The Drake Equation

The Drake equation, which we encountered in the very first lecture of this class, is a way to take the question "How many communicative civilizations are there currently in our galaxy?" and break it into several factors that we estimate as best we can. In this class we will go into detail about this equation. We will find that we now have a decent idea of the values of a couple of the factors, but that many are still guesswork. We'll do our best to make our guesses informed. We will also discover that some people have reformulated the equation by adding a number of other factors they consider crucial to having technologically adept life.

The remarkable and subtle effect of this is that, depending on how many factors you think appropriate, you can get the conclusions you want while appearing reasonable and conservative throughout. That is, if you think many civilizations exist, you can use the Drake equation to demonstrate this. If you think we are the only ones, you can get the equation to say that as well. With this in mind, we should approach the Drake equation as a way of framing our discussion as opposed to as a method of determining the answer rigorously.

The equation itself and its factors

The original form of the equation was written by Frank Drake in 1960 in preparation for a meeting in Green Bank, West Virginia. It says:

$$N = R^* \times f_p \times n_e \times f_l \times f_i \times f_c \times L \; . \tag{1}$$

Here:

- N is the number of currently active, communicative civilizations in our galaxy.
- R^* is the rate at which stars form in our galaxy.
- f_p is the fraction of stars with planets.
- n_e is the number of planets that can potentially host life, per star that has planets.
- f_l is the fraction of the above that actually do develop life of any kind.
- f_i is the fraction of the above that develop intelligent life.
- f_c is the fraction of the above that develop the capacity for interstellar communication.
- L is the length of time that such communicative civilizations are active.

Note that "fraction of the above" means that all the previous conditions have been satisfied. For example, when we consider f_c we assume that intelligent life has already developed.

The context of this equation was that Drake and others were considering how likely it would be that if we observed, say, radio waves from various stars that we might detect signals of intelligent origin. The general idea is that by breaking down the big question into various sub-questions, it is ultimately possible to make a reasonable estimate of the final answer. In doing it this way it is also implicitly assumed that no factor is so small as to render the others meaningless. For example, if you think that f_i is equal to 10^{-10}, then no amount of optimism about the other factors will compensate.

Are these the right factors, or do we have too many or too few? Obviously we can group some of the factors. For example, $f_p \times n_e$ is just the average number of potentially habitable planets per star in our galaxy. However, the point of the equation is to break up questions into manageable factors, so it is reasonable to avoid more grouping.

The real question is whether we have too *few* factors. For example, as we will discuss towards the end of this lecture, proponents of the "Rare Earth" idea think that f_l needs to be broken up into factors that include the probability of a large Moon and the probability there is a large planet such as Jupiter to protect us from too much asteroidal bombardment. We'll discuss these issues along the way.

The star formation rate R^*

The first factor is one for which we have a pretty good number. A simple estimate just takes the total number of stars in our galaxy, and divides by our galaxy's age. There are around $200 - 400$ billion stars in the Milky Way, and we are roughly 12–13 billion years old That gives a rate of 15–30 stars per year. However, it turns out that the star formation rate in the universe was much higher 10 billion years ago than it is now. Therefore, most stars in our galaxy are much older and lower-mass than ours. We can nonetheless estimate the current rate by looking at stars more massive than our Sun, which don't live long and thus provide a reasonable snapshot. The answer is that about 5–10 stars per year are forming in our galaxy.

So much for the easy part. Now we start moving into the unknown.

The planetary fraction f_p

This is a factor whose value was completely up in the air twenty years ago, but for which we are now narrowing in on a number. Still, we have to be cautious.

Our initial tendency is just to use the fraction that is emerging from current surveys: roughly 5% of Sun-like stars that have been observed have had planets detected. There are, however, at least two ways that this number could change significantly. One is the point we made while studying extrasolar planets: only massive and fairly close-in planets can be detected by most ongoing surveys. We are therefore missing a potentially large number of planets. As observation times get longer it will become easier to see planets with long orbital periods (e.g., Saturn), and close-in but low-mass planets can be seen by watching for the slight dips in light that occur if the orbit is such that the planet passes in front of the star.

The second point is that our Earth-centered bias has caused us to look mainly at stars similar to our Sun. But only a relatively small fraction (maybe 5–10%, depending on your definition) of stars are like our Sun. Since f_p is the fraction of *all* stars that have planets, this can make a factor of 10 difference. The big question is basically what fraction of low-mass stars have planets, and at this stage not enough have been surveyed for us to tell with confidence.

What is your best guess for this factor?

The number n_e of habitable planets in a planetary system

For the first two factors we had some observational guidance. From this point on, however, we are unfortunately restricted to Earth and our Solar System for information. This means that we can try to put in various theoretical considerations but our understanding is only tentative.

