Life in the Universe

The Drake Equation

Ah, Spring, when an astrophysicist's mind turns to Life. Life in the Universe, that is.

by Eric Schulman

Editor's note: This is Part 1 of a 4-part series and appeared in *Mercury*, May/June 2000.)

Astrophysicists like to be quantitative rather than qualitative. We like to say a star is 8.5 solar masses instead of saying it's massive. We like to say a galaxy is 30 million light-years away instead of saying it's nearby. And when asked how many civilizations in the Galaxy send messages over interstellar distances, many of us would prefer to calculate the number instead of merely saying "a lot," "a few," or "one."

Frank Drake (SETI Institute) did such a calculation in 1961. He devised an equation with seven terms—three astronomical, two biological, and two sociological—and used it as an organizational tool to help guide discussions at the first conference on Searching for Extraterrestrial Intelligence. At this conference, ten scientists from different fields came to the National Radio Astronomy Observatory in Green Bank, West Virginia, to chat about the possibility of life elsewhere in the Galaxy.

Drake provided the eponymous equation, and the group as a whole came up with estimates for each of the parameters. In the box you see the famous equation, Drake and company's values from 1961 (including a range of values for some parameters), my current best guesses and ranges, and the ratio of their guesses to my guesses. Your first thought might be that Drake and I appear to disagree about everything except the final answer of 50,000 communicating civilizations in the Galaxy. That was certainly *my* first thought. Let's take a closer look at how I came up with my estimates for the astronomical terms in the Drake equation.

I calculated the Galactic star-formation rate averaged over the history of the Galaxy by dividing the number of stars in the Galaxy (about 200 billion) by the age of the Galaxy (about 10 billion years). It is probably correct to within a factor of two or so.

To determine the fraction of stars with planets, I broke the problem up into another equation, $f_P = f_{Z,t} \times f_{disk} \times f_{planets}$, where $f_{Z,t}$ is the fraction of stars in the Galaxy that have at least a third of the heavy elements (Z; everything but hydrogen and helium) as our Sun and are at least five billion years old. Without a certain fraction of heavy elements, planets cannot form. And planets that are too young would not have had time to develop a communicating civilization. If we choose Z = 1/3 solar and t = 5 billion years, $f_{Z,t}$ is 0.1, to within a factor of two or so. f_{disk} is the fraction of stars that formed disks. This is probably fairly high, perhaps 0.5 to within a factor of two or 50. $f_{planets}$ is the fraction of stars with disks that formed planets. This is probably fairly high, perhaps 0.5 to within a factor of two or so.

Multiply them together and you get 0.025 (with a range of 0.003 to 0.2). Multiply this by R_* and we get a formation rate of stars with planets of 0.5 per year. Do the same with Drake's R_* and f_P, and we get a formation rate of stars with planets of 0.35 per year, which is the same as my estimate to within 50%. This is quite good agreement when you take into account all the times I said "to within a factor of two or so" above.

I don't have enough space here to talk in detail about my estimate for n_H, but it involves a number of terms: the fraction of stars of spectral type F, G, K, and M (the lifetime of more massive stars is probably too short for intelligent life to arise); the average number of planets that form at the right distance from the star—oceans of liquid water must exist on the planet for billions of years; the fraction of such planets that are the right size; the fraction of such planets with stable climates (is a large moon required?); the fraction of such planets not continually bombarded by comets (is a Jovian planet required in the outer solar system?); the fraction of planets not destroyed when Jovian planets born in the outer solar system migrate into the inner solar system.

