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The Fermi Paradox and the Emergence of Intelligent Extraterrestrial Civilizations

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Abstract

Whether intelligent species exist in our galaxy has long remained an unresolved question within the Fermi Paradox. While numerous theories have been proposed to address the Fermi Paradox and theories and estimates as to the possible number of intelligent civilizations in our galaxy has been proposed. The Fermi paradox also has hidden implications which may be explored utilizing the interrelationship between astrophysics, neurobiology, and complex network theory and which provides a deeper understanding of the mathematical implications behind the origin and evolution of life in the universe.

Key Words: Key words: Astrobiology, Fermi paradox, Complex systems

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1. Introduction

If there exists extraterrestrial intelligence in the cosmos, where are they? This question posed by Enrico Fermi arises from millennia of human contemplation about our own existence: “Are we alone?” “Is there life on other planets?” And, if there is intelligent life, why haven’t they made their existence known to us? This inquiry, known as the Fermi Paradox, delves into the scientific puzzle surrounding the potential existence of extraterrestrial intelligence. This question has sparked vigorous debates among scientists for decades (Prantzos, 2020; Frank & Sullivan, 2016; Forgan, 2019; Webb, 2015). Human endeavors in space exploration have made significant strides over these years, with space telescopes and probes having surveyed the majority of planets and their satellites in our solar system. Scientists have even sought to detect microwave signals and have attempted to transmit messages toward thousands of planets, yet, there has no answer, and as of now, no conclusive evidence has been obtained for intelligent life except on Earth and in our atmosphere.

Given the immense number of star systems in the observable universe, and the numerous Earth-like worlds in our own galaxy, as well as planets billions of years older than our own, it should be expected that intelligent life has evolved on hundreds if not thousands of worlds within our galaxy. Fermi, acknowledging the vast distances and time required to travel between solar systems, that ships abandoned or those piloted by robots should have been detected in our solar system. Yet they have not. It is possible that Earth is not of interest to highly intelligent extraterrestrials? Or, might they be employing a stealth technology which makes them invisible to our instruments of detection? Yet another possibility, these civilizations have all eventually gone extinct. However, we should expect there would be some evidence that they had long ago colonized other worlds. As of this writing, there is no evidence of human-like intelligence, except on Earth.

Frank Drake (Drake, 1961) has estimated the number N of intelligent civilizations in the Milky Way with which humans could potentially communicate via radio, is as follows:

$$N = R^* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L, \qquad (1)$$

The variables in Equ.1 are defined as follows: R^* represents the average rate of star formation in the Milky Way, f_p denotes the proportion of star systems that have planets, n_e stands for the number of Earth-like planets per star system, f_l represents the proportion of habitable planets where life could evolve, f_i is the probability of developing intelligent species, f_c signifies the probability of these intelligent species communicating, and L denotes the lifetime of a technological civilization. Scientists hold considerable disagreement regarding the values of these variables in Equ.1, and these variables significantly impact the resulting value of N. According to calculations, N could ultimately fall within a wide range from 1 to 1 million, showcasing a substantial margin of error.

Equ.1 involves multiple probabilities being multiplied together. If the existence of life itself is the result of a series of low-probability events, compounded and combined over billions of years, then even if extraterrestrial civilizations have the capability to conquer the galaxy, the occurrence probability would still be exceedingly small, which can explain the Fermi Paradox. However, why the existence of life is a low-probability event is the focus of this paper. Based on a unique mathematical assumption — The scale-free feature of star systems in the universe generating complex intelligent life — we can explain why the emergence of intelligent life is a low-probability event. Understanding this reasoning entirely helps us fully comprehend the Fermi Paradox, as detailed in the following section.

