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Exoplanet Discoveries and the Fermi Paradox

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Abstract

Frank Drake examined the probability of extraterrestrial intelligence by developing his famous equation in the 1960s, which stated that the number of intelligence species in the galaxy is the product of 7 factors, from the rate of star formation through the probabilities of planets, habitability, life arising, communicating civilizations developing, and their expected lifetimes. Drake concluded that the number of intelligent species in the galaxy was on the order of one thousand to 100 million, with the nearest being perhaps 80-800 light years away. With Drake's numbers, it appeared that we should hear from the extraterrestrials rather soon; but after half a century of watching and listening, we have no evidence of them. The recent astronomical evidence for thousands of planets in other solar systems enhances the Fermi paradox between the increasing number of potentially habitable planets in the Galaxy and the lack of any evidence of extraterrestrial civilizations. This prompts a new look at several potential answers to the paradox, covering some aspects not often addressed by space scientists and SETI researchers. These answers involve space science, life science and social science. The astronomical probability of habitable planets is reviewed, emphasizing the potential rarity of Earth-like planets, and the orbital wandering of "hot Jupiters." The probability of the evolution of complex life is reviewed from a biological standpoint, from unicellular organisms to more complex life forms. The likelihood of the survival of intelligent species is reviewed from a physical anthropology standpoint, including past instances of near-extinction of the human species. The potential causes of the decline of societies are discussed, along with the expected lifetime of civilizations based on Earth experience. Finally, all these factors are combined into a new look at the Drake Equation to develop a revised estimate of the number of intelligent species in the galaxy.

I. INTRODUCTION

In 1959, Cornell physicists Giuseppi Cocconi and Philip Morrison published an article in *Nature* in which they pointed out the potential for using microwave radio to communicate between the stars. In 1960, Frank Drake at the National Radio Astronomy Observatory in Green Bank, West Virginia, first used the 85-foot radio telescope to listen for extraterrestrial signals from the nearby Sun-like stars Tau Ceti and Epsilon Eridani at the 21-cm hydrogen line. Although it had negative results, it pioneered a new branch of science, the Search for Extraterrestrial Intelligence (SETI). Drake called it Project Ozma[1].

As a part of this effort, Frank Drake introduced his famous equation predicting the number of communicating civilizations in the galaxy. The Drake Equation in its original form is:

$$N = R^{*} \cdot fp \cdot ne \cdot fl \cdot fi \cdot fc \cdot L$$

where:

N = the number of civilizations in our galaxy with which radio-communication might be possible,

R* = the average rate of star formation in our galaxy,

fp = the fraction of those stars that have planets,

ne = the average number of planets that can potentially support life per star that has planets,

fl = the fraction of planets that could support life that actually develop life at some point,

fi = the fraction of planets with life that actually go on to develop intelligent life (civilizations),

fc = the fraction of civilizations that develop a technological civilization, and

L = the length of time for which such civilizations release detectable signals into space.

Table 1 summarizes these parameters and the initial estimates of their values in the 1960's. Using their guesses, they expected the number of civilizations in the galaxy to be as few as 20 or as high as 50 million. The nearest one could range from 80 to 8000 light years away. Drake said that considering the uncertainties, he expected N ~ L, giving N of 1000 to 100,000,000 societies, and the nearest could be as close as 40 light years away.

Table 1. Initial Estimates of the Number of Civilizations in the Galaxy

Drake Parameter	Original Estimate
Rate of star formation in the Galaxy	1/year
Fraction of stars with planets	0.2-0.5
Number of habitable planets per star	1-5
Fraction of those with life	1
Fraction of those with intelligent life	1
Fraction with technological civilization	0.1-0.2
Lifetime of technological civilizations	10^3-10^8 years
Number of civilizations in the Galaxy	20 to $5x10^7$

Encouraged by these estimates, the Soviet Union performed some all-sky searches[2] during the 1960's, and NASA Ames and JPL established SETI programs in the 1970's[3]. In the late 1980's, Ames examined 1,000 Sun-like stars in a Targeted Search, capable of detecting weak or sporadic signals, and JPL systematically swept all directions in a Sky Survey; but the program was terminated by Congress in 1992. More recently, the SETI Institute and UC Berkeley formed a joint project to build a SETI-dedicated array of telescopes that will equal a 100-meter radio telescope, the Allen Telescope Array. SRI International replaced Berkeley, and under funding from Paul Allen of Microsoft, the initial 42 dishes of the planned 350 have been completed.

