Is the apparent absence of extraterrestrial technological civilizations down to the zoo hypothesis or nothing?*

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Abstract
The 'Fermi Paradox' refers to the mismatch between a widely held expectation that advanced technological life should be common in the Universe — recently given impetus by the discovery that other planetary systems are common — and the absence of any evidence for it. In this Perspective, we briefly review attempted solutions to the paradox and conclude that either (i) extraterrestrial technological civilisations are extremely rare (or absent) in the Galaxy; or (ii) that they exist but are deliberately hiding from us, a scenario generally known as the 'Zoo Hypothesis'. In this sense, we propose that the answer to the Fermi Paradox is 'the Zoo Hypothesis or nothing.' We argue that, given a strong commitment to the continued exploration of the Universe, humanity may be able to distinguish between these two alternatives within the next half-century.

How common is technologically advanced life in the Universe? This question has intrigued humanity for centuries, yet, despite great progress in our understanding of both astronomy and biology, we still don't have an answer. What we do know is, however common technologically advanced extraterrestrial intelligence (ETI) may be, we have yet to see any obvious signs of them or their activities. Is this non-observation significant? Can the absence of evidence be construed as evidence of absence? This question is the essence of Enrico Fermi's famous question, "Where is everybody?", asked during a lunch-time conversation at Los Alamos in 1950[1] and now generally known as the Fermi Paradox (for a critique of this term see ref. [2]; for an excellent recent historical discussion, showing that the basic idea long pre-dates Fermi's question, see ref. [3]). Similar questions can also be asked of the failure of the Search for Extraterrestrial Intelligence (SETI) to detect artificial extraterrestrial radio signals, and the lack of evidence of alien engineering or industrial activities (now collectively known as technosignatures[4,5,6]), giving rise to what David Brin called 'The Great Silence'.[7]

As originally formulated, Fermi's question concerned the absence of evidence for ETI on Earth today, although it is now also usually taken to include a lack of evidence for ETI visitations in the geological past. Of course, we wouldn't necessarily know if ETI had visited Earth millions or billions of years ago without detectably interfering with our planet, but we can be sure that Earth has not been colonised by one or more alien

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civilisations because that would have precluded our own evolution. This point remains the central observation (what Michael Hart called ‘Fact A’ in his insightful and influential analysis almost half a century ago[8]) that all proposed answers to Fermi’s question must address. It is important to note that Fermi’s question is only a paradox if the widespread existence of ETI is assumed – if ETI do not exist then there is no paradox, just a straightforward answer to the question. However, the latter possibility seems difficult for many people to accept, in part because it seems like a violation of the ‘Copernican principle’ that we don’t occupy a privileged position in the Universe.[9]

In recent years, Fermi’s question has become more pressing as we have learned that planets are ubiquitous companions of stars. Indeed, to a first approximation, it appears that all stars are probably accompanied by planets of some kind, and something like 30-60% of stars have planets located in circumstellar habitable zones where liquid water may be stable on their surfaces.[10] Thus, it would seem that there are billions of potentially habitable planets in this Galaxy alone – if life is rare in the Universe, it is unlikely to be because of a shortage of planets. Because this observation at first sight appears to strengthen the likelihood that ETI should be common, which would indeed turn Fermi’s question into a paradox, we here first summarise the range of attempted solutions before moving on to discuss reasons why technologically capable ETI might not be common after all.

Proposed solutions to the paradox

Over the years, multiple solutions to Fermi’s question have been proposed (for comprehensive reviews see refs.[7,11,12,13,14]). There is a variety of ways of classifying these solutions (a useful summary of the relationships between them is provided in ref. [15]). Here, we follow Michael Hart[8], who noted that most fall into three distinct categories: physical, temporal and sociological explanations.