2. Theory

Before starting to estimate the number of intelligent extraterrestrial life forms, it is crucial to address the characteristics required for intelligent beings. The Drake equation starts with the premise of having Earth-like habitable planets as a basis for discussing the emergence of intelligent life forms. However, we aim to bypass this issue and directly investigate into the past accomplishments in neurobiology (Herculano-Houzel, 2009). To produce intelligence, organisms undoubtedly require an adequate amount of neurons and their connections (that is called synaptic connections), with the latter being especially crucial (Raman, et al. 2019). The neural network formed by neurons is the fundamental element of intelligent life, with complexity representing its intrinsic feature. The algorithms behind recently popular artificial intelligence (AI) are also motivated by the observation that human intelligence emerges from highly connected networks of relatively simple and non-linear neurons learn by adjusting the strengths of their connections (Hu, et al. 2021). This tells us that the information contained in the probability multiplication within the Drake equation $(f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c)$ could be embedded within the network of connections among neurons. Thus, we can simplify the problem in this way if we use the number of connections in the neural network, much deeper elements than language or brain size regarding the generation of intelligence (Falk, 2022), to represent the level of intelligence.

Although extraterrestrial races might not be composed of neurons forming a network, we will use the unit of neural network in AI models — perceptron (Block, 1962) — as the basic units for discussing the network systems of intelligent beings. Consider the concept of perceptrons is a machine learning algorithm that classifies inputs into two categories using a neural network. The total connections between these perceptrons could be conceived as representing the level of intelligence of an individual intelligent being. Additionally, within a star system, there might be numerous planets that host highly intelligent species. To avoid concerns regarding the number of planets, we will consider the species with the maximum value of total number of connections between perceptrons to represent the highest level of civilization within the star system. Hence, it is reasonable to assume that the number of star systems in the galaxy, N_s, is a function of the total number of connections between perceptrons, N_p:

$$N_s = f(N_p). \quad (2)$$

The above relationship describes that the galaxy contains N_s star systems, each including the most intelligent species with total number N_p of connections between perceptrons. It is generally understood that the number of connections between individual perceptrons can represent the memory units of an organism; usually, more connections signify higher level of intelligence. However, the recent work (Raman, et al. 2019) has suggested that there is an optimal value for the number of connections. Exceeding this optimal value would be detrimental to the survival of the individual. Therefore, for a species to form a more intelligent civilization, it must form communities through the aggregation of individuals. This concept is similar to the idea of "Two heads are better than one." Ants or bees serve as typical examples. Hence, N_p here needs clarification: it represents the total number of connections between all perceptrons of the entire species, not an individual.

With the above relationships established, we will lay out the overall logical framework of this theory based on two perspectives: (1) The relationship in Equ.2 is monotonically decreasing. This is not an assumption but rather an observation based on our experience within the solar system. As we have never encountered any intelligent extraterrestrial civilizations, it implies that the maximum value of N_s should occur when N_p equals zero. This suggests that on most planets or satellites, there is no life. Consequently, as N_p increases, N_s should follow a decreasing function. (2) The total number of connections between perceptrons have upper and lower limits. The lower limit is determined by the number of neural connections of human beings. Our experience indicates that a N_p lower than that of human would not generate consciousness or intelligence. Therefore, we can directly use the total number of connections between perceptrons of a single individual to determine the lower limit of N_p. However, once it exceeds this lower limit, the total number of connections between perceptrons will proportionally increase with the number of species individuals. This aligns with the aforementioned idea of communities: intelligent civilizations are established by a collective of individuals rather than a single individual, hence N_p will equal the total number of the connections between individual perceptrons times the total number of individuals. Furthermore, the upper limit is determined by the size of the planets where individuals reside. As N_p is directly proportional to the total number of individuals, it allows us to establish the upper limit.

The next question is, what function relationship does Equ.2 exhibit? Let us assume that each star system in the universe represents a node in a network. It can be expected that the number of connections between nodes would necessarily be positively correlated with N_p. The larger the N_p, the more connections the intelligent beings in that star system would have with other star systems. Thus, Equ.2 describes a function similar to the degree distribution function of that network. In the realm of network science, there are three common distributions: the first is the uniform distribution arising from a regular network. Based on the current observations of the universe and the first perspective mentioned before, there is no reason to believe that the number of lifeless planets would be equal to the number of planets hosting advanced intelligent life. Therefore, we can reasonably exclude the regular network. The second is an exponential distribution with random characteristics of a disordered network. And the last is a power-law distribution with the scale-free features between the regular network and the disordered network. Certainly, we do not exclude the possibility of other distributions. However, the validity of any other distribution should confirm to the observations of the Fermi Paradox. In the following section, we will determine through the estimation of N_s which distribution is more prevalent in the mathematical distributions within the universe.