SETI has examined about 1000 stars, without detecting any artificial signals, but a related search technique, looking for extraterrestrial planets, or exoplanets, has borne fruit[4]. There are 3 main methods for exoplanet detection. Most have been detected by the transit method, which detects the slight dimming of the star's light as a planet moves in front of it. This method detects only planets whose orbital plane is in our line of sight, but the NASA Kepler space telescope mission has discovered over 1100 such exoplanets.

Next is the radial velocity method, in which a star's motion in the direction toward and away from Earth can reveal the periods, distances, and sizes of planets. This method has detected more than 500 exoplanets. The third method is even more serendipitous, depending on Einstein's general theory of relativity and its prediction that light from a distant star can be gravitationally lensed by the mass of a foreground star and planet. Only 26 planets have been discovered by this microlensing method, and follow-up observations are very difficult. Including all detection methods, such as astrometry and direct imaging, the number of confirmed and candidate exoplanets now totals more than 4200[5].

The exoplanet search results seem to indicate that on the average, there is about one planet per star in the Galaxy, and we would expect that many of these are apparently in the habitable zone of their parent stars. The sheer number of exoplanets is surprising; it appears that almost every star in our galaxy has planets and there may be on the average one habitable planet per star. In 1950 Enrico Fermi was lunching with colleagues at Los Alamos, and the discussion led to extraterrestrial intelligence and life on other planets. Fermi pondered for a moment and then suddenly said "Where *is* everybody?"[6] This has come to be known as the Fermi Paradox. With so many planets, and the apparent technical possibilities of interstellar travel described by Mole[7] and Woodcock,[8] it is puzzling that we see no extraterrestrials on Earth.

Michael Hart reviewed this paradox[9], classified the potential explanations as physical (astronomical, biological or technical problems), sociological (interest, motivation, political problems), and temporal (we are the first). He concluded that the likely answer is that extraterrestrials do not exist. Hart was writing in 1975, before the discoveries of exoplanets, but this only intensifies the paradox. We will review the current observational and theoretical evidence for the parameters in the Drake Equation, and try to determine a rational explanation for the lack of evidence of extraterrestrials. We will review each of the potential parameters for an explanation, from stars and planets to life, intelligence, and civilization.

II. GALAXIES AND THE MILKY WAY

The Sun is in the Milky Way galaxy, a barred spiral about 100,000 light years across the spiral arms, containing about 200 billion solar masses. The Milky Way is brighter and has higher metallicity (presence of elements heavier than hydrogen and helium) than 98% of all galaxies[10]. The presence of heavier elements allows stellar nebulas to condense and form solar systems with planets, along with asteroids, comets, and meteors, and is necessary for the development of life. The Milky Way's oldest stars are about 13 billion years old, almost as old as the universe. The Milky Way includes dark matter and other mass beyond the spiral arms but let us leave out stars in globular clusters in the halo of the galaxy, and also stars in the galaxy's companions the Magellanic Clouds, and just consider the galaxy population across the diameter of the spiral arms. The central bulge has about 40 billion stars, and the disk has about 120 billion stars.

Just as a star has a habitable zone over which a planet can have liquid water, the galaxy also has a habitable zone, as shown in Figure 1. This idea was first suggested by Marochnik and Mukhin[11]. The galactic habitable zone is an annulus beginning outside the core and extending far out along the spiral arms. In this zone stars are safe from the black hole at the galaxy center that consumes stars and gas and creates dangerous radiation and energetic particles, and from X-ray stars that make that area unsuitable for life. The outer edge of the habitable zone is far out on the spiral arms, where stars are poor in "metals" (elements heavier than hydrogen and helium), and do not have the building blocks to form rocky, habitable planets.

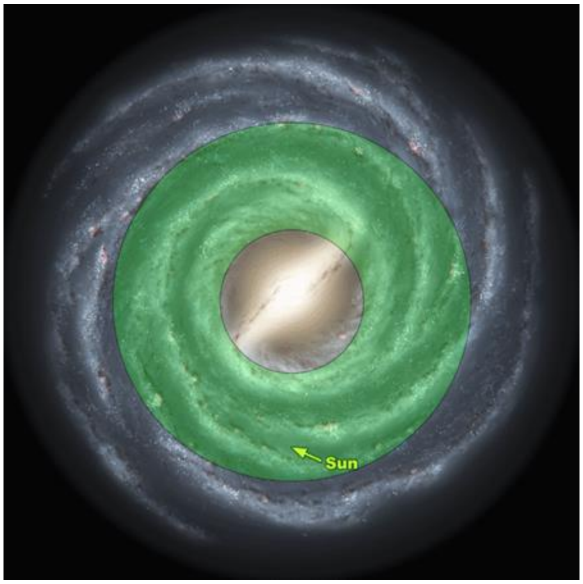

Figure 1. A Plan View of the Milky Way Galaxy and its Habitable Zone (From Marochnik)

