The Fermi Paradox

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Introduction

The multitude of stars in the heavens have long inspired the question, "Are we alone in the cosmos?" Sheer numbers alone indicate at least a chance that some of those star systems harbour life. Given the existence of multiple instances of life it follows from simple reasoning that, if any of those life-forms was able to travel from star to star, the entire Galaxy could be colonised in a matter of a few million years. However, despite the protestations of UFO enthusiasts, we see no concrete evidence of alien life visiting our planet or even the region. This absence of evidence leads to a conclusion that aliens do not exist, contrary to our expectation that they do. This paradox is called the Fermi Paradox and is the subject of this paper.

What is the Fermi Paradox?

Legend has it that, during a 1950 lunch-time discussion on the possibility of extraterrestrial (ET) life, Enrico Fermi, Nobel Laureate and well known player in the Manhattan Project, made a quip to the effect of, "Where is everybody?" [1] Fermi was referring to the the absence of evidence for the teeming masses of ETs that were theorised to exist. Briefly stated, the reasoning is:

> If only a small portion of the stars in the Galaxy supported planets and a small portion of those supported intelligent life then we could have millions or even billions of intelligent lifeforms in the Galaxy. If only a handful of these intelligences with a modest amount of technology decided to colonise nearby stellar systems

> they could achieve it in a time frame of hundreds of years. If such colonies were used as launchpads for further expansion then the entire galaxy could be colonised (exponentially) in a matter of 20 million years. Why then do we not see evidence of ET colonisation around us?

Whether or not this remark was really made by Fermi, or at made at all, is not particularly relevant to the issue being addressed. The key point is valid nonetheless: the seeming paradox between our expectation of ET life and the absence of any concrete evidence of their existence. This paradox has come to be known as the Fermi Paradox.

The reasoning presented above has two underlying assumptions on which it leans heavily:

- Life is not rare.
- Civilisations migrate.

Either assumption provides points on which debate may be entered into. The following sections address these assumptions.

Life is Not Rare

The assumption that life is not rare in our galaxy is implicit in the Fermi Paradox. The belief that ET life was common in the galaxy is long held but until recently little had been done to substantiate this belief. Drake [2] attempted to quantify the problem through what has come to be known as the Drake Equation. Shlkovskii and Sagan [3] expanded Drake's equation into more manageable components. The Drake equation (in the expanded version) and its components are:

$$N = R f_p n_e f_l f_i f_c L$$

where:

- N is the expected number of places in our galaxy at which a technologically capable civilisation exists at present.
- R is the average rate of Sun-like star production in the Galaxy. This an observable quantity and the only factor in this equation that is known with any certainty.

- f_p is the proportion of these stars that are accompanied by planets. The early expectation was that all Sun-like stars will have planets, making this factor 1. However, current searches, by Marcy and Butler and others, indicate that $f_p = 0.1$ is a more defensible value.

- n_e is the proportion of these planets that are suitable for the formation of life. Planets must fall in a habitable zone about their star and be otherwise suitable for life. This a very difficult factor to quantify given our knowledge of only a single example. This discussion will use $n_e = 0.24$ as derived in the HET608 course material [4].

- f_l is the proportion of suitable planets on which life does evolve. This factor is either very small, if mankind is unique, or close to one if life is common. For illustrative purposes I will use $f_l = 0.5$.

- f_i is the proportion of life-bearing planets where intelligence arises. Optimists would assert that several intelligence have evolved on earth and this factor should therefore be close to 1. Pessimists point out that one intelligence has evolved out of some millions of species, and place this factor at 10^{-6}. For illustration I will use $f_i = 0.1$.

- f_c is the fraction of intelligences that develop the ability to communicate beyond their world. We really have nothing on which to base a educated guess about this factor. For illustration I will use $f_c = 0.5$.

- L is the number of years these communications remain detectable. Given the time to evolve life on Earth, the projected life of our Sun, and the extinction history on Earth, estimates of $L \sim 10^7$ are not uncommon.

Using the values presented above and in Table 1 the number of detectable civilisations in our galaxy is $N = 1 \times 0.1 \times 0.24 \times 0.5 \times 0.1 \times 0.5 \times 10^7 = 6000$.

Factor	Value	Ref	Factor	Value	Ref
R	1	[4]	f_p	0.1	[4]
n_e	0.24	[4]	f_l	$10^{-8} \Rightarrow 1$	[4]
f_i	$10^{-6} \Rightarrow 1$	[4]	f_c	$0 \Rightarrow 1$	[4]
L	$70 \Rightarrow 10^7$	[5]			

Table 1: Drake Equation Factors: Typical values.