3. Estimation on the number of intelligent civilizations

In the following, we will use some mathematical rules and well-known knowledge to determine the number of star systems in the Milky Way that might host intelligent civilizations. First, let us list some established facts as a reference for subsequent analysis:

A. The total number of stars in the Milky Way (Masetti, 2015): 100 to 400 billion (Maximum: $4 \cdot 10^{11}$)
B. The total number of neural connections in the human brain (Zhang, 2019): up to 1000 trillion (Maximum: 10^{15})
C. Current world population on Earth (Worldometer): 8 billion ($8 \cdot 10^{9}$)
D. Upper limit of Earth's population (United Nations Population Division): 10.4 billion ($1.04 \cdot 10^{10}$)
E. Upper limit of planetary mass (Schlaufman, 2018): 4 to 10 times the mass of Jupiter (Maximum: 10 times Jupiter's)

F. Jupiter's volume compared to Earth's volume (Williams, 2021): Approximately 1321 times

G. Total number of stars in the observable universe (Traversa-Tejero, 2021): 4.5 septillion ($4.5 \cdot 10^{24}$)

According to Facts B and C, the minimum of total number of neural connections should be:

$$10^{15} \cdot (8 \cdot 10^{9}) > 10^{24},$$

which is the lower limit of N_p. In addition, considering the maximal volume limit for species inhabiting a planet and the saturation of Earth's future population, as described in Facts D, E, and F, the upper limit for N_p is:

$$10^{15} \cdot (1.04 \cdot 10^{10}) \cdot 10 \cdot 1321 < 10^{30}.$$

With the constraints mentioned above, we start to boldly assume the relationship between N_s and N_p. The most straightforward assumption would be a random distribution, akin to an exponential decay formula resembling a Gaussian distribution:

$$N_s = A \cdot e^{-\frac{(N_p)^2}{2\sigma^2}}. \qquad (3)$$

The parameter A represents the amplitude of the distribution and σ is the standard deviation of the distribution. Interestingly, with a reasonable σ, if N_p takes the lower limit (10^{24}), N_s will almost approach zero. This clearly contradicts reality because there is at least one Earth-like planet in the universe (where $N_s \geq 1$). Therefore, we can immediately dismiss the possibility of a random or any other exponential distribution.

In the field of network science (Newman, 2013; Siegenfeld & Bar-Yam, 2020), there has been a highly popular power-law distribution, where the degree distribution of network nodes exhibits the scale-free feature. Due to this feature, such network architectures are typically quite robust. Therefore, we can assume that the $N_s - N_p$ curve follows a shifted power-law relationship:

$$N_s = A \cdot \left(N_p + 1\right)^{-k}, \qquad (4)$$

The shifted constant is merely introduced to prevent divergence of the function in the absence of life (where $N_p = 0$). The other two parameters, A and k, can be determined based on the two conditions:

a. The area under the $N_s - N_p$ curve must equal the total number of stars in the Milky Way or the observable universe. This condition uniquely determines A;

b. Based on the upper and lower limits of the total number of connections between perceptrons ($10^{24} < N_p < 10^{30}$), we can obtain:

- Upper limit: $If\ N_p = 10^{30}\ and\ N_s < 0.5$ (rounding to 1), $then\ k > 0.148$,
- Lower limit: $If\ N_p = 10^{24}\ and\ N_s > 0.5$ (rounding to 1), $then\ k < 0.184$

The two limits of the exponent k determine the plausible range for the existence of intelligent civilizations. Finally, according to this range, we can determine the total number of star systems in the galaxy that might host intelligent life. In the next section, the estimated results are examined.