The habitable zone of our galaxy might therefore occupy the area between perhaps 13,000 light years and 33,000 light years from the center, with the Sun at a comfortable 27,000 light years from the center. However, some authors think it is much tighter[12], perhaps extending just from 23,000 to 29,000 light years. These two values mean that 13% to 37% of the 120 billion stars in the galactic disk are in the galactic habitable zone—or 15 to 45 billion stars.

III. STARS AND THE SUN

The earliest stars condensed from nebulas that were entirely hydrogen with a little helium, and their nebulas could not form rocky planets. When that first generation of massive stars became supernovas, they created the heavier elements by nuclear synthesis, and spewed them out when they exploded. New stars forming from those clouds had rocky minerals and could form planetary systems. A certain amount of metallicity is required for terrestrial planets, but too much can result in the "hot Jupiter" effect, when the giant planets form quickly, grow very large, and then migrate inward from their normal orbits, wiping out the terrestrial planets[13]. This is shown in Figure 2, with giant planet frequency vs. metallicity in the upper chart, and planet frequency vs. stellar mass in the lower chart[14]. Stars with higher metallicity are more likely to have "hot Jupiters" (close-in giant planets), and stars with higher mass are more likely to have giant planets with tilted orbits, which interfere with the normal development of terrestrial planets and life. Stars near the galactic center have the highest metallicity, and stars far out in the spiral arms have the least.

It is not clear what minimum metallicity is required to create a planetary system, but as the metallicity increases, a higher fraction of stars have close-in giant planets, and this is bad news for the terrestrial planets. For stars with less than ¼ the Sun's metallicity, no hot Jupiters were detected; at ½ the Sun's metallicity, 2% had hot Jupiters; at the Sun's value, 4% do; and at twice the solar value, 9% do[15]. This is another reason the galactic center is not in the habitable zone—too many metals, and too many hot Jupiters. We estimate that about 10-50% of stars may have the appropriate metallicity and an appropriately located Jovian planet[16].

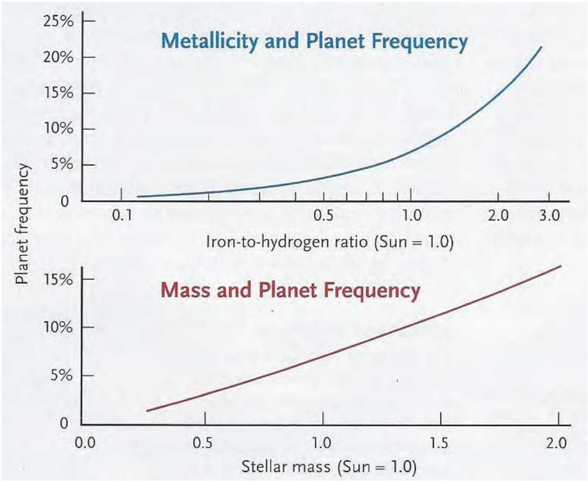

Figure 2. Planet Frequency vs. Stellar Metallicity and Mass (Johnson, *Sky & Telescope*)

Apparently Earth barely escaped being destroyed by Jupiter in the early solar system[17]. After Jupiter formed, it began migrating inward. The formation of Saturn halted Jupiter's migration by orbital resonance, and brought it back to its current location. But during its journey, Jupiter took mass from the forming Mars and prevented the formation of another terrestrial planet where the asteroid belt is now.

Stars can be characterized quite well by their temperature and luminosity, or color and brightness. The Hertzsprung-Russell diagram, shown in Figure 3, is the standard way of doing this. Most stars fall on the main sequence, which runs from white hot and high luminosity to cool red and low luminosity, from upper left to lower right in the figure. As stars get older, they burn their fuel faster, and they migrate to the upper left on the main sequence. At the end of their lives, they migrate to the giant or supergiant phase, then to white dwarfs, neutron stars, or black holes.