Part of the issue with this factor is what we mean by habitable. As we discussed, Venus may have had liquid water on its surface when it was young. Mars may have subsurface liquid now, and in the future when the Sun is brighter it will be more conducive to life as we know it. We also note that in principle our terrestrial planets could have orbits that are closer to each other without suffering catastrophic instabilities. This means that if another system really is closer-packed, n_e could be significantly larger. In addition, as we discussed, moons of giant planets could have liquid water and enough energy, stability, and chemical components that they would be habitable by our definition. All of these considerations suggest making n_e reasonably high.

On the other hand, the orbital properties of the extrasolar planets we have discovered thus far are not favorable to the existence of terrestrial planets. For example, in every case that there is a massive planet in a close orbit, we believe that it had to get there by first forming far out, then drifting inward. As it drifted, it would have kicked out any planetesimals that were starting to come together to form Earth-mass planets. In addition, we saw that many extrasolar planets are in moderately to highly eccentric orbits. They therefore move across a wide range of radii, putting any terrestrials in that orbital range at risk.

We also know that for planets around low-mass stars, residence in the traditional habitable zone means that the planet will be close enough to the star that gravitational tidal forces will lock one face of the planet towards the star at all times. This might be quite unfavorable to life if it leads to strong winds and a large temperature gradient across the surface. This could be mitigated by a thick atmosphere, but it is still not promising. These last two considerations suggest a lower n_e.

And then there are the 95% of nearby Sun-like stars that do not have detectable planets. How should we factor those in? It could be that none have planets. It could be that all have systems of terrestrial planets. It's unclear.

What is your best guess for this factor?

The fraction f_l of habitable planets that develop life

Suppose we have a planet with liquid water, stability, energy, and good chemical components. How likely is it to develop even rudimentary life?

As promised, we are moving into progressively more uncertain territory. In our only example, we have one planet in our Solar System that we know is capable of supporting life, and we did. The fraction is therefore $f_l = 1$!

For a more realistic estimate we can consider how life evolved on Earth. An optimist would note that our record of *identifiable* life goes back 3.8 billion years. Given our history of bombardment by asteroids, this is essentially as early as the record could be. Clearly not much more than 100–200 million years was required to produce life. It might have been a lot less than this, because as we discussed the very first life was undoubtedly simpler than what we have currently. If this situation is common then f_l really might be close to 1.

On the other hand (and there is always another hand!), we can note that the early constant bombardment kept Earth's surface hot enough to prevent life from forming. Some people think that Jupiter has helped keep asteroidal impact rates down because of its gravitational influence. This is actually not so clear, but suppose it were true. Without such a protecting influence, could it be that more major impacts would occur frequently enough to prevent life from getting a toehold?

Another consideration is where we are in the galaxy. We are far enough from other stars that it is highly unlikely that a supernova will go off close enough to sterilize our planet. This would not be true if we were closer to the center of our galaxy, where there are more stars in a given volume. In such an environment a planet might be rendered uninhabitable so frequently that life could never arise.

Earth's magnetic field is yet another issue. The Sun produces an abundance of high-energy particles, mainly protons and other nuclei. These are generated all the time, but the highest fluxes are produced by giant solar flares. The particles have an electric charge, so when they interact with our magnetic field they can be deflected. In particular, the particles are funneled to near our magnetic north and south poles, where the electrons they strip from atmospheric molecules produce beautiful aurorae.

But what if our magnetic field were much weaker than it is? Then the charged particles would be able to land over much more of the Earth. The energy of these particles is such that they can easily break molecular bonds, causing mutations or preventing formation of complex organic molecules. This is especially important for planets around low-mass stars, because low-mass stars have much more violent flares than our Sun does.

My feeling about this is that the danger is not really all that great. For example, note that the Earth's magnetic field has fluctuated in strength and direction innumerable times in our history, without obviously leading to mass extinctions. Currently the north magnetic pole of the Earth is in Canada, where there is plenty of life (albeit limited somewhat by the cold). In addition, life in the deep ocean would be completely protected by the thick water layer. Still, we don't know for sure.

What is your best guess for this factor?

The fraction f_i that develop intelligent life

If life develops, what fraction of planets will evolve intelligent life? For us it's one of one, but what is typical?

A pessimist would point out that it took about three billion years on Earth to even get to multicellular life. We are appearing just now, but if a factor of two longer had been required then the Sun would have been too hot for liquid water to be common on Earth. Maybe we just got really lucky.

In support of the luckiness hypothesis is that there are a number of accidents that appear to have been critical to our existence, and possibly to the existence of any intelligent life on Earth. Stephen Jay Gould suggested that without the fortunate survival of *Pikaia*, the forerunner of all vertebrates, though the Ordovician mass extinction, animals might not have had skeletons and thus would have been limited in size and possibly intelligence. We also know that although mammals are easily the most intelligent animals on Earth, it appears probable that without an asteroidal hit and the (probably random) survival of mammals through the K-T extinction, we would still be nocturnal rat-sized things trying to avoid being eaten or squashed by dinosaurs. From this perspective, intelligence is anything but inevitable.