4. Discussion and conclusion

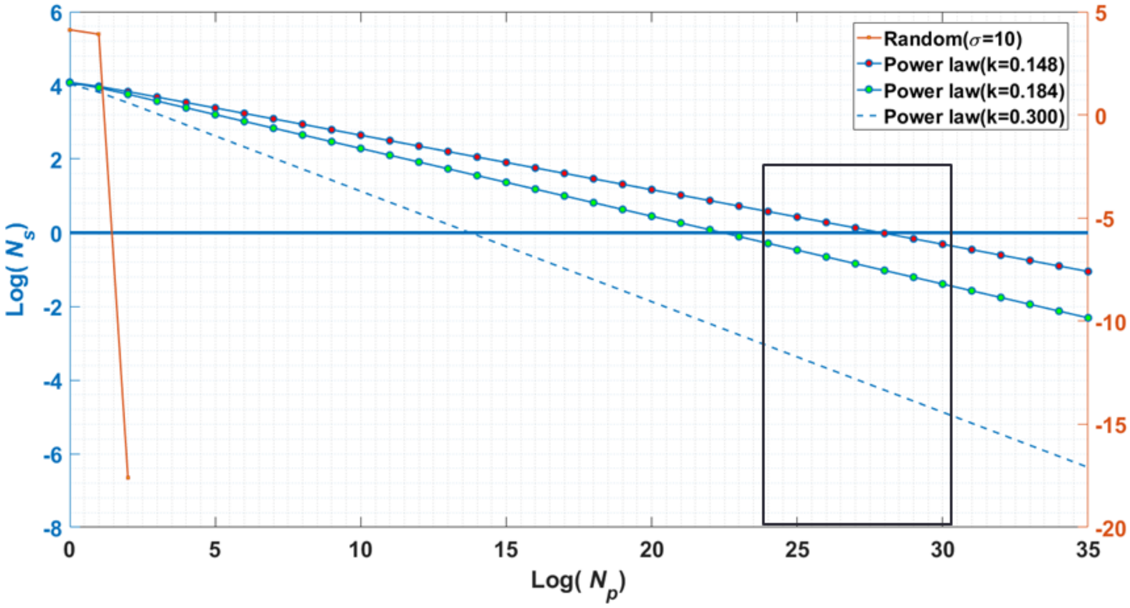

Fig.1 The plot of $\log(N_s)\ vs\ \log(N_p)$ for the Milky Way. Using a log-log plot (base 10), we show a random distribution (in orange and displayed on the right axis) alongside power-law distributions for various scenarios (in blue and shown on the left axis). The dashed line represents an unrealistic power-law distribution, while the red and green dots respectively indicate the upper and lower limits of a reasonable range ($10^{24} < N_p < 10^{30}$, outlined in the black box) for the power-law distribution. The blue horizontal line means $N_s = 1$.

In Fig.1, it is evident that the random distribution does not align with the circumstances of Earth as discussed before, which can be disregarded. The power-law distribution uses the upper and lower limits of N_p to determine the range of the exponent ($0.148 < k < 0.184$). The smaller k values, the closer alignment of the line to the horizontal axis. The blue horizontal line at $N_s = 1$ is marked in Fig.1 to aid in observing how the line spans a reasonable interval. Subsequently, by calculating the area under the red-dot blue line (representing the upper limit of N_p) within the black box, we derive $N_s = 10$ (rounding to the nearest integer, approximately 9.6). This suggests that in the Milky Way, there should be around 10 star systems hosting civilizations equal to or more intelligent than human civilization. This result is all estimated based on the 6 facts (A-F) mentioned previously, and therefore the number should not deviate beyond an order of magnitude from adjusting the upper and lower limits of N_p, leading to $N_s = 7\sim14$. Hence, it is plausible to believe that out of the 400 billion stars in our galaxy, only 10 stars might host intelligent life forms.

This outcome is astonishing since the recent work (Westby & Conselice, 2020) managed to arrive at a result within the same order of magnitude after considering numerous factors that were not accounted for in our work. The reference concluded that there should be at least 36^{+175}_{-32} intelligent civilizations in the Milky Way. The convergence of such closely aligned results from two independently calculations support the belief that the degree distribution of intelligent civilizations in the Milky Way may also exhibit a scale-free characteristic commonly observed in network science.

