Life in the Universe

"Are we alone?" is a question that is both profound and eternal. People have probably been asking it in one form or another since the dawn of history. Early on, of course, no one knew whether other parts of the Earth contained humans or monsters, which is probably a major driver behind many cool myths. Now we have explored enough of the Earth to know that dragons aren't waiting around the next bend, but we have seen life in places that we could not previously have imagined: near undersea volcanic vents, in frozen or acidic wastes, and even miles deep in solid rock.

Our search for other life has therefore moved outward. Could life exist elsewhere in our Solar System? How about orbiting another star? Would we feel excited by alien microbial life, or do we hope for E.T. or Mr. Spock? If intelligent aliens are out there, is there a chance that we could communicate with them?

We are at a disadvantage in searching for extraterrestrial life of any kind, simply because we only know of life on our planet. In particular, we therefore don't know how many of the circumstances that have allowed such diversity of life on Earth are essential for life elsewhere. Must the host star be similar to ours? Does life have to develop on a planet, or could it be on the moon of a planet or elsewhere? If a planet is required, need it be in an orbit similar to ours? Does it have to have the same composition, and be the same size as the Earth? Our natural tendency is to look for situations similar to ours, but that may be too restrictive.

In this class our task will be to explore various aspects of life in the universe. This will include relevant aspects of cosmology, star and planet formation, chemistry, biology, and of course specifically life on Earth. We will also have some fun speculating about how we would detect life elsewhere (intelligent or otherwise) and current attempts to do so.

I do want to issue one warning. Evolution has been central to the development of life on Earth, and is such a simple and general process that it undoubtedly plays an equally essential role in life anywhere. As a result, we will have several classes on both the fact of evolution (which is established as clearly as any fact in science), and the theoretical underpinnings (which, like any theoretical concepts, are under development at the frontiers). If for any reason you are offended by evolution, this really isn't the course for you and I want you to know that now.

What is life?

As our first step towards a search for life, we might want to define what life is. Surely that can't be too difficult? Let's take a quick poll. How many people think that a rock is alive? A snowflake? Clay? A virus? A bacterium? A fly? A person? I'm guessing that most of you would say that the first three are not alive, that the last three are, and that you are less certain about the virus. However, as we'll discuss when we go over possible origins of life, there are reasons to think that some clays have properties similar to primitive life, and snowflakes also fit some of the definitions (although I'd have a tough time assigning life to a snowflake). What definitions have people used for life?

There is no general agreement, but most people feel that for something to be called alive it must demonstrate the following properties: (see the Wikipedia page on life):

1. Homeostasis. Living things need to have a regulated internal environment. This need not be perfect regulation (note that you can survive a fever, and cold-blooded animals can change their body temperature significantly), but reasonable limits need to be maintained.
2. Metabolism. There must be intake of matter which is then processed to extract energy and build up new components of the living thing.
3. Growth or reproduction. During at least some phase of the existence of the living thing, it must be able to grow or reproduce.
4. Adaptation. It is necessary that, possibly over many generations, the living thing and its descendents must be able to change in response to its environment.

For the large complex life that we're used to, these are obvious. However, very small life can make even these basic requirements less obvious. For example, there are spores and bacteria that can go into a state in which they don't eat or grow; they just sit there. This can happen if they are in an environment without any water. Even with larger things, it can be that some members of the species are always, inevitably, sterile (such as with ant workers). There are also much larger examples of sterile or almost sterile things, such as mules or ligers, although they do grow (which is why we said grow *or* reproduce above).

You'll note that we carefully avoided saying that it is essential for life to be made of cells, because viruses don't have cells. We also note that viruses and some bacteria actually can't perform certain critical biochemical operations by themselves, needing a host organism. Do we then consider these to be independent life? We also have to realize that the very earliest homeostatic, metabolizing, growing/reproducing, adapting organisms on Earth had to be much simpler than what we see now (even simpler than viruses). It seems highly likely that the transition between life and non-life was gradual.