Using the lowest figures for Table 1 would lead to the conclusion that we are the only civilisation in the Galaxy. However, using even slightly more optimistic figures leads to thousands or even millions of potential communicable civilisations. Drake's own estimates gave a civilisation count of $N = 10000$ [5].

The Drake equation provides a basis upon which both sides of the "Life is not rare" debate can agree. However, that agreement does not extend to the conclusions drawn, and these are diametrically opposed. Using the lowest possible estimates for the factors in the Drake equation leads to the conclusion that life on Earth is unique in the Galaxy. The uniqueness viewpoint is one supported by many religious belief systems, although not in any scientific sense. Nonetheless, widespread belief provides a comfortable historical backdrop against which to draw the conclusion of uniqueness (See Tipler [6]).

Proponents of the uniqueness viewpoint rely, in general, on the n_e, f_l and f_i factors of the equation to nullify the potentially large effects of the L factor. Using our solar system as an example they argue that life has arisen on Earth uniquely.

With an optimistic size for the habitable zone about our Sun, only Venus, Earth, the Moon, and Mars fall inside or nearby. It's hard, to imagine any form of life on the scorchingly hot surface of Venus. We have actually looked on the Moon and Mars and found no forms of life, even microbial, using tests that would surely have succeeded on Earth. Even discarding the concept of a habitable zone does not substantially change the situation. Mercury provides only scorching hot or bitterly cold environments exposed to harsh radiation from the Sun. Amongst the Jovian planets only some of the moons seem like candidates for life searches. Europa and Titan are interesting, but Europa is far more inhospitable that our own Antarctic and both are well outside the habitable zone about our Sun. The moons of the ice giants, Uranus and Neptune, seem even less hospitable. Life on Earth seems, in all likelihood, to be unique out of the tens of candidate bodies in our solar system.

The experiments of Miller and Urey [7] during the 1950s showed that amino acids could be synthesised from a replica of the early Earth atmosphere. However, these researches have been under constant attack from religious standpoints and for numerous statistical reasons. The general thrust of these arguments that the distance between the amino acid production in the experiments and DNA-based, replicating organisms is huge. So, the reasoning goes, the high likelihood of life arising from Miller-Urey type conditions has not been demonstrated and therefore f_l should be assigned a value close to zero.

The existence of life is not a guarantee that intelligence will develop. In minimising the value of f_i only a simple observation is required: of the approximately two million catalogued species on Earth only one has developed intelligence: hence f_i is in the order of 10^{-6}. Estimates of the total species count vary from ten million to one hundred million, serving to drive the factor even lower.

The lifetime (L) factor in the Drake equation is not immune from criticism either. History is littered with the rise and fall of civilisations. With the fall of each civilisation some part of the accumulated knowledge and the achievements of that civilisation are lost. There's no real reason to expect the current technologically capable, and financially sound, civilisations will last longer than earlier counterparts. Further, there's no reason to expect that any successor civilisation will pick up signal transmissions or colonisation practises where the fallen one left off. If that's the case then L is measured in hundreds or at best thousands of years. The other factors in the equation can only serve to reduce the total communicable civilisations.

Colonisation

From the viewpoint of the early twenty-first century the idea of colonising even the closest of neighbouring planets seems far off. Colonisation of other solar systems seems almost unachievable, and the whole galaxy a fantasy. However, it may not be such an utterly unachievable goal as it first seems.

For a simplistic and optimistic example, let's assume that our technology, within the next several hundred years, can devise a spacecraft capable of travelling at 0.5% of the speed of light (about 100 times the speed that Voyager 1 is travelling). At this speed a trip to our nearest neighbourhood star, at 4.3 light-years, would take about 860 years. We then launch missions to each of the nearest stars. Upon arrival in the new star system the crew set about establishing a colony, expanding population, sourcing resources, and building further craft for the leap to further stars. After, let's say 1,000 years, the colony can mount missions to their nearest stars. This pattern is repeated, with each successive generation reaching more stars. For example, assuming four missions from each launch point the second generation would colonise 16 star systems, the third would colonise a further 64, and so on. The total number of colonised star systems after n generations can therefore be calculated as:

$$N(n) = \sum_{0}^{n} 4^n$$

A little calculation shows that after just 10 generations a million star systems could be populated. A billion star systems would take only 15 generations, and 100 billion only 23 or 24 generations. With each generation taking just shy of 2,000 years, the entire galaxy could be populated in just 48,000 years.