Needless to say, many of these numbers were guesses on my part, but I came up with n_H of 0.04 (or 1 in 25) with a possible

$$N = R_* \times f_P \times n_H \times f_L \times f_I \times f_C \times L$$

	Drake et al. (1961)		Schulman (2000)		Drake / Schulman
R_*	1 star/yr	20 star/yr	10 – 40 star/yr		0.05
f_P	0.35	0.2 – 0.5	0.025	0.003 – 0.2	14
n_H	3	1 – 5	0.04	$10^{-7} - 1$	75
f_L	1		0.01	$10^{-300} - 1$	100
f_I	1		0.5	0.01 – 1	2
f_C	0.15	0.1 – 0.2	0.5	0.01 – 1	0.3
L	$3\text{x}10^5$ yr	$10^3 - 10^8$ yr	10^9 yr	$10^2 - 10^{10}$ yr	0.0003
N	50,000	$20 - 5\text{x}10^7$	50,000	$1 - 10^{11}$	1

R_* Average Galactic star-formation rate
f_P Fraction of stars with planets
n_H Number of habitable planets per star with planets
f_L Fraction of habitable planets on which life arises
f_I Fraction of life-bearing planets with intelligent life
f_C Fraction of intelligent civilizations that communicate across the Galaxy
L Average lifetime of communicating civilizations
N Number of communicating civilizations in the Galaxy

range of 10^{-7} to 1. You probably noticed that my value was a factor of 75 smaller than Drake's value. Did you also notice that Drake's possible range spanned a factor of 5, while mine spanned a factor of 10 million?

The average number of habitable planets per system is not a value that one can just pull out of a hat based on our current knowledge of star and planet formation. I have tried to mitigate this problem by pulling values for twenty parameters out of my hat. But these parameters aren't the same ones that I would have used ten years ago, and they probably won't be the same parameters I'll use ten years from now. As time goes on, we'll learn more and more about star and planet formation. But at the moment n_H is one of the most uncertain parameters in the Drake equation.

In my opinion, the *most* uncertain parameter in the Drake equation is f_L. Next time I'll talk about why.

Is Life Common?

There are compelling reasons to suspect that life will almost always arise on habitable planets. But a compelling observation suggests otherwise.

(**Editor's note:** This is Part 2 of a 4-part series and appeared in *Mercury*, July/August 2000.)

Last time we talked about the astronomical terms in the Drake Equation ("Life in the Universe, …"). Now let's talk about f_L, the fraction of habitable planets on which life arises. Many scientists believe that life will almost always appear on habitable planets. Observations from biology and geophysics bolster this belief, as do some philosophical arguments. Let's start with the philosophy.

Copernicus taught us that we are not in a special place in the Universe—Earth is not at the center of the Solar System. Later we discovered that the Sun is not at the center of the Galaxy. And that our Galaxy is just one of many in the Universe. So why should Earth be the only planet in the Galaxy or the Universe to have life?

Another philosophical argument—perhaps less rigorous than the first—is that it would be awfully lonely to be the only life in the Universe. Surely we have kindred spirits somewhere. They may be far away. They may be broadcasting on frequencies we haven't searched yet. But they're out there.

From geophysics we learn two things—life on Earth began very early, and it probably couldn't have begun much earlier.

Fossils from 3.5 billion years ago demonstrate that life must have arisen at least that long ago. The Sun formed about 4.6 billion years ago and Earth formed about 4.5 billion years ago. Chemical evidence from 3.7 billion-year-old rocks (high Carbon-12 to Carbon-13 ratios, in case you're interested) suggests that life was around way back then.

Why couldn't it have arisen much earlier? We know the answer thanks to the *Apollo* program.

The astronauts who landed on the Moon became famous… and also brought back 382.5 kilograms of lunar rocks. From radioactive dating of these rocks and counts of the number of craters in different areas of the Moon, we have a good idea of the meteorite impact rate over the past 4.5 billion years.