Taking a closer look, the chance of encountering intelligent extraterrestrial life within the Milky Way is only about one in 400 billion ($2.4 \cdot 10^{-11}$). It is crucial to note that this estimation involves calculating the ratio of star systems hosting intelligent life to the total number of star systems in the entire galaxy, which represents the so-called a priori probability. According to Bayes' theorem (that posterior probability is equal to standard likelihood times priori probability), the probability of encountering intelligent extraterrestrial species (posterior probability) should be further multiplied by the standard likelihood. Similarly to Equ.1, however, the standard likelihood undoubtedly correlates with the technological level of these intelligent beings and thus should be probability (≤ 1) as well. Hence, in this context, the highest likelihood of occurrence is considered, setting the standard likelihood to 1.

For reference, in the United States, the odds of winning the Powerball lottery and getting struck by lightning each year are approximately $3.4 \cdot 10^{-9}$ (Florida Lottery) and $6.6 \cdot 10^{-7}$ (National Lightning Safety Council), respectively. As a result, the chance of encountering intelligent extraterrestrial species in the Milky Way is remarkably low but not entirely zero. It appears that the Fermi Paradox is a paradox that can be mathematically understood; perhaps Fermi and his colleagues simply were not fortunate enough because of the hidden scale-free characteristic.

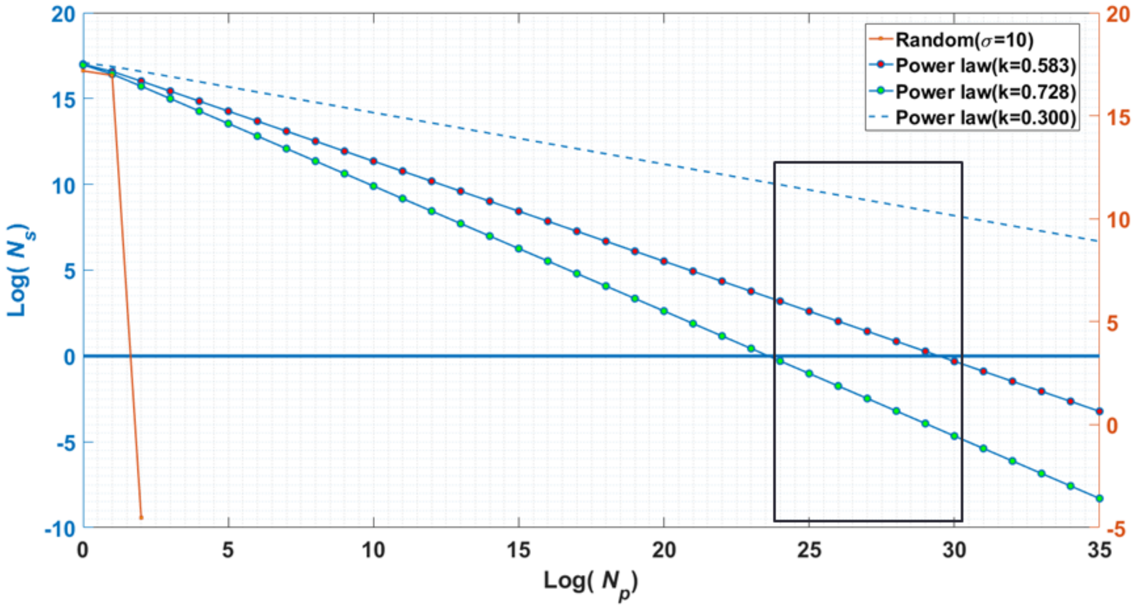

Fig.2 The plot of $\log(N_s)$ vs $\log(N_p)$ for the observable universe. The content is similar to that depicted in Fig. 1.

Fig.2 considers the observable universe hosting stars that exceed the stellar count of the Milky Way by 13 orders of magnitude (Fact G). Adhering to the previous calculations, when the parameter A increases, the range of the exponent k must also increase ($0.583 < k < 0.728$) to encompass the upper and lower limits demanded by N_p (the range within the black box). Consequently, this calculation allows for as many as 1145 intelligent civilizations in the observable universe. Although N_s has increased by two orders of magnitude, the likelihood of encountering them ($2.5 \cdot 10^{-22}$) is even much lower than within the Milky Way ($2.4 \cdot 10^{-11}$). Enlarging the scope to the observable universe, this framework still addresses the Fermi Paradox.

