on Earth. This bias will now emerge again, because we will talk about the "habitable zone". This is technically the region around a star or in a galaxy where conditions are favorable for life as we know it. Often, however, it is implicitly extended to imply that this is the only place life could develop, period. As we have emphasized throughout, that is reaching a bit. Indeed, some have gone so far as to dispute that the concept of a habitable zone is useful at all. However, we'll give it a try because we know life can exist there. We are in the position of a drunk at night looking for his keys under a lamppost. Asked if he dropped them there, he responded "no, but this is the only place I would be able to see them."

What do we mean by habitable zone?

The standard definition is that the habitable zone is the range of distances from a star in which liquid water could exist. As discussed in the third supplement, if you take into account that our Sun has become gradually more luminous as it has aged, a relatively narrow range of distances from the Sun (between 0.95 and 1.15 AU) has been continuously in the habitable zone.

Criticisms of the habitable zone concept

Although the idea of a habitable zone is a staple of astrobiological discussions, it has received significant criticism. I think this is justified. The potential problems are:

- We are being very human-centered here. Our study of extremophiles indicates that many creatures could live in environments lethal to us. For example, if we moved the Earth out to 2 AU, I would expect the Earth's internal heat to produce a region favorable to liquid water a few miles down in the crust. Why couldn't life originate there?
- Even if oceans of liquid water are required for life, we have examples in our own Solar System of such oceans far from the "habitable zone". The prime example is Jupiter's moon Europa. We'll discuss this in far more detail in a later class, but Europa is kept hot by tidal squeezing from Jupiter. It is certainly not warmed to any significant extent by the Sun, because Jupiter and its moons are 5.2 AU away from the Sun! Therefore, this is an effect that could in principle happen much farther away as well.
- Variations in a planet's mass can make a big difference in at least a couple of ways. For one, higher mass means a longer time to cool down, leading to greater internal heating. For another, higher mass means a greater ability to hold on to an atmosphere and possibly greenhouse gases. We could also imagine that a stellar system formed later than the Sun might have larger amounts of carbon and oxygen (since there would have been more time for other stars to form them), so could it be that they would have a greater greenhouse effect?

Obviouly we don't know for sure what is required for life and how much stronger the requirements are for intelligent life. Nonetheless, I think that at least some treatments of the habitable zone are too dogmatic in what they consider essential.

As we discuss in our third supplement, high-mass stars last only a short time (possibly not enough for life to appear) and very low-mass stars would require planets to be so close to be in the habitable zone that the star's gravity would force such a planet to always have one face to the star. Thus most people think that stars *around* the Sun's mass should be best for life. It also seems to many people that it is helpful to have just one star, rather than a binary, in the system (see Isaac Asimov's "Nightfall" for a vision of some problems of having many stars in a system!). But what about our location in the galaxy?

The galactic habitable zone

Our last restriction has to do with where we are in the galaxy. It has been argued that, once again, we are in an especially nice place. The argument relies on two requirements: that there be enough heavy elements to form terrestrial planets, and that there be a small enough number of massive stars around that we can avoid nearby supernovae.

The heavy element issue comes back to how we get carbon, silicon, and so on. You recall that these are produced in stars, meaning that for the elements to be reasonably common requires several generations of stars to have evolved and dispersed the elements. There is, naturally, more gas nearer the center of our galaxy than near the edges. As a result, more stars have formed in the inner regions of the galaxy, and the fraction of heavy elements drops as one goes farther out. Therefore, it is argued, life can't form too far out because there wouldn't be enough silicon and iron to seed the grains that eventually formed terrestrial planets.

The supernova issue is that if the number of stars per volume is too high, supernovae will occasionally happen close enough to raise the temperature significantly and wipe out life. One might add that close enough stars will also risk going through the planetary system and ejecting planets or at least causing comets to rain down doom on any hopeful life. But since the number of stars per volume is greater closer to the galactic center, it is argued that life can't form too far in either.

My perspective on this is that it is probably true qualitatively. Yes, if you have a star that is 100,000 light years from the galactic center it probably has 1/100 of the abundance of heavy elements that we do, and that might be challenging. Yes, if you have a star that is within 100 light years of the galactic center the number of stars is large and planets would be horribly harassed. However, there is probably a 10,000–20,000 light year range around the Sun in which the number of stars per volume is pleasingly low and plenty of stars have enough heavy metals to form terrestrial planets (assuming that's necessary). I don't see that this is really restrictive. Frankly, I suspect that the people who push this as an issue have a motive to show that the Earth is extra special. I don't need that; I love the Earth for what it is and don't feel threatened by the possibility that there may be many other beautiful life-supporting planets out there!