Our sun is a G2 star on the main sequence, brighter and more massive than about 90% of all stars. Astronomers classify stars according to their intrinsic brightness and temperature into classes O, B, A, F, G, K, and M, from brightest to coolest. These classes are subdivided into G0-G9, for example, so the Sun is close to class F. The stars you see in the night sky are not a representative sample, because the brighter ones can be seen over longer distances.

A star's location on the main sequence is determined by its mass, M, because its luminosity L is proportional to a power of the mass. For stars similar to the Sun, the luminosity is proportional to M^4. The lifetime of a star is proportional to its available mass divided by its rate of energy production, or luminosity, so the lifetime is proportional to M/L, and to M^{-3}. The brightest stars are the most massive, burn their hydrogen fuel faster, and have shorter lifetimes. Table 2 summarizes stellar classes and their corresponding masses, luminosities, lifetimes, and other parameters.

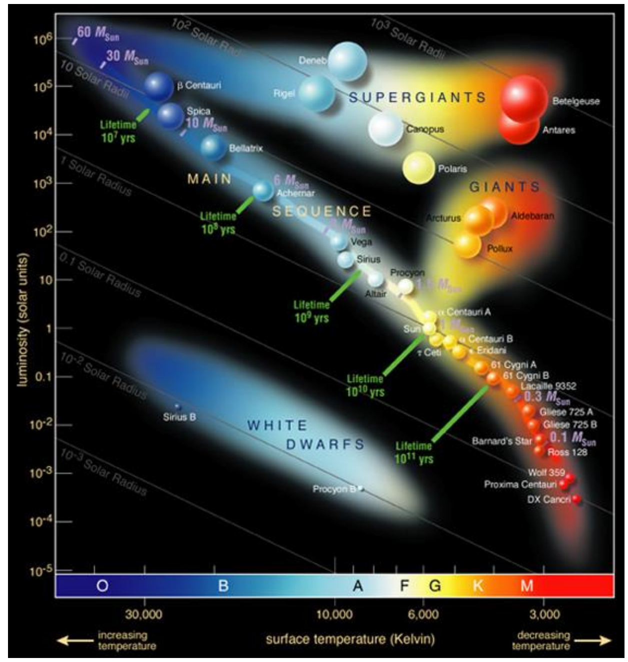

Figure 3. The Hertzsprung-Russell Diagram of Star Color and Brightness (Wikipedia, "Rigel")

Table 2. Stellar Parameters vs. Spectral Class

Star Example	Mass, Sun = 1	Brightness, Sun = 1	Lifetime*, Myr	Habitable Life, Myr	Habitable Zone, AU	Class	% of all stars†
O6	40	300,000	5	2	550	O	0.0001
B5	6	800	30	15	28	B	0.1
A5	2	20	370	170	3.7	A	0.7
F5	1.3	2.5	3,000	1,500	1.7-2.1	F	2
G2 (Sun)	1	1	10,000	4,500	0.95-1.15	G	3.5
K5	0.7	0.16	44,000	20,000	0.4	K	8
M5	0.2	0.008	250,000	100,000	0.1	M	80

*Lifetime on the Main Sequence, excluding the red giant and white dwarf stages
†Excludes giants and white dwarfs, 0.4% and 5%, respectively

The Sun will have a lifetime on the main sequence of about 10 billion, or 10^{10} years, which is apparently sufficient for life, intelligence, and technical civilizations to arise. F5 stars have lifetimes of only about 3 billion years, which may not be enough time for technical civilizations. For A, B, and O class stars, lifetimes are extremely short; none of the planets around these brightest stars in the sky can have developed intelligent life.

The habitable zone about a star is the annulus of planetary distances over which liquid water can exist on the surface. As the star ages and its luminosity increases, the habitable zone moves outward. The continuously habitable zone is that narrower zone that stays in the habitable zone as the star gets brighter. Brighter stars have wider habitable zones that are farther out, but dimmer stars have zones that are progressively narrower, and go to zero width at about spectral type K5. This is shown in Figure 4, from Pierce[18]. Stars brighter than F7 have broader continuously habitable zones, but their lifetimes are probably too short for intelligent life to develop.