The main proposed physical explanation is that interstellar space travel may be impossible, owing to the large distances between stars and the huge energies that would be required to travel between them in a timely manner (requiring velocities of a significant fraction of the speed of light). Hart, rightly in our view, rejected this as plausible solution to the Fermi Paradox because, although difficult from an engineering perspective, sub-relativistic spaceflight is not physically impossible (for reviews see[16,17,18]) and there seems nothing to stop sufficiently advanced ETI civilisations from developing this capability if they had a reason to do so. Note that we don’t here assume that *all* ETI would necessarily embark on a full-scale galactic colonisation programme: as Hart pointed out, there will surely be a spectrum of motivations (indeed, to suggest otherwise would be to fall into the ‘monocultural fallacy’ proposed in ref.[19]). We merely stress that interstellar travel is unlikely to be physically impossible. Note also that not all proposed schemes for interstellar ‘colonisation’ require high velocities – interstellar velocities as low as tens of km/s, already achieved by our own Pioneer, Voyager and New Horizons spacecraft, might be sufficient to spread microorganisms through the Galaxy (so-called directed panspermia[20]). And even if physical interstellar travel were to prove impossible for some currently unknown reason, it wouldn’t explain the absence of SETI detections, or other remotely detectable technosignatures, which can hardly be claimed to be technical impossibilities (although, as discussed below, it is true that current searches for these are far from comprehensive).

Temporal explanations arise from considerations of the age and size of the Galaxy. On the one hand, the great age of the Galaxy, ~13 Gyr[21], implies that the probability of multiple ETI co-existing at the same time is low unless they are very common and/or very long-lived, whereas the size of the Galaxy implies that sparsely distributed ETI may not have had enough time to contact each other. However, although the first of these temporal considerations is a plausible explanation for the lack of SETI detections, neither of them addresses the Fermi Paradox in its strongest form. Given that interstellar travel is not physically impossible, it is easy to show that any ETI civilisation with the desire to do so could visit, and potentially colonise, every habitable planet in the Galaxy on a timescale that is short compared to the age of the Galaxy.[5,22,23] It follows that the first technological civilization with the ability and inclination to do so could have colonized the Galaxy before any competitors evolved.[24] In principle, this could have happened billions of years ago, when the Earth was inhabited solely by micro-organisms and was wide open to interference from outside. However, the unbroken thread of biological evolution on Earth indicates that our planet has not been colonized, or otherwise seriously interfered with, since the first appearance of life on Earth. We note that this key observation is not addressed by models[23,25,26] which indicate that finite colonisation speeds, coupled with finite ETI lifetimes, can result in volumes of the galactic disk, perhaps including the Solar System, that are free from extraterrestrial visitors at any given time. We don't dispute the validity of these models but argue that they are not plausible solutions to the Fermi Paradox, which must consider four billion years of Earth and Galactic history. Of course, had life been deliberately introduced to Earth, for example, through a programme of directed panspermia[20], this act would constitute such interference, but the fact that Earth life appears to have been left to evolve on its own for four billion years since then would still point to the rarity of ETI interactions with our planet.

Sociological solutions to the Fermi Paradox relate to (unknowable) behavioural aspects of ETI. These include suggestions that ETI destroy themselves before they have a chance to make themselves felt on the Galactic stage, that they may be long-lived but have no wish to extend their influence beyond their home worlds, or that they do engage in interstellar exploration but have strong ethical principles against interfering with worlds that are already inhabited. However, all such suggestions have a fundamental flaw: they can only plausibly resolve the Paradox if some combination of them have applied to *all* ETI in the history of the Galaxy, which becomes increasingly implausible with increasing numbers of ETI. Although we know nothing of alien sociology, it seems inevitable that the propensity for self-destruction, interstellar colonisation, etc., must be governed by probability distributions of some kind. The greater the number of ETI that have existed over the history of the Galaxy, the more populated will be the non-self-destructed and/or pro-colonisation wings of these distributions, and it is these ETI that we do not observe. On the other hand, if the numbers of ETI have always been small, these distributions will have been sparsely populated and the non-observation of ETI in their expansionist wings follows naturally. Amri Wandel[27] has recently argued that non-technological life may be so common that ETI might only be interested in visiting planets on which an advanced technology has appeared, and so past visits to Earth during the geological past might not be expected. However, this view again assumes the same motivations for all ETI (surely improbable, as discussed above; note that it also predicts that non-technological life will be common, which will soon be susceptible to observational constraints, discussed below). Thus, the purported sociological solutions are viable if ETI are rare, in which case there may be no paradox to explain, but are weak solutions if ETI are common, leaving the paradox intact!