From the fundamental biochemical standpoint, even among things that most people would say are definitely alive there are wide variations. All the big things we're used to use oxygen in one way or another as their basic source of energy. However, there are microbes that instead use sulfur or nitrogen as their basic source. One consequence of this has to do with how we would establish that a planet around another star has life. It has been suggested that since free oxygen doesn't last very long in most atmospheres, if we see the spectral signature of oxygen then there must be life. That may or may not be true, but the existence of bacteria and archea that are otherwise powered means that the absence of atmospheric oxygen does not have to rule out life (indeed, in the first billion plus years of life on Earth, atmospheric oxygen was rather low).

The Drake equation

As you can see, we are in a position of great uncertainty about extraterrestrial life. Estimates of the probability that there currently exist other intelligent civilizations may seem completely doomed. It is, however, useful as an organizational tool to follow the path first laid out by Frank Drake in 1960 at Green Bank, WV as preparation for a historic meeting on searches for extraterrestrial life.

What Drake pointed out is that although we may not know the final answer to how many current civilizations to expect, we can write the answer as a product of factors so that we see more clearly which factors are uncertain, and which are basically under control. We'll see this equation later in the class after we've gone over a number of the inputs, but it's fun to give it a shot now. One warning: after Drake's original introduction of his equation, many variants have been proposed. If you increase the number of factors, you can get the answer to be as small as you like. We'll start with a slight modification of the original:

$$N_c = N_* \times f_p \times n_e \times f_l \times f_i \times f_c \times f_s \; . \tag{1}$$

Here N_c is the number of civilizations with which we could potentially communicate; $N_* \approx 2 \times 10^{11}$ is the number of stars in our galaxy; f_p is the fraction of those stars that have planets; n_e is the number of potentially inhabitable planets per star that has planets; f_l is the fraction of those planets that develop life; f_i is the fraction of the ones that develop life that eventually develop intelligent life; f_c is the fraction of the ones with intelligent life that release detectable signals of their existence; and f_s is the fraction of the Galaxy's lifetime that they do so.

The only very well-known factor here is N_*. Discoveries of extrasolar planets over the last ~ 20 years have given us a decent handle on f_p, although as we'll see the detections are strongly biased towards planets that have a small probability of hosting life as we know it (i.e., Jupiter-mass planets closer to their star than Mercury is to the Sun). Still, let's take some guesses at the values of the rest of the factors. What product do we get? Most groups are optimistic enough that the number turns out to be reasonably large. The basic cause of this, of course, is that N_* is so tremendously large.

However, suppose that we are convinced for other reasons that we are alone in the galaxy. It is easy to put in other factors that reduce the value practically as much as we would like. For example, it has been argued that the following things could be crucial:

- The host star type. The argument goes that much more massive stars than the Sun don't live long enough for life to develop, and much less massive stars have tremendous flares that would wipe out life. This introduces another factor $f_{\rm Sun}$, which is about 0.1.
- An orbit like Earth's, and a planet very like Earth in that orbit. It has been suggested that a high-eccentricity orbit (rather than the nearly circular one we have) would subject any life to variations too extreme to survive. Also, if the planet in question is too small it can't retain an atmosphere and will lose its internal heat quickly. A planet that is too large might have any solid surface buried under an atmosphere too thick for light to be used as energy. This might put in another couple of factors: $f_{\rm orbit}$ and $f_{\rm Earth}$, each of which are comfortably less than 0.1 in some people's reckoning.
- Other special characteristics about the Solar System and Earth in particular. For example, it has been proposed that Jupiter acts as a critical shield for us against marauding asteroids, and that having a large moon stabilizes the Earth's rotation axis in a way that allows life to develop. Again, we could put in factors $f_{\rm Jupiter}$ and $f_{\rm Moon}$ and argue that each is conservatively no more than 0.1.