Taking a less optimistic viewpoint we could still expect the Galaxy to be completely populated on a timescale measured in millions of years. Allowing

50,000 years for each generation, and only two outgoing colonies from each launch point, we'd require 36 generations or 1,800,000 years for 100 billion colonies. Even using current rates of travel, say 17 kilometres per second, which makes the trip to Alpha Centauri about 80000 years the calculation is still measured in millions of years.

Accompanying any technology capable of interstellar transport is likely to be a very accomplished computation technology. Such a technology could include automatons capable of self-replication with something resembling human-level intelligence. Machines of this nature, as proposed by Tipler [8] and often referred to as von Neumann machines, could be dispatched as proxies for biological colonists and remove several of the problems facing manned colonisation. A machine could remain dormant for much of the journey and requires little life support. Machines do not breed and therefore resource usage does not climb as it would with a living biological crew.

Opponents of the premise that civilisation with colonise nearby worlds argue that colonisation is not the natural consequence of the development of intelligence, or that other factors act to limit such colonisation. This section deals with the key objections.

From our point of view the journey to our nearest stellar neighbour is technologically challenging. There would be many, many obstacles to overcome before such an undertaking could be made. Some of these challenges are:

- Providing propulsion for travel at even a modest fraction of the speed of light. Current chemical mechanisms can manage in the vicinity of 0.01% if pushed to the limits. Hart [9] calculates that to accelerate to $0.1c$ and decelerate on arrival using nuclear fusion as a fuel source would require the craft to leave with approximately ten times its payload mass in fuel. Given the abundance of hydrogen this fuel is not exceptionally difficult to source and it can be supplemented by various means to reduce departure weight. Other possibilities involve the use of solar sails during the early and late flight stages.

- For manned missions, providing a self-sustaining environment that is capable of supporting many generations of human life. Aspects that must be addressed include; life support, waste management, radiation protection, genetic variance in the crew to avoid inbreeding problems, ability to sustain population size and balance during flight etc. It may be simply impossible to ensure the stability of biological systems in the face of the hostile radiation environment and lack of the many environmental features that allowed terrestrial life to evolve. Further, the long-term mental health of the crew and their offspring may be hard to guarantee.

- For unmanned missions, devising robotic systems that are self-healing and able to autonomously function. These systems must be able to find suitable material with which to replicate themselves. The replication must be perfect or the risk of producing dysfunctional colonising craft increases. As with biological systems there may be some fundamental limit to the accuracy with which reproduction can occur over many generations

Any of these technological challenges provides many stumbling blocks to the success of such a mission. The failure to provide adequately for any contingency will most likely lead to the failure of the mission therefore, the argument goes, the probability of success on a technological front is very slim.

The sheer cost of mounting a mission to the nearest star is a factor running against the possibility that any civilisation will undertake the journey. The manned missions to the Moon cost many billions of dollars, absorbed a substantial portion of a nation's resources, and carried three men a mere million kilometres or so. The massive craft required to send a manned mission to the nearest star would cost an immense amount just to build. A manned craft would by necessity be a massive construct and therefore require a commensurately large investment in energy to accelerate it to a significant portion of the speed of light. Such an immense investment may, like the Apollo programme, suffer from a crisis of funding when the political climate or other circumstances change.

If the presence of large number of other civilisations and the inevitability of colonisation is accepted then the absence of evidence must be explained. Many arguments can be put forward to explain the lack of evidence we have of any colonising intelligence. Hart [9] divides these arguments into four categories: physical, sociological, temporal, and a category for those claiming the Earth *has* been visited. A selection of these arguments are:

- *Physical Reasons.* In this category fall all the physical reasons that a civilisation would not have made it here. Astronomical reasons such as the radiation hazards and distance, technological hurdles, exhaustion of local resources, or biological difficulties are good examples.

- *Sociological Reasons.* This is clearly the largest category of reasons for the absence of alien visitors to Earth. Any, all, or none of these reasons may be valid and there's essentially no way to quantify the likelihood of any.

The possibility that no civilisation has had sufficient motivation to warrant the jump off their home world is a commonly given sociological reason. If home world resources are such that migration is not essential to survival then a civilisation may choose not to migrate. Other civilisations may choose a purely agrarian lifestyle and have no need of space travel.

Perhaps to a colonising force our solar system is simply not an attractive target. A resource hunting coloniser may choose to ignore Earth in favour of a system with more numerous terrestrial planets. Alternatively, a potential coloniser may view our solar system as simply too uninteresting or backward in terms of civilisation.

