



Estimating The Number of Intelligent Extraterrestrial Civilizations: A Probabilistic Approach to the Drake Equation

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ABSTRACT: Astrobiology seeks to address some of humanity’s most profound questions: Are we alone in the Universe? and What are the conditions necessary for life to emerge? One of the key theoretical tools in this pursuit is the Drake Equation, formulated in 1961, which provides a probabilistic framework for estimating the number of intelligent extraterrestrial civilizations in the Milky Way. In this paper, we revisit the Drake Equation using updated astronomical and biological data, along with simplified probabilistic assumptions. By applying current observational evidence of exoplanets, laboratory studies of prebiotic chemistry, and estimates of stellar and planetary habitability, we obtain a tentative value of ~72 civilizations capable of interstellar communication via radio astronomy. The result highlights the paradox first identified by Enrico Fermi -if intelligent life is so probable, why have we not yet detected it? We discuss possible resolutions to the Fermi Paradox, including distance, evolutionary differences, and the possibility of self-destruction. Finally, we outline future directions for astrobiology, observational astronomy, and SETI that may refine these estimates and potentially resolve one of the greatest scientific mysteries of our time.

KEY WORDS: Astrobiology, Drake Equation, Exoplanets, Fermi Paradox, SETI.

1. INTRODUCTION

The discovery of thousands of exoplanets over the past three decades has revolutionized our understanding of planetary systems and renewed interest in the search for extraterrestrial life. A landmark moment occurred in 1977, when a strong narrowband radio signal was detected at the frequency of neutral hydrogen (1.420 GHz), precisely where researchers had theorized an artificial signal might appear. This signal, now famously known as the “Wow! Signal,” was traced to the region of the globular cluster M55 (Marvel, 2001). Although its origin remains unexplained, it continues to stimulate scientific debate. More recently, in December 2020, a potential new source was suggested – star 2MASS 19281982-2640123 (Caballero, 2020) – rekindling interest in the possibility of extraterrestrial radio transmissions. The detection of an artificial radio signal would represent one of the most compelling pieces of evidence for the existence of intelligent extraterrestrial civilizations.

Parallel to radio astronomy, the search for exoplanets has fundamentally transformed our knowledge of planetary systems beyond our own. Multiple detection techniques have been developed, with the transit method proving the most efficient, accounting for more than 70% of confirmed discoveries (NASA Exoplanet Archive, 2025). As of June 14, 2025, 5,921 exoplanets orbiting 4,422 stars have been confirmed, with the Kepler Space Telescope alone responsible for detecting 3,328 of them. Since the launch of the Transiting Exoplanet Survey Satellite (TESS), the total number of planets discovered via the transit method has risen to 4,387, yielding a success rate of approximately 74.1%. This efficiency underscores why the transit method has become the cornerstone of modern exoplanet discovery

Kepler’s mission, in particular, has yielded several groundbreaking discoveries. Notable examples include Kepler-186f - the first Earth-sized planet found within the habitable zone of its host star (Quintana, 2014) – and Kepler-16b, the first confirmed circumbinary exoplanet, orbiting two stars (Doyle, 2011). Another intriguing case is KIC 8462852, also known as “Tabby’s Star,” which exhibits irregular, aperiodic dimming events of up to 20% in the stellar flux (Simon, 2016). These unusual patterns have sparked considerable debate, ranging from natural astrophysical explanations to more speculative hypotheses.

Among the most fascinating exoplanets discovered to date is K2-18b, which scientists consider a promising candidate in the search for life beyond Earth (Foreman-Mackey et al., 2015; Benneke et al., 2017). In 2025, dimethyl sulfide (DMS) was detected in its atmosphere (Madhusudhan et al., 2025), a molecule often considered a potential biosignature. Although this is not definitive



proof of life, it makes K2-18b an exciting target for future investigations and highlights the rapid progress in identifying exoplanets with conditions potentially suitable for life.