The Drake Equation: $N = R_* \times f_P \times n_H \times f_L \times f_I \times f_C \times L$

	ESTIMATE	RANGE	DESCRIPTION
R_*	20 */yr	10–40 */yr	Average Galactic star formation rate
f_P	0.025	0.003–0.2	Fraction of stars with planets
n_H	0.04	10^{-7}–1	Number of habitable planets per star with planets
f_L	0.01	10^{-300}–1	Fraction of habitable planets on which live arises
f_I	0.5	0.01–1	Fraction of life-bearing planets with intelligent life
f_C	0.5	0.01–1	Fraction of intelligent civilizations that communicate
L	10^9 yr	10^2–10^{10} yr	Average lifetime of communicating civilizations
N	50,000	1–10^{11}	Number of communicating civilizations in the Galaxy

The impact rate four billion years ago was 100 times the current impact rate. Every million years or so an asteroid with a diameter of about 16 km would hit Earth. Such an asteroid impact was enough to kill the dinosaurs 65 million years ago. If that wasn't bad enough, every ten million years or so an asteroid would hit with ten times the energy of the dinosaur killer. So life would have had a difficult time getting started under such conditions.

We probably owe our existence in part to Jupiter, which has been sweeping the Solar System of Earth-crossing asteroids for 4.5 billion years. Without Jupiter, the impact rate would not have decreased nearly so much with time. It might be 10,000 times the current impact rate, which would result in dinosaur-killing asteroids every 10,000 years.

If life arose as early as it possibly could have, it follows that it didn't take long to get started. And if it didn't take long to get started, it must have been very probable, and therefore, a common occurrence in the Galaxy. According to the geophysical argument, at least. And there is some biological evidence that supports this theory.

Biology teaches us that the building blocks of life are simple. Life is mostly composed of carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) atoms arranged in particular ways. The nucleotides in our DNA are composed of about a dozen C, H, O, and N atoms (the DNA chains that wrap the nucleotides in double-helices also have some phosphorus). The amino acids that make up our proteins are composed of between 10 and 27 C, H, O, and N atoms (two amino acids also have an atom of sulfur). Small organic molecules like nucleotides and amino acids can be produced by relatively simple chemical reactions.

Since the 1950s scientists have been trying to replicate conditions on the early Earth to learn more about the origin of life. In 1953, Stanley Miller and Harold Urey found that adding energy to ammonia, methane, and water would produce hydrogen gas and glycine, the simplest amino acid. But what if there wasn't much ammonia and methane on the early Earth? Other researchers found that adding energy to hydrogen cyanide and water would also produce glycine. Further research revealed that a wide variety of atmospheric compositions could result in the creation of amino acids.

Even if we don't know exactly what conditions were like on the early Earth, it seems likely that organic molecules were abundant. Radio astronomers have claimed to find glycine in interstellar clouds. Other researchers have simulated comets smashing into the early atmosphere. Shock heating of the comets—composed of water, carbon dioxide, methane, nitrogen, and hydrogen sulfide—would have produced a host of simple organic molecules.

We believe that the building blocks of life were probably common on the early Earth. We know that life on Earth arose almost as soon as it possibly could. We have philosophical reasons to believe that f_L is large. What's the observation that goes against this reasoning?

The observation is that there's no good evidence that extraterrestrials have ever visited Earth. Why does this suggest that f_L is very small? I have an elegant proof, but unfortunately it's too long to fit in the margin. You'll have to wait.

Is Life Uncommon?

We don't know how life arose on Earth, but we do know it could have happened through an improbable accident.

(**Editor's note:** This is Part 3 of a 4-part series and appeared in *Mercury,* September/October 2000.)

Last time we discussed reasons for believing that life will almost always appear on habitable planets (i.e., that f_L in the Drake Equation is close to 1). Now let's look at some reasons why f_L could be very close to zero.

There is evidence for life on Earth 3.7 billion years ago, soon after the last of the sterilizing asteroids hit the planet. And we've found fossils of relatively advanced bacteria from 3.5 billion years ago. This suggests that life arose very rapidly, and some people conclude that it therefore must have been very probable.

But we don't know whether the early origin of life on Earth was because life was very probable or because we were very lucky. Or perhaps the probability of life arising early was much greater than the probability of life arising later. Comets smashing into Earth's early atmosphere would have rained down a wide variety of organic molecules (July/Aug 2000, p. 10). And comet and asteroid impacts would have released a lot of energy to speed up chemical reactions in the early oceans. In general, life prefers a stable environment, but maybe it needed a kick in the pants to get started.