The Zoo Hypothesis

We suggest here that the most plausible 'sociological' solution to the Fermi Paradox that is consistent with ETI being common, yet not observed, is that they are deliberately hiding from us. This possibility is generally known as the 'Zoo Hypothesis' after the proposal by John Ball[28] that Earth is effectively a zoo maintained by ETI, although the idea was anticipated by Olaf Stapledon in his 1937 science fiction epic *Star Maker* [ref.[29], p.155] and as the 'Prime Directive' in the 1960's *Star Trek* TV series. It also appears to have been Brin's preferred explanation for his 'Great Silence'[7]. Certainly, it seems reasonable to assume that any ETI technically able to traverse interstellar space would be able to remain hidden should they wish to do so. However, like other proposed sociological explanations, the Zoo Hypothesis is also vulnerable to the 'monocultural fallacy'[19]: to explain the Fermi Paradox in a Galaxy where ETI are common, all these different, independently evolved civilisations would need to agree on the same rules for the zoo. Moreover, to account for the apparent non-interference with Earth's biosphere over its history, these rules may have had to remain in place, and to have been adhered to, ever since the first appearance of colonising ETI in the Galaxy, which might be billions of years if ETI are common. Indeed, Stapledon [ref.[29], p.168] anticipated this problem when he noted, from the point of view of a future fictional observer, that "different kinds of races were apt to have different policies for the galaxy."

One way that the Zoo Hypothesis might be reconciled with many independently evolved ETI if the first civilisation to arise in the Galaxy (that is, Ronald Bracewell's 'pre-emptive civilisation[24]) adopted a policy of non-interference with inhabited planets and imposed this culture on all subsequent ETI. Although this strategy may be difficult in practice [30] (at least in absence of speculations regarding faster-than-light communications[31]), it might be helped if the pre-emptive civilisation had appeared relatively recently in Galactic history. Given that the average age of rocky planets in the Galaxy is about 7 billion years[32,33], this possibility may at first sight seem unlikely. But there are aspects of early galactic history (for example, a possibly active galactic nucleus, supernovae and close stellar encounters) that may adversely affect the evolution of life even if planets themselves are already common. Some models of these processes suggest that galactic habitability may have increased significantly only within the last few billion years.[34]Even so, the timescales of cultural evolution (hundreds to thousands of years), and even plausible galactic colonisation timescales (millions of years), are so much shorter than those of galactic evolution that we might still expect multiple technological civilisations to have arisen before our own. For example, it took about 2 billion years until Earth developed an oxygen-rich atmosphere that allowed complex animals to evolve[35,36]. If this were accomplished just 1% faster on some other planet, which could have occurred due to a multitude of biological and geological processes, a technological intelligence could presumably have appeared 20 million years ahead of us.

A major uncertainty involves the motivation of the 'zoo keepers'. If, as Wandel[27] proposes, only technological life is of interest to ETI then we might only have to account for hundreds or thousands of years of non-interference (depending on how far away human technologies might be noticeable[37]). It is easier to envisage that a dominant

ETI would be able enforce its rules over this much shorter time period. Moreover, it is conceivable that they might initiate contact gradually, or choose to do so only after a certain technological (or philosophical?) maturity is achieved by the inmates of the zoo. We acknowledge that some may be tempted to interpret a subset of unidentified aerial phenomena (UAP)[38] as possible indications of such a scenario. However, all such interpretations currently lack any independent supporting evidence, and imply a highly populated Galaxy that is difficult to reconcile with other aspects of the 'Great Silence'.