Lastly, boldly assuming that the total number of stars in the entire universe could reach 10^{50}, the range of the exponent k would extend to $1.428 < k < 1.784$. Although the number of the star systems hosting intelligent civilizations could amount to $5.45 \cdot 10^{7}$, the likelihood of the encounter plunges to $5.5 \cdot 10^{-43}$, that is still a significantly lower probability. Therefore, it is reasonable to speculate that if the number of stars in the universe approaches infinity, the likelihood of Earth encountering intelligent civilizations will take a limit of zero, which means it is impossible to see them and effectively addressing Fermi's question once again. What is particularly remarkable here is: the only assumption of this theory is that the number of star systems in the universe will follow a power-law (scale-free) degree distribution of the number of the connections between perceptrons (the units of intelligent life). As long as the relationship between N_s and N_p adheres to the power-law distribution with a range of N_p, this method can essentially compute the likelihood of encountering other intelligent civilizations under various scenarios.

Another noteworthy consideration is: what if we specifically demand a very small number of stars in the system, such as only 10 (which must include our solar system)? In this scenario, requiring the total area under the $N_s - N_p$ curve to equal 10 means that N_s closing to the lower limit of N_p would be less than 1. This contradicts empirical experience and fails to meet the restriction that includes our solar system (where $N_s \geq 1$). Additionally, if there were only 10 stars, attempting to fill the infinite possible values of N_p on the horizontal axis in Fig.1 and Fig.2 would result in the plot with discontinuous points. This situation could not form a continuous power-law curve. Therefore, in this paper, we only consider scenarios where the total number of stars in the system is greater than 10^{8} (which would host 4 intelligent civilizations and yet the likelihood of an encounter is only $3.6 \cdot 10^{-8}$).

Next, let us discuss the habitable planet problem within Equ.1. According to the report from the European Southern Observatory, the estimated age of the Milky Way is about 13.6 billion years ($1.36 \cdot 10^{10}$ years) (Legassick, 2015), nearly as old as the observable universe. Astronomers, in the study conducted in 2004 using the Very Large Telescope Ultraviolet Visual Echelle Spectrograph, discovered beryllium within two stars of the globular cluster NGC6397. This discovery pushed the transition time between first and second-generation stars ahead by 200 to 300 million years, estimating the age of the globular cluster to be about 13.4 billion years. Using the current age of Earth at 4.5 billion years as a reference and subtracting this from the age of the formation of the first stars in the Milky Way (13.4 - 4.5 = 8.9), approximately two-thirds of the time could allow for the development of intelligent civilizations. We further assume another 20 million years of development on Earth to reach a Type II civilization (Kardashev, 1964). Hence, out of 10 star systems where intelligent civilizations might be encountered, only about 7 ($\approx 10 \cdot 2/3$) species of Type II civilizations could potentially exist within the age of the Milky Way. However, these 7 species could only exist within their respective star systems and not transition to a Type III civilization yet. To make contact with humanity, a Type III civilization is necessary. Yet, the total number of star systems possessing a Type III civilization should be significantly less than 7, indicating that encountering them at present would be extremely challenging. It is not just low probability, but it is also plausible that not even a single planet has completed its development, similar to some undeveloped tribes existing while our Earth's cities have progressed.