1.1. Drake Equation

In 1961, the American astronomer Frank Drake of Cornell University proposed a probabilistic mathematical framework to estimate the number of extraterrestrial civilizations in our galaxy capable of interstellar communication. This framework, now famously known as the Drake Equation, combines a series of measurable quantities and probabilities, such as the number of stars in the Milky Way and the likelihood that planets develop life. The equation also accounts for the average lifespan of civilizations capable of transmitting signals across interstellar distances (Maccone, 2010)

Drake's objective was not to provide a definitive answer but rather to stimulate scientific dialogue and encourage the systematic exploration of life beyond Earth. The Drake Equation is expressed as follows:

$$N = R_* f_p n_e f_l f_i f_c L, \quad (1)$$

where R_* is the average rate of stars formation in the Milky Way; f_p – the fraction of stars that have planetary systems; n_e the average number of the planets per system that could support life; f_l – the fraction of those planets on which life actually emerges; f_i – the fraction of planets with life that developed intelligent beings; f_c – the fraction of civilizations, that developed technology capable of interstellar communication.; L – the average lifespan of such civilizations. All parameters except R_* and L represent probabilities, reflecting our uncertainty about the processes that lead to life and intelligence. Consequently, the Drake Equation does not yield a single definitive number but highlights where empirical research is most urgently needed.

In this study, we propose an approach to constraining the Drake Equation, starting with the best-known parameter: the number of stars in the Milky Way, estimated at approximately 400 billion. The subsequent step involves estimating the number of planets, an area in which recent discoveries, such as K2-18b, provide valuable insights. Observations from modern astronomical instruments like the Kepler and TESS space telescopes reveal that planetary systems are common rather than exceptional. This knowledge allows for more informed estimates of f_p than were possible in Drake's time.

1.2. Exoplanets and the Search for Biosignatures

Among the most intriguing exoplanet discoveries is K2-18b, a planet located in the habitable zone of its host star. It is considered one of the most promising candidates in the search for extraterrestrial life (Foreman-Mackey et al., 2015; Benneke et al., 2017). In 2025, molecules of dimethyl sulfide (DMS) were detected in its atmosphere (Madhusudhan et al., 2025). On Earth, DMS is almost exclusively produced by biological processes, making it a potential biosignature.

Although the detection of such molecules does not constitute definitive proof of life, it significantly informs the values of f_l (the fraction of planets where life emerges) and potentially f_i (the fraction of planets where intelligence evolves). Each new observation reduces uncertainty in these parameters, transforming what was once purely speculative into measurable science.

The discovery of planets like K2-18b demonstrates the rapid advancement of exoplanetary research. What Drake formulated as a speculative framework more than sixty years ago is increasingly being constrained by observational data, bringing humanity closer to answering one of its most profound questions: *Are we alone in the universe?*

2. AN ATTEMPT TO SOLVE THE DRAKE EQUATION

For our estimation, we utilized data from the Kepler Space Telescope, NASA's Exoplanet Archive (NASA Exoplanet Science Institute, 2025), and the Stellarium software (Zotti et al., 2021). During its primary mission, Kepler confirmed 2,781 exoplanets, and an additional 547 were confirmed during its extended K2 mission (NASA Exoplanet Statistics, 2025), yielding a total of 3,328 confirmed exoplanets attributed to Kepler.

Using Stellarium, we calculated that Kepler's field of view was approximately 13.5° in declination and 14.1° in right ascension, corresponding to an area of 190.35 square degrees, or 0.05798 steradians (sr). Given that the total celestial sphere covers 4π sr, the ratio between the full sky and the region observed by Kepler is:



$$\alpha = \frac{4\pi}{0,05798} = 216.74 \tag{2}$$

This indicates that the entire sky is roughly 217 times larger than the area observed by Kepler. By extrapolating Kepler’s yield across the full sky, the expected number of detectable exoplanets from Kepler-like observations is

$$N_{hyp} = \alpha \cdot 3328 \approx 721,311 \tag{3}$$

Kepler’s mission concluded on October 30, 2018. As of June 2025, a total of 5,921 confirmed exoplanets in 4,422 planetary systems have been detected using all methods (NASA Exoplanet Archive, 2025). Of these, 4,378 planets were discovered via the transit method, including contributions from other surveys such as TESS and NGTS. The remaining 1,043 planets (17.6%) were detected through non-Kepler transit methods.

Thus, the estimated number of exoplanets detectable using the transit method alone is approximately:

$$N_{tr} \approx 722,354 \tag{4}$$

Although substantial, this number does not account for the total expected population of planets in the Milky Way. To improve our estimate, we introduce the multiplicity coefficient.