If the Galaxy is already largely colonised then they may well be overarching government or policy that forbids colonisation of worlds that already support life. An extension of this logic can lead to what has been dubbed the "Zoo Hypothesis" in which select planets, including Earth, are left alone on ecological grounds or because they have yet to reach sufficient technological or social maturity.

Some argue that civilisations provide sufficient buffer to prevent expanding aggressive colonisation from passing through them. The exponential growth required for the fastest possible colonisation of the Galaxy requires unfettered access to the 'next' star system. However, if the prime planets in such star systems are already occupied then there may be substantial resistance to expansionist neighbours settling in, or passing through, the solar system. This certainly would be the response of earth-bound governments to any attempt by an ET to colonise Earth and therefore seems a reasonable thing for an ET to do.

Civilisations self-destruct before achievement of interstellar travel. The so-called "Self Destruction Hypothesis" makes the assumption that, shortly after developing nuclear capabilities, civilisations exterminate themselves. Underlying this position is the assumption that intelligences will behave as we have: a potentially flawed viewpoint.

- *Temporal Reasons.* Perhaps we are the oldest civilisation in the Galaxy and therefore precede the general wave of galactic colonisation. If the premise that millions of civilisations exist now is accepted then the odds that we are the oldest are very slim indeed. A civilisation that evolved a mere one percent faster than homo sapiens will have arisen some 45 million years ago if their star was formed at the same time as ours. Given that generations of stars have come and gone before ours it seems likely that other civilisations are much older than ours.

- "They Are Here" Reasons. If mankind is already the result of a colonisation effort then we may not see any further contact. In support of this viewpoint is the appearance of advanced societies, with elements in common, in disparate parts of the world. The continuous evidence of human evolution across the globe, and the absence of technologically advanced artifacts in the archaeological record weigh heavily against this possibility. Why, after all, would you travel across the Galaxy to live like a stone age hunter?

  Current scans of the solar system are unable to routinely detect objects smaller than a a hundred metres or so unless in close proximity to Earth. Our systems are able to detect transmissions from craft such as Pioneer 10 only because we know they are present, what and how they transmit, and how to cooperate to best use the poor signal we get. It seems reasonable,therefore, to expect that we could simply overlook even a swarm of small ET craft moving about in our solar system.

  UFO enthusiasts contend that there is evidence, and some of it substantial, that we are visited by other intelligences. However, few serious scientific minds accept the evidence as presented, preferring to wait for more concrete evidence before accepting this viewpoint. UFO enthusiasts often take this as a sign of governmental conspiracy to suppress knowledge of the visits they *know* are occurring.

A civilisation's ability to achieve goals by communication instead of physical travel provides an interesting potential explanation for the absence of physical evidence of visitation. Scheffer [10] provides an in-depth analysis of this possibility. He argues that the cost and practicality of transmitting the necessary information to construct an artificially intelligent machine are far more palatable than options involving crewed flight or von Neumann machines. Scheffer also outlines a method to bootstrap the process by sending a series of more complex machines to an alien receiver, each capable of building the next, more complex. Each machine is essentially teleported at light-speed. The cost benefits of this scheme are measured in orders of magnitude. Scheffer goes on to conclude that if such a system were used, the Galaxy would most likely be populated with a single civilisation and that eavesdropping for the signals is unlikely to be fruitful. The latter conclusion supports an absence of evidence but also bodes ill for SETI searches.

Summary

The Fermi Paradox relies on the assumptions that life is not rare in our galaxy, and that life will colonise nearby star systems.

The Drake equation is held up by all parties in the debate as a reasonable way to gain an understanding of the extent of life in the Galaxy. However, the conclusions reached using the equation are diametrically opposed: life is common or unique. While the present paucity of information to support assessment of the various factors remains little progress is likely to be made.

Colonisation the entire galaxy in the time frame that's dramatically shorter than the age of the galaxy seems entirely feasible using technology that's not far out of our reach. Colonisation could be biological, mechanical using self-replicating machines, or achieved by effectively teleporting a machine to the destination. How ever colonisation is achieved, life, or the signs of life, could reasonably be expected to be pervasive. We don't see these signs. Some argue that this is because the assumed propensity to colonise is not universal or that a myriad of other reasons prevent the attempt. Others argue that we are simply not looking while a fringe argue that we are actively being deceived.

There is no hard resolution to the paradox at the time of writing. The discovery of a foreign spacecraft in our solar system, or a signal from another stellar system would do a lot to bolster the respective assumptions.

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