Of course, the above simple estimation does not account for the effect of the extinction of intelligent civilizations over time. It is possible that in the ancient history of the universe, there were not merely 10 intelligent civilizations in the galaxy. In other words, before the emergence of humanity, thousands of intelligent civilizations may have already visited Earth, rendering the Fermi Paradox irrelevant. This possibility has been brought back into focus by recent observations of unusual light dipping and dimming patterns from many stars (Boyajian et al., 2016; Schmidt, 2019), which suggest the potential existence of Dyson spheres (Dyson, 1960) associated with Type II civilizations. Nevertheless, regarding the timing of the emergence and extinction of intelligent civilizations in the universe, we can utilize the stochastic nature of the Monte Carlo method to simulate the number of connections between perceptrons (e.g. $N_p(t)$) corresponding to the number of star systems (e.g. $N_s(t)$) hosting intelligent civilizations at each point *t* in time. Ultimately, under the condition that the $N_s - N_p$ curve satisfies a power-law relationship shown in Equ.4, there is an opportunity to determine the timing of the emergence of intelligent civilizations by the Monte Carlo optimization. This could provide a different approach for future research on the duration of intelligent civilizations in the universe.

In summary, the main conclusions in this paper are twofold: (1) Hypothesizing that the development of intelligent civilizations among cosmic stellar populations exhibits characteristics without scale, we estimated the number of stars in the Milky Way and the observable universe that harbor intelligent extraterrestrial species. We found that there are only 10 intelligent civilizations in the Milky Way, a number consistent in orders of magnitude with the results in the reference (Westby & Conselice, 2020), indirectly supporting the assumption of scale-free characteristics in the observable universe. (2) Expanding this assumption to the entire universe, we can deduce that the chances of humans encountering intelligent extraterrestrial civilizations approach zero, indirectly explaining the Fermi Paradox. Though the conclusion may not be surprising, the simple mathematics with the scale-free property hint at the fundamental physical nature of the universe. While the search for intelligent extraterrestrial civilizations has long been a goal for humanity, understanding why we have yet to encounter them and whether there are deeper implications to provide some guidance for future searching methods.

It is worth noting that a more cautious explanation, as mentioned in the literature (Gallup & Faliveno, 2022), is that the intelligent life comparable to human intelligence is extremely rare (Mayr, 1995), which aligns with the conclusion in our work. A possible reason is that considering the series of steps necessary for the emergence of intelligent life on Earth, the evolutionary transition time needed for intelligence might exceed the habitable period of many planets (Snyder-Beattie et al., 2021). However, our study is the first to mathematically demonstrate from the different perspectives of complex network theory that higher intelligence civilizations should be extremely rare in the universe.

Turning to the controversial issues concerning life on Mars, even if we accept that simple multicellular organisms like fungi, algae, and lichens are thriving on Mars and the possibility that life evolved to the level of metazoan invertebrates (Joseph et al. 2023ab), there is no evidence that vertebrates or any higher forms of intelligence life evolved. As per what may resemble wreckage on the surface (Joseph & Schild 2023; Padhy, 2023) these discoveries are yet to be confirmed and not alter the conclusion that intelligent life may be rare in the galaxy.

Returning to Earth, humans are not only inventing new technologies at an astonishing pace that are radically transforming human society, but our species' brains are also continuously evolving. If we cannot imagine the technologies that the most intelligent species on the only known habitable planet might possess in the near future, how can we possibly understand the thoughts of rare intelligent extraterrestrial life that may have surpassed our current capabilities billions of years ago? Understanding them could provide various answers to the Fermi Paradox, however we believe that the answer of "extremely rare intelligent civilizations" itself conceals a deeper mathematical significance in the universe.

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References

Block, H.D. (1962). The Perceptron: A Model for Brain Functioning. I, Rev. Mod. Phys. 34, 123.

Boyajian, T.S., et al. (2016). Planet Hunters IX. KIC 8462852–where's the flux? Monthly Notices of the Royal Astronomical Society, 457(4), 3988-4004.

Drake, F.D. (1961). Project Ozma, Physics Today, 14 (4), 40–46.

Dyson, F.J. (1960). Search for Artificial Stellar Sources of Infrared Radiation, Science, 131 (3414): 1667–1668.

Falk, D. (2022). Implications of Brain Evolution in Cetaceans and Primates for Highly Intelligent Extraterrestrial Life, Journal of Astrobiology, Vol 12, 45-64.

Florida Lottery (https://www.flalottery.com/exptkt/pwrball-odds.pdf).

Forgan, D.H. (2019). Solving Fermi’s Paradox, Cambridge University Press.