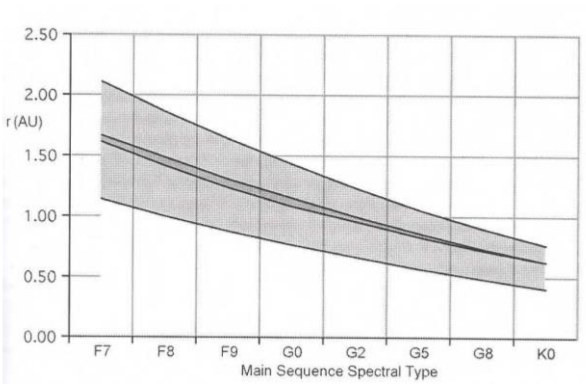

Figure 4. Hart's Continuously Habitable Zone for F7-K0 Stars

There are far more class M stars than others, but their continuously habitable zones may be zero width, because the location changes by more than its width as the star heats up. Even if there is a CHZ, it is so close to the star that planets would have tidally locked rotations. This situation is sketched in Figure 5, from Impey[19]. The tidal lock radius intersects the inner edge of the habitable zone at about spectral class K5.

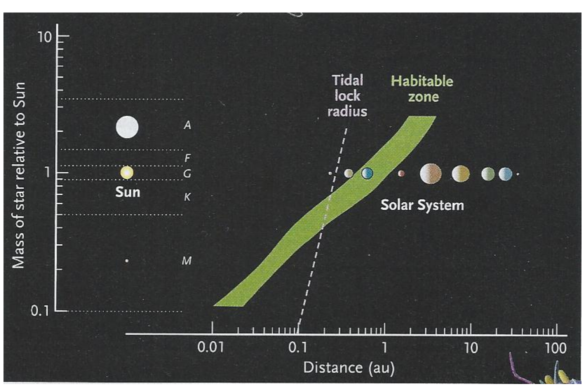

Figure 5. Habitable Zone and Tidal Lock Radius vs. Star Class (From Impey)

The sunward side of a tidally locked planet would be hot, and the night side would be frigid; the night atmosphere might even freeze, and life might not survive. In addition, M stars often produce flares with radiation that would sterilize close-in planets.

The Sun's habitable zone has been approximated by different authors; Figure 6 shows the most recent results. Kasting[20] (1993) placed the current habitable zone of 0.95-1.37 AU (left), and the 4.6-billion- year continuously habitable zone (CHZ) of 0.95 to 1.15 AU (right). This is broader than the 1979 Hart limits[21] of 0.95-1.01, because it takes into account the carbonate-silicate cycle that provides a negative feedback on the amount of carbon dioxide in the atmosphere, keeping it within bounds and moderating the temperature, as we shall see later.

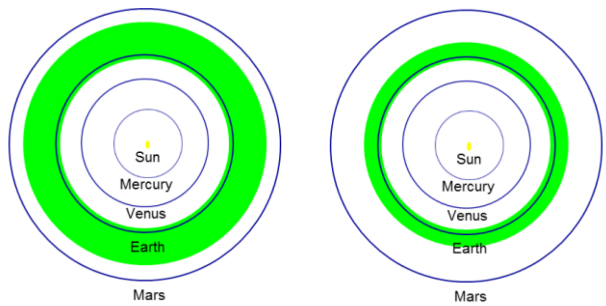

Figure 6. Left: The Sun's Habitable Zone; Right: The Continuously Habitable Zone

The Sun is about 30% brighter now than it was at the beginning of its main sequence life, and 800 million years from now another 8% increase will make it too hot for liquid water to exist on Earth. The Sun's habitable life is thus only about half of its main sequence lifetime.

In summary, the minimum range of suitable stars is class F7 to K0, which is 4.1%, and a generous maximum range might be F5 to M0, which is still just 12.5% of all main sequence stars.

IV. PLANETS AND THE EARTH

The Kepler space telescope, launched in 2009, has provided some evidence of the number of stars that have planets. Kepler is a 0.95-m Schmidt camera that views a 12°-wide field over the constellations Cygnus and Lyra. It observes 145,000 main-sequence stars down to 12th magnitude continuously, looking for brightness changes from transiting planets[22]. As of June 2014, it had confirmed 977 planets in 400 systems, with another 3277 unconfirmed.

Since Kepler can detect an Earth-sized planet at 1 AU from a Sun-like star at orbital inclinations of up to 0.25°, it can detect only 0.5% of all solar systems. Since it has discovered planets about 400 stars out of 145,000 observed, we can estimate that about 55% of all main sequence stars have planetary systems.