That gives you a taste; it has also been suggested by those who want us to be alone that our position in the Milky Way galaxy is specially privileged, for example. If we think that there are millions of civilizations around, we have to answer a question first posed by Enrico Fermi: where are they, then?

Barring truly amazing timing, we don't expect to be able to resolve in this class whether life elsewhere (even microbial life) exists. However, the goal is to understand the context and current searches, and to thus get a little closer to comprehending the vastness and diversity of the universe.

The scale of the Universe, and an inventory

- Space is big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist's, but that's just peanuts to space. – Douglas Adams

Truly, the universe is a large place. If we are to consider the possibility of life anywhere else in the universe, we have to open our mind up to the various possibilities. As part of this, we need to take stock of what is in the universe, and the scales that we deal with. A prerequisite for this is that we need to be able to use the units that are common in astronomy. After we go through that, we'll discuss different scales.

Units in Astronomy

Even with scientific notation, astronomers like to have at hand a number of specialized units that are reasonable measures of the systems in question. For example, we could indicate the masses of stars in units of kilograms. However, it is more convenient to give their masses in units of the mass of the Sun, and to remember (or have in some reference) that the Sun's mass is about 2×10^{30} kg. We could measure distances to other stars in meters, but again that is not well matched to the actual distances. Instead, distances are measured in units of parsecs. One parsec is about 3.086×10^{16} meters, and is the distance that light in a vacuum travels in about 3.26 years. There is also, of course, the light year, which is 9.46×10^{15} meters, but parsecs are preferred by astronomers because they are more directly related to observations (in particular, they relate to a measure of distance called parallax). With scientific notation in hand and a list of such constants (I don't expect you to memorize these numbers!), it is straightforward to convert back and forth.

Armed as we now are, we can start surveying the universe. We'll do this by moving outward: planets, stars, galaxies, and the universe itself.

The Solar System

Our Solar System is the one place in the universe that we know absolutely can support life! Therefore, as we go through this course, please have in the back of your mind the question of whether you think we are extremely special in this respect (e.g., having many unusual properties that are crucial to life arising), or whether many systems are likely to be similar to ours.

The important occupants of our Solar System are:

- The Sun. This contains all but about 0.1% of the total mass in the Solar System. The Sun (like the rest of the Solar System) is about 4.6 billion years old, and is a star with somewhat above average mass. It is a pretty stable star, with flares that can affect our atmosphere a bit but that is a reliable source of heat and light. When it was younger its luminosity (a name for the energy per time that it puts out) was maybe 2/3 or 3/4 of what it is now.
- Mercury. The nearest of all planets to the Sun (it has an orbital semimajor axis of just 0.4 AU, where 1 AU [astronomical unit] is about 1.5×10^{11} meters and is the average distance of the Earth from the Sun). It is also the smallest of the major planets, and as a result has essentially no atmosphere. Views of its surface make it look a lot like the Moon, with many large craters.
- Venus. This planet orbits at 0.7 AU, and has a very thick atmosphere with 100 times atmospheric pressure on Earth, made mainly of carbon dioxide. It has the highest surface temperature of any planet, even more than Mercury, because of the greenhouse

effect of the carbon dioxide. It is about the same size and mass as the Earth, leading many breathless science fiction authors throughout the years to imagine it as a steaming jungle, but with no liquid water, rains of sulfuric acid, and a temperature hot enough to melt lead the prospects seem dim.