The big problem in estimating f_L is that we are ignorant about how life came to be. We think that the building blocks of life—amino acids, sugars, nucleotides, etc.—were common four billion years ago. What we don't know is how they managed to come together in such a way that they could reproduce themselves.

Reproduction for terrestrial life is an intertwined dance between proteins and nucleic acids. Our DNA specifies how to put amino acids together to form the proteins that do the bulk of the work in our cells. Without proteins, life as we know it cannot exist. But without a genetic code, amino acids don't spontaneously form the proteins required to produce an entity capable of reproduction. I suppose they could, but it would be so improbable that most researchers assume that life couldn't have arisen that way.

But what if they're wrong? Many current cosmological theories suggest that we live in an infinite universe. In an infinite universe, anything that could possibly happen will happen. In fact, it will happen an infinite number of times.

Let's assume that f_L is small, say 10^{-22}. In that case, you wouldn't expect a particular planet to develop life. But if you looked at 100 billion planets—a galaxy—you'd expect somewhat greater chances, on the order of 10^{-11}. And if you looked at 100 billion galaxies, you'd expect that one of them would contain one planet that developed life. There are about 100 billion galaxies within our observable Universe.

If f_L is about 10^{-22}, not only would we be the only life in the Galaxy, we'd be the only life in the currently observable universe. But 10^{-22} is rather high if we're looking at the probability of amino acids, nucleic acids, and sugars banging together until they form a reproducing entity through random chance. 10^{-300} or 10^{-3000} might be closer to the mark. In an infinite universe, it doesn't matter. We know that f_L is greater than zero because we're here. And in an infinite universe, an f_L greater than zero means an infinite number of planets with life.

On the other hand, many biologists firmly believe that the leap between simple organic molecules and reproducing entities is not so large. There may be unknown chemical reactions that could have built up complexity over millions of years until simple life appeared. This life could then have evolved into our distant ancestors, the bacteria of 3.7 billion years ago.

So f_L could actually be close to 1. Let's be less optimistic and say f_L=0.01. On how many planets would this life have developed intelligence? We don't know, but I think that once multicellular life appears, intelligence will almost certainly follow within a billion years or so. Some researchers believe that the big stumbling block is not life itself, but multicellular life, which took another three billion years. I have my doubts that multicellularism is such a big hurdle, so I'll set f_I=0.5. How many of these intelligences will develop the technology needed to communicate across interstellar distances? I don't see water dwellers like octopi building radio telescopes, but I may be underestimating what they could do with another few hundred million years of evolution. Let's say f_C=0.5.

Give our average civilization a lifetime of a billion years, and what do you get? About 50,000 civilizations in the Galaxy (if my assumptions in the past few columns are correct). The nearest would be about 1000 lightyears away, assuming they stayed in their own solar system. But if even a small fraction of intelligent civilizations decided to explore the Galaxy, someone should have visited Earth billions of years ago, when the most advanced creatures on Earth were single-celled bacteria.

So where is everyone? Tune in next time for that.

Where Are They?

There are two likely reasons why we haven't heard from ET.

> "There are two possibilities—they are unable to respond, or they are unwilling to respond."
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> —Captain Spock "The Wrath of Khan"

(**Editor's note**: This is the last part of a 4-part series and appeared in *Mercury*, November/December 2000.)

In about 400 B.C., the Greek philosopher and mathematician Metrodorus of Khíos wrote, "It goes against nature in a large field to grow only one shaft of wheat, and in an infinite universe to have only one living world." The analogy is both flawed and profound. It's flawed because "large" and "infinite" are very different. It's profound because it neatly addresses the possibilities of where the extraterrestrials might be.

On the one hand, the Galaxy could be a field and technological civilizations shafts of wheat. In this case, the Galaxy is full of intelligent life. But we have searched for extraterrestrials and haven't found any credible evidence for them. No repeated sets of prime numbers in our radio telescope data. No devices of alien manufacture left at purported UFO landing sites. No evidence that alien visitors disrupted the evolution of life on Earth during the past few billion years.