2.1. The Multiplicity Coefficient

From current statistics, the ratio of confirmed exoplanets (N_0) to host stars (S_0) is:

$$k = \frac{N_0}{S_0} = \frac{5921}{4422} \approx 1.34 \tag{5}$$

This “multiplicity coefficient” k indicates that on average, each star with planets host of 1.34 planets. Over the past 5 years, the value of k has varied by less than 1%, so it can be treated as approximately constant for large scale estimates.

Subtracting planets detected by transits (4,378) from the total confirmed (5,921), gives the number of non-transit planets detected:

$$N_1 = 1543 \tag{6}$$

The corresponding number of stars hosting these planets is:

$$S_1 = \frac{N_1}{k} \approx 1151 \text{ stars} \tag{7}$$

The ratio between the total number of the stars in the Milky Way ($S_{MW} \approx 4 \times 10^{11}$) and this sample is:

$$p = \frac{S_{MW}}{S_1} = 3.48 \times 10^8 \tag{8}$$

Extrapolating this to the whole Galaxy, the number of non-transit planets is:

$$N_2 = p * N_1 \approx 5.36 \times 10^{11} \tag{9}$$

Thus, the total number of exoplanets in the Milky Way is:

$$N_x = N_2 + N_{tr} \approx 5.36 \times 10^{11} \tag{10}$$

Thus, our approach estimates approximately 536 billion exoplanets in the Milky Way, consistent with independent astrophysical estimates ranging from 100–400 billion planets (Cassan et al., 2012; Winn & Fabrycky, 2015). His finding supports the hypothesis that planets are at least as numerous as stars in our galaxy.

2.2. Beyond Planets: Moons and Interstellar Objects

Some large moons could be considered “planet-like” if they orbited stars directly. Among the 211 natural satellites in the Solar System, three – Ganymede, Titan, and Callisto -are comparable in size to Mercury. For example, Callisto has a radius of 2,410 km, whereas Mercury’s radius is 2,440 km. This indicates that approximately 1.4% of moons are large enough to qualify as planet-sized bodies. While no exomoons have been conclusively confirmed to date, several candidates have been proposed. ALMA



observations, for instance, suggest a possible moon-forming disk around the young exoplanet PDS 70c, with a potential satellite mass of 0.03 Earth masses (Benisty et al., 2021). The search for exomoons has thus become a growing subfield within exoplanetary science (Ruffio, 2023).

In addition to moons, two interstellar objects have been observed passing through the Solar System: 'Oumuamua in 2017 and 2I/Borisov in 2019. Spectroscopic studies of Borisov revealed volatile compounds such as CO, C₂, and CN (Bodewits et al., 2020; Kareta et al., 2020), confirming that organic precursors to life exist even in interstellar bodies. 'Oumuamua, with its unusual trajectory and elongated shape, sparked debate over whether it could have an artificial origin (Loeb, 2022), although most studies support a natural explanation (Trilling et al., 2018).

These findings highlight that the inventory of potentially habitable or biologically relevant bodies extends beyond traditional exoplanets to include moons and interstellar objects, expanding the scope of astrobiological exploration.

3. RESULTS AND DISCUSSION

Having calculated the approximate number of planets in the Milky Way ($\sim 5.36 \times 10^{11}$), we can now estimate the likelihood of intelligent extraterrestrial civilizations using the Drake Equation. As noted earlier, this estimate cannot be taken as exact, since many parameters are probabilities rather than directly measured values. Nevertheless, these probabilities are increasingly informed by observational and experimental data from space telescopes, planetary probes, and laboratory experiments (Delev & Dimtrova, 2025).