The planets in any solar system condense from the initial nebula, and they seem to form at distances that meet the Titius-Bode law of planetary orbit spacing, which for the terrestrial planets amounts to a ratio of about 1.63 in orbital radius. Since the Kasting CHZ has a span of 1.21 in radius, one would expect that about 74% of the solar systems would have a planet in the CHZ, but there could never more than one, unless they were satellites of a giant planet. For the Hart CHZ with a span of 1.06, about 65% of solar systems would have a planet in the CHZ.

A planet in the continuously habitable zone must have liquid water during its entire lifetime for the development and continued survival of life. It would need enough water for oceans, and enough land to provide shallow water and room for animals; it is hard to imagine intelligent ocean life developing tool use, fire, and civilization. With the presence of plate tectonics, there is a negative feedback mechanism[23] that maintains a reasonable temperature despite solar warming. Figure 7 shows the Earth temperature and CO_2 variations since the Cambrian. The temperature does cycle between ice ages and warm periods with no polar caps, but the overall temperature range stays within a range of 12°C to 22°C.

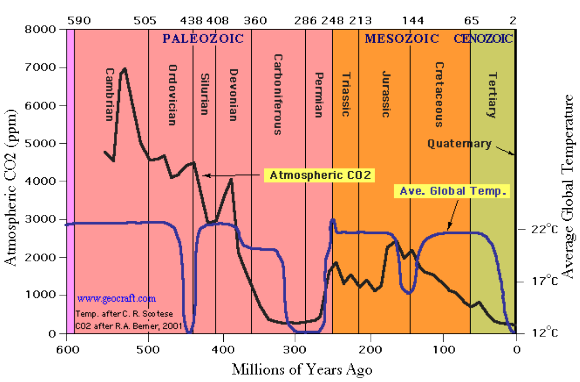

Figure 7. Earth Climate since the Cambrian
(From Scotese, Geocraft.com)

There are other requirements for planets to host life, including enough mass to retain an atmosphere, but not enough to create a gas giant; a molten interior with a magnetic field and plate tectonics; and a large moon to drive and perhaps to create plate tectonics and to stabilize the inclination of the axis[24]. The requirements for plate tectonics, a magnetic field, and a large moon were first pointed out by Pearson[25], and later independently by Ward and Brownlee[26]. Figure 7 shows just how comparatively large Earth's Moon is compared with the other satellites in the Solar System.

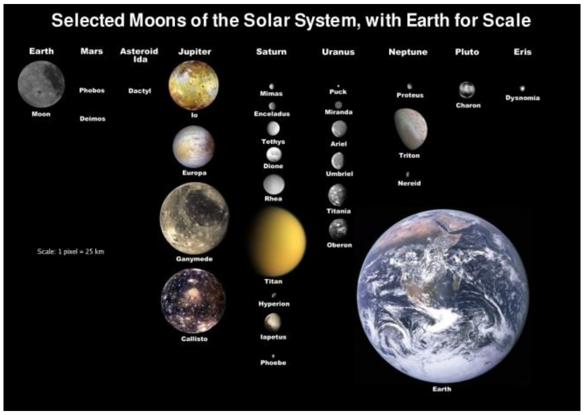

Figure 8. The Earth-Moon Double Planet (NASA)

The Earth's moon is so large that the pair are really a "double planet," and that may be part of the reason for the rarity of habitable planets. This was apparently first pointed out by Isaac Asimov[27] in 1975, when he noted that the Moon, unique among the planetary satellites, is attracted by the Sun more than twice as much as by the Earth, and its orbit is always concave toward the Sun, making it more a planet than a satellite.

The Moon was apparently created by the collision of a Mars-size proto-planet with the proto-Earth[28]. It was formed much closer to Earth than it is now, and could have created the Earth's plate tectonics, which are unique in the solar system, and may be necessary for life. Plate tectonics recycles minerals, stabilizes the climate, and provides radiation protection through the magnetic field. But the rarity of such a collision with the formation of a double planet argues for the uniqueness of Earth and our civilization. A generous estimate of the portion of such double planets would be perhaps 10%, and it might be 1% or even less. Earth-Moon is the only double planet example known.