Frank, A. & Sullivan, W.T. (2016). A New Empirical Constraint on the Prevalence of Technological Species in the Universe, Astrobiology, Vol.16, 5.

Gallup, G.G. & Faliveno, H.E. (2022). Extraterrestrial Intelligence: A Cognitive Evolutionary Perspective, Journal of Astrobiology, Vol 12, 65-75.

Herculano-Houzel, S. (2009). The human brain in numbers: a linearly scaled-up primate brain, Frontiers in Human Neuroscience, Vol.3, Article 31.

Hu, X., et al. (2021). Model complexity of deep learning: a survey, Knowledge and Information Systems, Vol. 63, 2585–2619.

Joseph, R., Schild, R. (2023). Mars: Humanoids, Bodies, Bones, Skulls, UFOs, UAPs, Spacecraft Wreckage, Journal of Astrophysics and Aerospace Technology 11;14.

Joseph, R., Duvall, D., Schild R. E. (2023a) A Mass Extinction on Mars? Evolution, Oceans, Obliquity, Colliding Worlds and the Magnetic Field Magnetosphere, Journal of Chemical, Biological and Physical Sciences.

Joseph, R. G., Rizzo, R. Gibson, C. H. et al., (2023b) Fossils on Mars: A "Cambrian Explosion" and "Burgess Shale" in the Lake Beds of Gale Crater? Journal of Astrophysics & Aerospace Technology 11:01

Kardashev, N.S. (1964). Transmission of Information by Extraterrestrial Civilizations, Soviet Astronomy, Vol.8, No.2.

Legassick, D. (2015). The Age Distribution of Potential Intelligent Life in the Milky Way, arXiv:1509.02832.

Masetti, M. (2015). How Many Stars in the Milky Way, NASA Blueshift.

Mayr, E. (1995). Can SETI succeed? Not likely, Bioastron News 7, 1995.

National Lightning Safety Council (http://lightningsafetycouncil.org/Odds.pdf).

Newman, M.E.J. (2013). Networks An Introduction, Oxford University Press.

Padhy, P. K. (2023). Is there Evidence of Humanoid Bodies, Bones, Skulls, UFOs, UAPs, Spacecraft Wreckage on Mars? Journal of Astrobiology, Vol 14, 47-49.

Prantzos, N. (2020). A probabilistic analysis of the Fermi paradox in terms of the Drake formula the role of the L factor, MNRAS, 493, 3464-3472.

Raman, D.V., et al. (2019). Fundamental bounds on learning performance in neural circuits, PNAS, Vol.116, no.21, 10537–10546.

Schlaufman, K.C. (2018). Evidence of an Upper Bound on the Masses of Planets and Its Implications for Giant Planet Formation, The Astrophysical Journal, 853:37.

Schmidt, E.G. (2019). A Search for Analogs of KIC 8462852 (Boyajian's Star): A Proof of Concept and the First Candidates, The Astrophysical Journal Letters, 880(1), L7.

Siegenfeld, A.F. & Bar-Yam, Y. (2020). An Introduction to Complex Systems Science and Its Applications, Hindawi Complexity, Vol.2020, 6105872.

Snyder-Beattie, A.E. et al. (2021). The timing of evolutionary transitions suggests intelligent life is rare, Astrobiology, 21:265-278.

Traversa-Tejero, I.P. (2021). Estimation of the Population of Stars in the Universe, Open Access Library Journal, Vol.8, No.12.

United Nations Population Division (https://www.un.org/development/desa/pd).

Webb, S. (2015). If the universe is teeming with aliens ... Where is everybody? Seventy-five solutions to the Fermi paradox and the problem of extraterrestrial life, Springer Press.

Westby, T. & Conselice, C.J. (2020). The Astrobiological Copernican Weak and Strong Limits for Intelligent Life, The Astrophysical Journal, 896:58.

Williams, D.R. (2021). Jupiter Fact Sheet, NASA.

Worldometer (https://www.worldometers.info).

Zhang, J. (2019). Basic Neural Units of the Brain: Neurons, Synapses and Action Potential, IFM LAB tutorial series 5.