The Miller-Urey experiment (Miller, 1953) demonstrates that under conditions similar to Earth's early atmosphere, organic compounds such as amino acids. This indicates that the basic building blocks of life can emerge naturally under planetary conditions, or even in interstellar environment. Furthermore, the hypothesis of panspermia suggests that life or prebiotic molecules might be transferred between planetary systems via comets, asteroids, or interstellar dust. From the latter we conclude the probability of finding life-supporting planets is high enough. For our model we suggest the factor:

$$n_e = 0.67 \quad (11)$$

Multiplying this factor by the total number of planets gives us total number of:

$$N_l = 3.59 \cdot 10^{11} \text{ life-supporting planets} \quad (12)$$

3.1. Probability of Life and the Emergence of Intelligent Civilizations

The next parameter in the Drake Equation is the probability of life emerging on planets situated within habitable environments, denoted as f_l . For life to arise, planetary conditions must be favorable, which requires consideration of both the Stellar Habitable Zone (SHZ) and the Galactic Habitable Zone (GHZ).

The SHZ refers to the orbital region around a star where liquid water can exist on a planet's surface, a key prerequisite for life as we know it (Kasting, Whitmire, & Reynolds, 1993). The GHZ, in contrast, encompasses a broader galactic context, including factors such as stellar metallicity, supernova frequency, and ambient radiation levels (Lineweaver, Fenner, & Gibson, 2004). Planets located too close to the Galactic center are exposed to intense radiation and gravitational perturbations, which may hinder the emergence of life. Conversely, planets in the outer Galactic disk or within globular clusters often exhibit low metallicity, reducing the abundance of heavy elements such as iron, magnesium, and calcium, which are critical for planetary differentiation and biochemistry.

Organic molecules have been detected in a wide range of environments, including interstellar molecular clouds, comets, and icy moons within the Solar System (Ehrenfreund & Charnley, 2000; Öberg, 2009). However, the mere presence of organic compounds does not constitute definitive evidence for life. Nevertheless, the history of Earth demonstrates that life can emerge relatively quickly once favorable conditions are established. The classic Miller-Urey experiment provided experimental evidence that amino acids—the building blocks of life—can form under prebiotic conditions (Miller, 1953). More recent studies have confirmed that complex organic molecules can form in interstellar ices under ultraviolet irradiation (Herbst & van Dishoeck, 2009).

Furthermore, life is highly adaptive and capable of surviving extreme environments, ranging from hydrothermal vents to high-radiation deserts (Cockell, 2015). Based on these considerations, and acknowledging the inherent uncertainties, a conservative value for the probability of life emerging on a habitable planet is adopted as:



$$f_i = 0.1 \tag{13}$$

This results that the estimated number of planets in the Milky Way that could host simple life forms is equal to:

$$N_{int} \approx 3.59 \times 10^{10} \tag{14}$$

planets with hosting simple life forms

3.2. Evolution of Intelligent Life

The next factor in the Drake Equation, denoted as f_i , represents the probability that life evolves into intelligent, complex organisms. On Earth, unicellular life dominated for approximately three billion years before multicellular life emerged, eventually giving rise to species capable of complex cognition (Knoll, 2015). The evolution of intelligence appears to require multiple evolutionary “leaps,” often triggered by environmental changes such as oxygenation events, climate shifts, or mass extinctions.

However, Earth provides only a single data point, and alternative evolutionary pathways may exist elsewhere in the galaxy. Intelligence is not an inevitable outcome of life, and even when it arises, technological capability may not necessarily follow. Cultural, ecological, and physiological factors could influence whether a species develops technologies capable of interstellar communication.

Given the uncertainties associated with the emergence of intelligence, a conservative estimate is adopted:

$$f_i = 0.001 \tag{15}$$

Applying this parameter yields an estimated number of planets hosting intelligent life in the Milky Way:

$$N_{int} \approx 3.59 \times 10^7 \tag{16}$$

planets with intelligent life.

This estimate underscores the rarity of intelligence relative to the prevalence of life in habitable environments and highlights one of the critical bottlenecks in the emergence of technologically advanced civilizations

3.3. Technological Civilizations and Communication

Even if intelligence evolves, not all civilizations develop technologies capable of interstellar communication. The parameter f_c represents the fraction of intelligent civilizations that achieve this stage. For example, humanity developed radio astronomy only in the past ~200 years, a small fraction of its existence. Cultural, social, or environmental constraints could prevent many intelligent species from developing radio technologies at all (Tarter, 2001; Wright et al., 2018).