V. LIFE, INTELLIGENCE, AND CIVILIZATION

The Sun and Earth were formed about 4.6 billion years ago, and by 3.8 billion years ago the asteroidal bombardment had ended and the Earth's surface was cool enough for liquid water; life began rather quickly after that, as indicated by sedimentary rocks of that age. But it was very simple life, single-cell bacteria, and it stayed that way for a billion years. Since it took so long to evolve into multi-cellular life, it may be that if there is other life on planets in our galaxy, it may be simply bacteria, with no higher life forms. The second step was the evolution of photosynthesis in these single-cell bacteria 3.4 billion years ago; third, complex eukaryotes with cell nuclei emerged about 2.5 billion years ago; fourth, sexual reproduction arose about 1.2 billion years ago; fifth, the Cambrian explosion of large multicellular organisms 600 million years ago; and finally, intelligent hominids arrived recently.

These six steps of life were described by Brandon Carter[29] as six unlikely events that were necessary for the emergence of intelligent life, somewhat evenly spaced over the Sun's stable lifetime, which is expected to end about 800 million years from now when it will be too hot to support intelligent life[30]. But these six improbable steps took 4.5 billion years of the 5.5-billion-year habitability window of the Sun, which makes it seem unlikely that intelligent life is common in the Galaxy.

The probability of intelligent life is particularly controversial, especially among life scientists. The famous biologist Ernst Mayr[31] said that since only one out of the billions of species that have existed on Earth has become intelligent, the probability fi must be very low. Simple, unicellular life developed in less than a billion years, but complex multicellular life did not arise until the Cambrian explosion, which occurred 3 billion years later. Gribbin[32] suggests that special conditions were necessary to spur evolution, and suggests that a comet collision with Venus 700 million years ago reversed its rotation and resurfaced the planet, while seeding Earth's atmosphere with reflective ice crystals, causing a Snowball Earth that led to the Cambrian explosion.

Research into extinction events has raised the possibility that life on Earth is relatively fragile. Examples of this fragility are the 5 major episodes of mass extinctions on Earth in the last half-billion years. The first was the Ordovician/Silurian mass extinction of 450 Myr ago; all life was in the oceans, and most of it perished. The next was in the late Devonian, 375 Myr ago, when ¾ of all species died out. The worst was the Permian mass extinction, 251 Myr ago, in which 96% of all species died. Next was the Triassic/Jurassic mass extinction of 205 Myr ago, and last was the Cretaceous/Tertiary mass extinction 65 Myr ago, which is well known for ending the reign of the dinosaurs. An asteroid that size hitting now would probably wipe out humanity.

There have also been two major instances of near human extinction, 1.2 million years ago and 70,000 years ago[33]. In the first event, the human population declined to about 18,500 individuals. In the latter event, in the late Pleistocene epoch, the human population declined to as few as 10,000 individuals, perilously close to extinction. Both were probably caused by intense volcanic activity.

The final factor in the Drake Equation is L, the lifetime of a civilization. We don't know how long our civilization will survive and be able to communicate with ET, but we do have some data from past civilizations on Earth. Michael Shermer[34] surveyed 60 historical civilizations, including the Sumerians, Babylonians, Egyptians and others, and came up with an average duration of 420 years. Using 28 examples more recent than the Roman Empire, the average is 304 years. Jared Diamond[35] reviewed 10 societies, finding that environmental devastation was a common factor in their demise after 300-800 years. And Oswald Spengler, in *Decline of the West*, said that cultures have a lifetime of about 1000 years.

One reason for a short lifetime of a civilization may be nuclear war that devastates their world. Modern Western Civilization is about 1000 years old, but has survived less than 70 years with nuclear weapons. It currently faces the prospect of suicidal fanatics attaining a nuclear capability, with an avowed goal of bringing on Armageddon. The Doomsday Clock of the *Bulletin of the Atomic Scientists* is now at 5 minutes before midnight, which makes the civilized lifetimes of millions of years quoted in early SETI work seem very optimistic.

VI. A NEW LOOK AT FERMI'S PARADOX

Since the discovery of the first exoplanet, orbiting Gamma Cephei in 1988, confirmed in 2003, there has been an explosion in exoplanet discoveries. It now appears that at least 70% of Sun-like stars have planets with orbital periods of less than 85 days, and astronomers now expect that, on average, every star should have at least one planet. This would total at least 100 billion planets in the Galaxy. At least two stars other than the Sun have 7 planets, and one, HD 10180, is suspected of having 9; it is magnitude 7.3, and is 127 light years away in the constellation Hydrus.