- Earth. Home sweet home! The only planet to have liquid water on its surface. It also has a moon that, although not the biggest in the Solar System, is by far the largest relative to its host planet (among the major planets).
- Mars. The red planet, and the host of even more breathless science fiction stories than Venus. Mars has only about 1/10 of the mass of the Earth, but being farther from the Sun (1.5 AU) it does have a thin atmosphere (1/170 of the Earth's). Mars has ice caps made of both water ice and dry ice, and we've explored it with a large number of probes.
- Jupiter. The biggest planet by far, it has more mass than all other planets combined. It also has four large moons, so that even at a distance of about 5 AU from the Sun, making the region quite cold, Jupiter's effects on some of the moons (Europa in particular) may allow them to have liquid water under many kilometers of ice. Could there be life in those oceans?
- Saturn. Many people's favorite because of its beautiful rings, Saturn also has the large moon Titan. Titan isn't squeezed by Saturn the way that Europa is by Jupiter, so at about 10 AU from the Sun it's mighty cold. However, the Huygens probe took photos that suggest that there might be liquid methane on the surface. Could this support life?
- Uranus and Neptune. The two outermost major planets, these are close to twins of each other. Uranus is at 20 AU from the Sun, and Neptune is at 30 AU, so it's frozen out there. These planets are themselves very large (14 and 17 times the mass of the Earth, respectively), and Neptune has the large moon Triton (which has nitrogen geysers!), but life prospects seem dim at this time.
- Asteroids. The "main belt" of asteroids lie between Mars and Jupiter, and are basically really big rocks. The largest one, Ceres, is about 1000 km in diameter (somewhat smaller than Texas), but the overwhelming majority that we've seen are just a few km across. Many of the asteroids are thought to be good fossil records of the beginning of the solar system. Their orbits sometimes cross that of the Earth and lead to occasional collisions, the most famous being the impact 66 million years ago that did in the dinosaurs and most other animal species on Earth.
- Comets and other small distant objects. Comets have long been feared as harbingers of doom, and even in modern times have inspired (if that's the right word!) cultists to join them by, er, shedding their bodily forms. It's probably safer to just appreciate them

for what they are, which is small icy bodies that come from the very distant portions of the Solar System (maybe 1,000 AU to 100,000 AU away). We are also discovering many larger objects that are closer by. For example, Pluto, which used to be classified as a planet, is now a "dwarf planet", orbiting at 40 AU. Comets contain simple organic materials, and some people think that this might be a way that the starter molecules for life could have been delivered to Earth.

Extrasolar planets

Before 1993 (i.e., in some of your lifetimes), the only planets we knew about were in our Solar System. However, since that point various surveys have detected about two thousand confirmed planets orbiting other stars, and thousands of other good candidates. I am proud to say that the first extrasolar planets were detected around a pulsar, but the rest are around ordinary stars. We'll talk in detail about these guys in a later class, but suffice it to say that it only recently did it become possible to detect an Earth-mass planet at an Earth orbital radius around another star. Techniques keep on improving, and within another several years it is expected that these detections could become routine. In the meantime, most systems thus far discovered look very little like our Solar System: they often have giant planets closer to their host stars than Mercury is to the Sun, and in many cases the orbits are highly eccentric as opposed to the nearly circular orbits in our system. On the other hand, only a small fraction of stars have been surveyed, so it is not clear whether our system is typical or extraordinary.

Stars

When we start going out to other stars, the distances get immense. The closest star to our Sun, Proxima Centauri, is 1.3 parsecs away. That's almost 10,000 times farther away than Neptune, the most distant major planet! Indeed, such huge gaps were one of the reasons that many people had difficulties accepting the Copernican universe; it just seemed like a waste of space.

Nonetheless, they really are that far away. Observations and theory have given us a pretty clear picture of the crude evolution of stars once they are on the "main sequence", which is the largest portion of their lives (during which they shine and support themselves by fusing hydrogen into helium). For the purposes of determining whether life could exist around various stars, the following facts are of relevance:

- Stars can extend from about 0.08 times the mass of the Sun to possibly hundreds of times the mass of the Sun, when they are born.
- The lower-mass a star is, the longer it is on the main sequence. Our Sun will last about

10 billion years total. Within a factor of about 10 of the Sun's mass (i.e., from mass $M = 0.1\ M_\odot$ to $M = 10\ M_\odot$), the lifetime scales roughly as M^{-3}. That means that a 0.1 $M_\odot$ star would live for a few trillion years, whereas a 10 $M_\odot$ star would live for only a few tens of millions of years.