Why technological ETI might be rare

If we cannot identify plausible solutions to the Fermi Paradox, with the possible exception of the Zoo Hypothesis, it follows that either life itself is uncommon or/and bottlenecks exist between the origin of life and the advent of technology. This dichotomy boils down to the question of whether there is one or more 'Great Filter'[39] that life must traverse to achieve a technological civilisation, and where in the history of life such filters might occur. Given that potentially habitable planets appear to be common, there are three reasons why technological civilisations might nevertheless be rare:

- The origin of life (abiogenesis) might have a very low probability.
- Even if 'simple', unicellular, life is common, the evolution of complex multicellular life might be rare.
- Even if multicellular life is common, the evolution of technologically advanced life might be rare.

We have very little understanding of how common environments suitable for the origin of life may be. We do have good evidence that life was established on Earth within the first few hundred million years (or the first 10-15 percent) of Earth's history. Assuming that life is indigenous to Earth (which is generally assumed but far from certain[20,40]), this timescale may imply that the origin of life occurs rapidly in suitable planetary environments (that is, warm, wet, rocky planets, with abundant volcanism and meteoroid impacts). That such environments are likely to be common in the Universe might imply that life itself is also likely to be common. However, we note that recent Bayesian analyses indicate that the early appearance of life on Earth, and the large number of apparently habitable planets, only set weak constraints on the probability that life should be common in the Universe.[41,42]

Fortunately, the prevalence, or otherwise, of abiogenesis is open to empirical testing, both by searching for independent origins of life in our own Solar System, and through surveys for spectroscopic biosignatures in the atmospheres of planets orbiting nearby stars.[43,44] Prime targets in our Solar System for a second independent origin of life would be early Mars, given its apparent environmental similarity to the early Earth; the sub-surface oceans of the icy moons in the outer Solar System; and Saturn's moon Titan which, despite its vastly different environment, contains all the ingredients that we understand would be needed for life.[45] If we do find a second independent origin of life in our Solar System, or on a planet orbiting another star, then we can conclude that the Great Filter is not located at the origin of life stage and that at least 'simple' life is likely be common in the Universe. Given the rate at which Solar System exploration and exoplanet studies are progressing, it seems plausible that we will have much greater clarity on the rarity, or otherwise, of abiogenesis within the next several decades.

Clearly, if technological life is rare, but abiogenesis is not, then there must be other 'bottlenecks' along the road of biological evolution between the origin of life and the emergence of technological civilisations. One possibility might be the 'Gaian bottlenecks' proposed by Aditya Chopra and Charles Lineweaver[46] who argued that life may fail to take hold on many of the planets on which abiogenesis occurs owing to its inability to maintain a habitable environment in the face of powerful planetary feedback loops. Another possibility might be the rarity of planetary atmospheres with sufficient free oxygen (a partial pressure >18%)[47] to permit controlled combustion which, arguably, may be necessary for the development of an industrial civilisation, even if high levels of intelligence can evolve with lower levels of atmospheric oxygen. It's difficult to know how likely this scenario is, given the complex interactions between life (photosynthesis) and geological processes, which likely control the oxygen concentration on any given planet, but this uncertainty may be open to future observational and theoretical tests.[47]

If life is able to establish itself on a suitable planet, at first sight, there appear to be many potential biological bottlenecks. These include the origin of cells having a eukaryotic level of complexity (including the endosymbiotic incorporation of once free-living microorganisms to form organelles such as mitochondria and chloroplasts), the evolution of complex multicellularity, and the evolution of intelligence and/or consciousness.[35,48,49] In principle, each of these steps might have been low-probability events, with the implication that intelligent multicellular organisms might be rare in the Universe even if life itself is not; this argument was first advanced by the co-discover of natural selection, Alfred Russel Wallace, over a century ago[50]. On the other hand, these transitions appear to have been achieved multiples time in the evolution of life on our planet, often expressed in different phenotypes[51,52,53]. Indeed, we would argue that intelligent life is quite common on our planet, occurring in a wide variety of animals such as octopuses, certain birds (for example, corvids and parrots), apes and cetaceans.