The sheer number of exoplanets makes Fermi's Paradox even more compelling. The pessimists' most telling argument in the SETI debate stems from a hard observation: the lack of extraterrestrial contact. A civilization lasting for millions of years would have plenty of time to travel anywhere in the galaxy, even at the slow speeds foreseeable with our own technology. The Earth should have already been colonized, or at least visited, but no evidence of this exists. Hence Fermi's question remains: "Where is everybody?"

Many explanations have been proposed to explain this lack of contact, but Webb[36] puts them into 3 classes:

1. They exist, and they are here. These include the "zoo" hypothesis, that we are in a preserve, and that we are the ETI who came here long ago.
2. They exist, but haven't communicated yet. There are few civilizations, too far apart; interstellar travel is too hard or too slow; or civilizations last for only a short time.
3. They do not exist. We are the first, or habitable planets are rare, or protective Jupiters are rare, or the Earth-Moon double planet is unique, or life is very improbable, or intelligence is rare.

If habitable planets are common, then something must prevent ETI from arising. This led to the Great Filter hypothesis[37], that one of the key factors in the Drake Equation is zero or near zero, acting as a filter to reduce the value of N. According to this view, either it is very hard for life or intelligent life to arise, or the lifetime of civilizations must be relatively short. The question then arises as to whether the Great Filter is behind us or ahead of us. If life is rare or intelligence is rare, then we are safely past it; but if civilizations destroy themselves, it is looming ahead of us. For that reason, Nick Bostrom[38] said it would be better for us if there is no life found on Mars, because then the Great Filter is more likely to be behind us!

Prominent authors take different positions on the proposed solutions to the paradox—there are no extraterrestrials, and we are alone in the galaxy (Mayr, Gribbin, Hart); extraterrestrial civilizations destroy themselves or die out before they reach the stars (Shklovskii in later years); or they exist, they do travel among the stars, but they haven't reached us yet (Jayawardhana); or they have reached us and we are in a "zoo" or "preserve."

Table 3 shows our revised view of the Drake Equation, with added parameters. Given the number of stars in the Galaxy, there are 11 factors that determine the expected number of existing civilizations that could communicate.

Our estimates for N are low because of 4 factors: in the worst case, only 0.05% of stars are suitable; only 1% of planets are double; only 10% of life develops intelligence, because of extinctions; and civilizations last just 550 to 5500 years. In the worst case, we are the only civilization in the Galaxy; in the best case, there may be 85 civilizations, and the nearest might be about 6600 light years away. But unless civilizations last much longer than all the examples on Earth, we could never have a two-way conversation.

Table 3. New Estimates of the Number of Civilizations in the Galaxy

Drake Equation Parameter	Low Estimate	High Estimate
Stars in the Galaxy disk	$120x10^9$	$200x10^9$
Fraction in the galactic habitable zone	0.13	0.37
Fraction of the right spectral class	0.04	0.125
Fraction with planets	0.55	1
Planets per star in the habitable zone	0.65	0.74
Fraction with a suitable metallicity & giant planet	0.1	0.5
Fraction that are double, with plate tectonics	0.01	0.1
Fraction of planets with prokaryotic life	0.5	1
Fraction of those with eukaryotic life	0.5	0.5
Fraction of those with intelligent life	0.1	0.5
Fraction developing technological civilization	0.5	1
Lifetime of civilizations / 5.5 Byr lifetime of planet	10^{-7}	10^{-6}
Number of civilizations in the Galaxy	0.0003	85

On the low estimate, these 4 factors are so low that they may constitute the Great Filter, and our civilization and others we find may be successfully past it, if civilizations can last long enough. On the high estimate, 85 civilizations is far fewer than Frank Drake and Carl Sagan expected, and if that is the case, it will be very difficult to succeed in SETI, but even more important to gain insights about the successes of any civilizations we do discover.

VII. CONCLUSIONS

In the early days of SETI, it was easy to imagine that in a galaxy of 200 billion stars there would be many examples of life, intelligence, and civilizations. It was even likely that there was a Galactic Empire, or at least a "galactic club" which humanity could join. But after fifty years of searching without success, we must conclude that the probability of extraterrestrial civilizations must be much smaller than we thought. After a review of the parameters in the Drake Equation, the pessimistic conclusion is that we are alone in the Galaxy, our life is precious, and we need to protect and extend it. A more optimistic conclusion is that there are perhaps 85 civilizations in the Galaxy, with the Great Filter behind them (and us), and if our civilization lasts long enough, we need to contact them to understand our destiny. In either case, the lack of suitable stars and the rarity of double planets make other life and ETI very rare or unlikely.

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