- Low-mass stars have flares, just as the Sun does, except that the very low-mass stars have flares that are a significant fraction of their total energy output. That means that the illumination from such a star would go up and down far more than the Sun's does.
- When low-mass stars finish with the hydrogen in their cores, they expand to become red giants. For example, the Sun will grow until it is roughly 1 AU in radius, compared with its current radius of roughly 1/200 of an AU. Such stars then sink back until they are "white dwarfs", about the size of the Earth but maybe 60% of the mass of the Sun. They then cool indefinitely. The red giant stage only lasts a few million years.
- When stars start out with at least $M = 8\ M_\odot$, they become giants, contract back to fuse helium to carbon, become supergiants, and so on. Eventually, they blow themselves to bits in supernovae. and leave behind beautiful remnants in the form of neutron stars or black holes (they're beautiful to me, at least). This is great for dispersal of many of the elements of life, but probably not such good news for any planets orbiting the star!

There are far more low-mass stars than high-mass stars. The Sun, for example, has a mass that is in the top 5% of the mass of all stars, and only about 0.2% of stars start out with more than 10 $M_\odot$.

The potential habitability of planets around stars of different masses is a matter of debate. High-mass stars live a short time, so life would have to evolve very rapidly. Low-mass stars give plenty of time, but their strong flares could prove challenging to life. My personal opinion is that since we can't observe other systems closely enough to determine if they have life (even microbial life), we shouldn't make statements about their habitability with too much confidence.

Galaxies

Galaxies are collections of stars, say between 10^7 of them and 10^{13} of them. Their typical sizes are measured in the thousands of parsecs. Our Milky Way probably has about 4×10^{11} stars, and we are about 8,000 parsecs from the center of the galaxy. Like anything else in universe, galaxies have undergone evolution with time. For example, when the universe was just a few billion years old (as opposed to its current 13.7 billion year age), collisions between galaxies were more common than they are now. The stars are so far apart that even when two galaxies of 10^{11} stars each collide, it would be unexpected if even one pair of stars hits directly. However, there is a lot of interstellar gas and dust in galaxies. This has low density (and I mean *really* low, as in typically about 10^{-21} the density of air!!), but there is so much of it that the gas/dust of one galaxy collides with the gas/dust of another. This can do spectacular things like produce a burst of star formation or feed the supermassive black hole that is at the center of all the large galaxies we've been able to examine so far.

Some people feel that life could only evolve at certain distances from the center of a galaxy. Too close to the center (e.g., 3,000 parsecs!) and there are so many supernovae that we would get high levels of radiation and cosmic rays. Too far away (say, 12,000 parsecs) and not enough heavy elements would be present to allow for the formation of solid planets like the Earth. Is this true? Again, I think we should be cautious about drawing definite conclusions at this point. For all we know, creatures at 1,000 parsecs from the center of our galaxy might require a certain level of radiation to exist, and they might be arguing that life could not possibly evolve 8,000 parsecs from the center!

There are, in any case, around 10^{11} galaxies in the observable universe, which is an amazingly large number. Multiplying this by the number of stars per galaxy gives something like 10^{21} stars total, any one of which could potentially have planets. This is more, by a large factor, than the number of sand grains on all the beaches on the entire Earth.

The universe

The universe has an age of 13.8 billion years (1.38×10^{10}). By one measure, then, the size of the observable universe is 13.8 billion light years. However, it appears that the totality of all there is (call it the cosmos) is at least significantly larger than what we see, and indeed could actually be infinite. We'll deal with some of the mind-boggling consequences of that in a later lecture. However, as we'll see in the next lecture, the development of the universe from a hot, dense, nearly uniform phase early to its current cold, tenuous, structured situation has implications for when life might possibly have formed.