We could instead assume that the universe is an infinitely large field and that the origin of life is highly improbable, as I discussed in my last column (see Part 3,"Is Life Uncommon?"). Even if we are the only life within 15 billion light-years, this field would be full because an infinite universe where life is possible contains an infinite number of inhabited worlds.

There's a third possibility. The Galaxy could be a field, and we could be the first shaft of wheat, destined to fill it with our descendants.

Why should *we* be the first civilization? Perhaps the origin of life is very unlikely. The development of complex life could be improbable. The evolution of intelligence might be highly unlikely. A chilling possibility is that the lifetime of technological civilizations is very short.

What could cause an entire technological civilization to die? Huge amounts of radioactive dust thrown into the atmosphere during a global thermonuclear war would lead to worldwide nuclear winter. Industrialization could always lead to irreversible global warming. Globalization—possibly aided by biotechnology—might inevitably lead to the spread of incredibly virulent diseases. Or perhaps civilizations fall victim to a technology we haven't discovered yet.

We do know that beings who remain on their home planet will eventually be destroyed. Large asteroid or comet impacts will cause global disasters every 100 million years or so. Nearby supernovae or gamma-ray bursts would devastate the upper atmosphere of inhabited planets. And after billions of years, main-sequence stars will evolve into red giants.

In order to survive, technological civilizations must develop interstellar travel. Some scientists are pessimistic about interstellar travel, but few would argue that one-way interstellar journeys are impossible (see "Prospects for an Interstellar Mission," July/Aug., p. 26). Interstellar travel is expensive, but a solar system-spanning civilization would be rich in resources. A civilization with 0.1c starships could colonize the entire Galaxy in about 100 million years.

Is 100 million years a long time? No. The Galaxy is about 10 billion years old. Stars of one-third solar metallicity or greater—probably required for terrestrial planet formation—were around billions of years before the Sun formed. If even one technological civilization had started colonizing the Galaxy 2 billion years ago, it would have reached Earth long before any life more complex than one-celled organisms had arisen here. So where are the extraterrestrials?

One possibility is that technological civilizations always choose not to colonize the Galaxy. They could all overcome their genetic heritage and practice zero population growth. Perhaps they discover immortality and none are ever willing to risk dying in some far-flung star system. But it only takes *one* exception to produce a Galactic Empire.

Another possibility is that all extraterrestrials obey a version of *Star Trek's* Prime Directive. Maybe they arrived in the solar system billions of years ago and have observed Earth ever since, waiting for us to become interesting. They may have extremely long lifetimes. They may be artificially intelligent robots. They may be waiting to initiate contact until we are advanced enough not to be completely overwhelmed by a civilization billions of years older than ourselves.

But perhaps the Prime Directive isn't sacrosanct. There are those who believe that aliens built the pyramids thousands of years ago. Some believe that aliens have been piloting flying saucers in our skies, mutilating cattle, creating crop circles, and abducting people for medical experiments. There is no credible evidence for these claims. Unless extraterrestrials introduce themselves to the world on *CNN*, I would argue that we have not yet been "contacted." Even so, it's *possible* that they are reading this right now. (If so, hi folks!)

In the end, I see two likely possibilities: They are unable to contact us because they don't exist, or they exist but are unwilling to contact us before we have developed the capability to handle it.

If the origin of life is highly improbable, Earth could have the only living things within 15 billion light-years. For me, this is the most convincing reason for us to be alone.

Because if life does arise, I'm optimistic that many planets will develop intelligence and that many intelligent species will avoid destruction by spreading throughout the Galaxy. They must protect nursery worlds like Earth for billions of years or else our ancestors would have been out-evolved long ago by colonists or even by stray microbes from a visiting spaceship.

The answer will be revealed in time, maybe even tomorrow. Stay tuned to *CNN*.

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