An optimist would counter by noting that intelligence, like strength, speed, claws, or whatever can be evolutionarily advantageous in many circumstances. For primates, our large brains probably developed in part due to our existence in jungles, where excellent vision and spatial judgment was good for moving through trees and detecting camouflaged predators. For dolphins, large brains are essential for echolocation. Mammalian predators or omnivores such as cats, dogs, and pigs also benefit from relatively high intelligence.

In addition, although it has hardly been a straight-line increase, the top-end intelligence on Earth has tended to increase with time. This makes sense if we believe that there will always be at least some evolutionary niches that use intelligence. Still, the huge surge in hominid intelligence over the last couple of million years is pretty well unprecedented.

With all that, what is your best guess for this factor?

The communicative fraction f_c

Of planets with intelligent life, what fraction will develop the capability for interstellar communication? We'll discuss this factor in greater depth later in the course. However, we should point out that intelligence by itself is not enough. The rapid rise of humans has been possible because we have augmented our intelligence with books and other records that can be passed on to succeeding generations and with machines that boost our capabilities enormously. For this we needed opposable thumbs. Is it a lucky break that we have these as well as intelligence? Would aliens also be so lucky?

What is your best guess?

The communicative lifetime L

Our last factor is the duration during which a communicative civilization would communicate. This is affected by a number of things. It could be that aggression is an inevitable trait and that it just as inevitably leads to destruction that, if not total, severely limits the time that civilizations can let their existence be known. It could be that even for stable advanced civilizations they don't talk much; for example, note that cable television does not broadcast signals into space, whereas ordinary TV does. On the other hand, perhaps most advanced species have very extended lifetimes, and that they communicate actively all the while.

With all this in mind, and given that we have had this capability for around 50 years, I could imagine L being anywhere from decades to billions of years. What is your best guess?

Estimates for N

We will now see that with all these factors it is possible to get a final answer that agrees with our preconceptions.

We'll start with an optimist. We'll say $R^* = 10$ stars per year, a reasonable value. We will also say that $f_p = 0.2$, which is slightly higher than current fractions but is plausible given how little we've searched. Then we will assume $n_e = 2$, which is again reasonable given that in the Solar System there might have been at least four such places (Venus, Earth, Mars, and Europa). We will also take $f_l = 1$, basing this on the rapidity with which life appeared on Earth. For f_i we will say $f_i = 0.1$, and this is probably conservative. We will also allow $f_c = 0.1$, and will assume L =10,000 years; surely conservative given that advanced civilizations will have many ways to stave off disaster. Our total number is then $N = 400$. There should be plenty of active, communicative civilizations in our galaxy.

Now the pessimist. A better value is $R^* = 5$ stars per year. We also take the observed value $f_p = 0.05$. We assume $n_e = 1$, which is probably a bit too high given the special circumstances with our Solar System (e.g., no close massive planets, and low eccentricity). We will say $f_l = 0.5$, again probably high because of many things that could sterilize a planet. The fraction of intelligent life is low; say $f_i = 0.01$, because there are multiple happy accidents that were required in our case. The likelihood that intelligence would also be paired with manipulative capability is not great, so we also choose $f_c = 0.01$. For lifetime, we note that even if we avoid destroying ourselves by war, our resource usage will reduce us to a level that is not consistent with interstellar communication. We therefore pick $L =$1,000 years, and think that this is probably too long. Our total number is then $N = 0.0125$. With high likelihood, we are the only such civilization in our galaxy, and indeed in the entire Local Group of galaxies.

What is your best number?

A word about Rare Earth

We close by noting that some authors have recently pushed the idea that our Earth is in such a privileged position that it would be very unlikely for another planet to win the lottery in the same way. Therefore, it is argued, we are almost certainly alone in our galaxy.

I think such people often have an agenda, but what are their points? Some of the supposedly crucial and special aspects of the Earth are:

- We are far enough from the galactic center to avoid supernovae, yet near enough to have plenty of heavy elements that facilitate terrestrial planet formation.
- Our atmosphere is a good thickness. Much less and liquids on the surface would be tough to maintain and day/night variations would be a lot larger. Much more, and surface sunlight would be minimal and there would be much less environmental variation to drive evolution.
- Plate tectonics have been an important stimulus for evolution.
- Our magnetic field protects us from cosmic radiation, allowing greater molecular stability.
- Having Jupiter in just the right place has reduced asteroidal bombardment. [In fact this is not clear; without Jupiter, a planet would probably have formed where the main asteroid belt is now, so we would have far *fewer* hits.]
- Our large moon stabilizes the tilt of our rotational axis, giving us good seasonal stability.

There are other suggestions as well but these are the sane ones. Without knowing of other life it is difficult to say for sure how important any of these factors are. My sense is that most of them are certainly nice for our life as evolved here, but that they are not make or break issues for life in general. What do you think?