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. 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.

In the next lecture we will think of another potentially limiting factor of life: mass extinctions, which (oddly) both give life a hard time and allow it to flourish.