For our model, we again adopt a conservative value:

$$f_c = 0.001 \tag{17}$$

This yields an estimated number of technologically capable civilizations:

$$N_{civ} \approx 3.59 \times 10^4 \tag{18}$$

3.4. Lifespan of Civilizations (L)

The final factor, L , represents the average duration over which a civilization remains capable of interstellar communication. This parameter is highly uncertain. Human civilization has conducted radio astronomy for less than 200 years, compared to Earth’s age of approximately 4.5 billion years, giving a fraction of:

$$\frac{200}{4.5 \times 10^9} \approx 4.4 \times 10^{-8} \tag{19}$$

If most civilizations endure for only brief periods before self-destruction, L remains very small. However, it is plausible that some civilizations persist much longer, stabilizing their societies and technologies. Civilizations around older main-sequence stars, particularly within the Galactic Habitable Zone (GHZ), may have existed for millions of years (Ćirković, 2004). For this calculation, we assume a modest probability:



$$L = 2 \times 10^{-4} \quad (20)$$

By combining the estimated fractions of technological civilizations and their lifespan, the expected number of active communicative civilizations in the Milky Way is:

$$n = N_{civ} \cdot l \approx 72 \quad (21)$$

3.5. Interpretation

Our estimate suggests that dozens of civilizations in the Milky Way may currently be capable of interstellar communication. Although small relative to the total number of planets, this number is scientifically significant and justifies continued searches by SETI programs.

This analysis also highlights critical bottlenecks in the Drake Equation. While habitable planets may be abundant, the probabilities of intelligence emerging, civilizations developing communication technology, and the long-term survival of those civilizations remain highly uncertain. Future observations with the James Webb Space Telescope (JWST), the planned LUVOIR mission, and next-generation Extremely Large Telescopes (ELTs) could help refine these estimates by detecting biosignatures and technosignatures in exoplanetary atmospheres (Seager, Bains, & Petkowski, 2016; Madhusudhan, 2019).

4. THE FERMI PARADOX

From the Drake Equation, we estimated that approximately 72 extraterrestrial civilizations in the Milky Way may currently be capable of interstellar radio communication. This leads to a natural question, famously posed by Enrico Fermi in 1950: “Where is everybody?” (Hart, 1975; Brin, 1983). Despite decades of systematic searches, no confirmed signals from extraterrestrial civilizations have been detected. This apparent contradiction between the high probability of extraterrestrial civilizations and the lack of observational evidence is known as the Fermi paradox (Sandberg, 2018).

A wide range of hypotheses, has been proposed to explain this paradox . below we discuss three primary classes of explanations: distance and communication limits, evolutionary disparity, and self-destruction.

4.1. Distance and Communication Constraints. The simplest explanation is spatial separation. The nearest star system, Proxima Centauri, lies 4.24 light-years away. A radio signal transmitted from Earth would take more than , 4 years for a reply to return. For stars located hundreds or thousand of light-years away, communication becomes increasingly impractical, requiring millennia for a two-way exchange (Tarter, 2001).

Moreover, the detectability of radio signals decreases with distance due to the inverse-square law of electromagnetic radiation. Civilizations using directed beams rather than isotropic broadcasts would further limit the probability of detection (Wright et al., 2018). It is also possible that advanced civilizations no longer rely on radio communication at all, instead using technologies beyond our comprehension, such as quantum communication or neutrino-based signaling (Messerschmitt, 2015).

4.2. Evolutionary Disparity. Another explanation is the difference in evolutionary stages between civilizations. More advanced civilizations may employ communication methods that are indistinguishable from natural cosmic noise to us, or may deliberately avoid contact, considering humanity too primitive to warrant attention (Ćirković, 2009). In this context, the Zoo Hypothesis suggests that extraterrestrial civilizations intentionally avoid interacting with Earth to allow for natural cultural and biological evolution (Ball, 1973).

Conversely, it is possible that humanity is among the first evolved civilizations in our galaxy. In this case, the apparent silence is not paradoxical but reflects the rarity of long-lived technological societies (Tipler, 1980; Hanson, 1998). Another variant, the Dark Forest Hypothesis, argues that advanced civilizations may deliberately remain silent to avoid detection by potentially hostile neighbors (Liu, 2008).