Still, the kind of technologically advanced life represented by humans appears to have only evolved once on Earth (Fig. 1), despite the prior evolution of intelligence in multiple different species. Is there something very special about humans, and, if so, what is it? Perhaps, a rare combination of certain traits such as big brains and high dexterity of the hands. Yet, other anatomical options would seem capable of yielding similar results — consider an octopus, for example, with its highly dexterous tentacles and neurons distributed throughout its body. Although it is true that octopuses, specifically, are aquatic animals, and this environment may militate against the evolution of technological intelligence[47, 54], the broader point about alternative evolutionary possibilities remains valid. Or could there be one single key trait, perhaps related to the development of language and a complex culture (see, for instance, ref.[55])? However this may be, the fact remains that in roughly 4 billion years of life´s history on our planet, we are the only species that evolved technologically advanced intelligence. This observation may suggest that Brandon Carter's conclusion, based on his interpretation of the anthropic principle, still holds: "civilisations comparable with our own are likely to be exceedingly rare (even if locations as favourable as our own are of common occurrence in the Galaxy)."[48] This reasoning would certainly answer Fermi's question, but it would dissolve the 'paradox' because it implies that ETI are rare or non-existent, and have been throughout galactic history. We note that Anders Sandberg et al.[56] and Andrew Snyder-Beattie et al.[57] have come to a similar conclusion by considering uncertainties in the Drake equation and the timing of evolutionary transitions, respectively.

Fig. 1. The only known inhabited planet in the Universe, showing the continent of Africa where the only known technologically advanced species (*Homo sapiens*) arose after a total planet-wide evolutionary history spanning almost 4.6 billion years. One interpretation of the Fermi paradox suggests that such evolutionary histories are rare in the Universe. (Image from Apollo 11/NASA).

Summary and Outlook

Further insights are only likely to come from a systematic exploration of the Universe around us. We should therefore continue the SETI surveys and conduct thorough searches for other technosignatures (including searches for ETI artefacts within the Solar System[58]) because we can only assert an 'absence of evidence' if we have searched for evidence sufficiently hard. In parallel, we should aggressively search for life elsewhere in the Solar System, and for biosignatures in the atmospheres of nearby exoplanets, because such observations have the potential to constrain the prevalence of abiogenesis in the Universe, and possibly also the prevalence of biological complexity and intelligence. If it turns out that extraterrestrial biospheres are rare then ETI will presumably be rarer still (but see ref.[5] for alternative possibilities), strengthening the argument that there is no evidence for them because they don't exist[8,48,56,57,59].

Alternatively, if biospheres, and especially complex biospheres, turn out to be common then technologically advanced life may still be rare if a 'Great Filter' occurs at the transition to technologically advanced life. In the absence of such a late-stage evolutionary filter, the Fermi Paradox would return, arguably leaving the Zoo Hypothesis as the last remaining plausible explanation. However, even this situation is not immune to observational constraints – if ETI are actively hiding from us, they may find it increasingly difficult in the face of our own rapidly increasing capabilities. Even if they can hide evidence of their technology (space probes, communications traffic, and so forth), hiding the large number of inhabited planets in the background implied by such a scenario would probably prove challenging (unless they are able to bring an astonishingly high level of technical sophistication to the task[60]). In any case, advanced technological civilisations may find it difficult to hide the thermodynamic consequences of waste heat production, which is indeed the basis of some current technosignature searches.[19] Moreover, any spacefaring civilisation is likely to generate a great deal of space debris, and the greater the number of ETI that have existed in the history of the Galaxy the greater the quantity of debris that will drift into the Solar System, where a determined search may discover evidence for it.[61]

Thus, the longer we don´t detect any signs of advanced intelligent life around us, the less likely the Zoo Hypothesis becomes as an explanation, forcing us to conclude that technological intelligent life is rare in the Universe. It is in this sense that we propose that the solution to the Fermi Paradox is 'the Zoo Hypothesis or nothing.' Fortunately, by undertaking comprehensive searches for biosignatures and technosignatures, both within the Solar System and beyond, we may have it in our power to distinguish between these possibilities within the next several decades.

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