4.3. Self-Destruction and the Great Filter. One of the most sobering explanations for the Fermi Paradox is the self-destruction hypothesis, closely related to the Great Filter theory (Hanson, 1998; Bostrom, 2008). This view suggests that while intelligent life may emerge relatively frequently, civilizations tend to destroy themselves before developing stable interstellar communication or expansion. The risks of self-destruction include nuclear war, uncontrolled artificial intelligence, ecological collapse, or global pandemics (Rees, 2003; Ord, 2020).



This scenario is connected with the Kardashev scale (Kardashev, 1964), which categorizes civilizations by their energy consumption (Kardashev, 1964). Humanity is currently a Type I civilization candidate, harvesting energy on the planetary scale. Progressing to Type II (stellar energy usage) or Type III (galactic energy usage) would require technological leaps that might also increase existential risks. Gray (2020) expanded the Kardashev framework to incorporate social and ecological stability, emphasizing that the survival of civilizations is not guaranteed by technological advancement alone.

Nonetheless, intelligence may also foster resilience. Civilizations capable of recognizing existential risks might transition toward sustainable and cooperative futures, extending their lifespan and increasing their detectability across cosmic timescales being extended in 2020 (Gray, 2020) and the so-called Great filter. The main idea of this hypothesis is that while evolving, civilizations get intelligent enough to develop rocketry, nuclear power and nuclear weapons. Thus, increasing the chance of self-destruction. However, being intelligent enough, they may stop using these technologies with bad intentions and turn them into intensions, capable of developing the civilization further.

4.4 Summary

In summary, the Fermi Paradox highlights the tension between the apparent abundance of habitable environments in the Milky Way and the absence of observed extraterrestrial contact. Possible resolutions range from simple communication barriers to profound existential filters limiting the longevity of civilizations. Whether humanity is alone, early, or simply too primitive to detect the signals of others remains an open and deeply consequential scientific question.

5. CONCLUSION

Astrobiology is a rapidly developing interdisciplinary field of modern astronomy that seeks to address some of the most profound scientific questions: *Are we alone and where do we come from?*; *“What is life and how did it emerge?; Under what conditions can life exist elsewhere?*. In this work, we applied basic mathematics and observational data, including results from NASA archives, to explore an innovative approach to one of the most enduring problems in astrobiology – the Drake Equation.

By adopting parameter estimates grounded in planetary science, chemistry, and evolutionary biology, we calculated that approximately 72 civilizations in the Milky Way may currently possess the ability to communicate via radio waves. Although our chosen coefficients represent reasonable approximations, it is important to emphasize that each factor in the Drake Equation is subject to significant uncertainty. Alternative assumptions can yield values ranging from zero to millions, and therefore no single solution should be regarded as definitive.

This uncertainty naturally leads into the Fermi Paradox: if the Galaxy should host dozens or even thousands of technological civilizations, why have we not yet detected them? Potential explanations include vast interstellar distances and communication limitations, disparities in evolutionary development, deliberate silence, or the self-destruction of civilizations before they can achieve interstellar contact. Concepts such as the Zoo Hypothesis, the Dark Forest Hypothesis, and the Great Filter illustrate the wide spectrum of possible resolutions, each carrying profound implications for our own future as a civilization.

Despite this silence, there have been intriguing anomalies, such as the WOW! signal detected in 1977 or the unusual light fluctuations of KIC 8462852 (Tabby’s Star), which remain unexplained and continue to inspire debate. While no one provide definitive evidence of extraterrestrial intelligence, they serve as reminders that our search is far from complete.

Ultimately, solving the Drake Equation is not about producing a final number but about framing the scientific problem and refining our understanding as new data become available. With the rapid advancement of observational technologies -next-generation telescopes, more sensitive radio arrays, and advanced biosignature detection techniques -we are moving closer to addressing one of humanity’s oldest and most profound questions. Whether the Universe is teeming with life or we are truly alone, the pursuit of this answer continues to expand both our scientific horizons and our philosophical perspective on humanity’s place in the cosmos.

In summary, while our current estimation yields approximately 72 potential civilizations capable of radio communication in the Milky Way, this number remains highly tentative. The coming decades promise transformative discoveries, as observational technologies mature and interdisciplinary research strengthens the foundations of astrobiology. Continued exploration—both observational and theoretical -will be essential in addressing the Fermi Paradox and in refining our understanding of humanity’s place in the Universe.



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