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RESEARCH ARTICLE

Formalizing the Fermi paradox and combining consistent explanatory hypotheses

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Abstract

A formalization of Fermi paradox inside the environment of classical propositional logic is proposed. The notion of *Silentium Universi set* is launched in order to establish that the Fermi paradox is truly paradoxical. Combining consistent explanatory hypotheses is taken into consideration and discussed inside this framework explaining what would count as a solution to the paradox. By the end, it is argued that Fermi paradox is an unsolvable problem in the domain of science.

Contents

Introduction

This research provides a formal framework in which Fermi paradox can be logically explained and analysed. There are several proposed theories and hypotheses to explain it. For instance, those discussed and compiled by Brin (1983), Webb (2015) and Ćirković (2018). Recently, there are still some brand new explanations and inquiries on the subject. Moreover, related themes and discussions are appearing very often in the domain of astrobiology, given that Fermi paradox is also strongly connected with foundations of theoretical astrobiology and issues concerning extraterrestrial life in general (cf. Döbler 2022 and Szocik and Abylkasymova 2022 just to mention a few examples). So, it deserves to be studied carefully inside a formal framework.

Considering the relevance of Fermi paradox to theoretical astrobiology, it is essential to state and formulate it precisely. Ćirković (2018) presents three possible forms of Fermi paradox (pages 4–10): the protoFP, the weakFP and the strongFP. The protoFP deals with the incompatibility between the non-appearance of extraterrestrials on Earth and all we think they could be able to perform, while the weakFP basically extends protoFP to the Solar System. The strongFP, which is the more general, complete and profound form of Fermi paradox, is stated as follows:

> 'The lack of any intentional activities or manifestations or traces of extraterrestrial civilizations in our past light cone is incompatible with the multiplicity of extraterrestrial civilizations and our conventional assumptions about their capacities.' (Ćirković 2018, p. 10)

The point raised by Ćirković is not only that we do not have any evidence of extraterrestrials (or their constructions) on Earth or in the Solar System, but in the whole past light cone of humanity. This is a very general form of the Fermi paradox and it contains weaker forms on it. If extraterrestrial forms of life and intelligence do not exist, this *lack* will persist forever (except if extraterrestrial intelligences develop in our future light cone), and our epistemic ignorance is, in fact, an illusion. But if they do exist, we have an issue on our detectability competence, because we are not able to detect them. It is this strongFP which is taken into consideration in the formal analysis and evaluation suggested in this paper.

The Fermi puzzle is, therefore, a reasoning on detectability and, thus, it is rather related with epistemic limits of human beings, and it is not, necessarily, a question which implies the existence or not of extraterrestrials, as some have suggested. Fermi paradox looks like the most relevant and important open problem concerning the limits of human knowledge, and it seems very far away to be fully understood. This paper is an attempt to formulate the paradox precisely inside the domains of formal logic pointing out its nature and complexity.

The road of this research is the following: first, the language and logic of Fermi paradox are taken into account. In these conditions, a formalization and a deduction of Fermi inference proposed by Freitas (1985) is considered and evaluated as a departure point. Second, further steps connected with the formalization of Fermi inference are exhibited. It is concluded, based on the notion of a *Silentium Universi set*, that the inference is, indeed, paradoxical. Thus, the context of Fermi paradox is clarified in the realm of propositional classical logic. No new solution, explanation or theory is proposed. However, by the end, a case of combination of consistent explanatory hypotheses is contemplated inside this new perspective showing that all we have, up to now, are explanations of the non-detectability of extraterrestrials rather than solutions to the paradox.

The language and logic of Fermi paradox

Let L be a language for classical propositional logic. So, L has a set p, q, r, ... of atomic sentences (i.e. propositional variables) and standard truth-functional operators such as implication $\rightarrow$ and negation $\neg$, and punctuation symbols (i.e. parentheses). In addition, logical consequence $\vdash$ is formulated in the usual way: it is defined between sets of premises and a single and unique conclusion. This inference relation can be a syntactical or a semantical logical consequence. These are sufficient linguistic minimal requirements to reason about the paradox.

The first logical approach to a kind of Fermi paradox has been developed by Freitas (1985). He argues that Fermi paradox is a logical fallacy, and considers two forms of it: the first one is an invalid inference and the second one is worth mentioning in detail. His argument assumes three sentences, and ETI (henceforth) stands for *extraterrestrial intelligences*. Let p be a formalization of 'ETI exist', while q be 'ETI are here' and r a formalization of 'ETI are observed'. Then, he presents the following inference as Fermi paradox (cf. Freitas (1985), p. 518):

(1) *If p, then (probably q).*
(2) *If (probably q), then (probably r).*
(3) *Not-(probably r).*
(4) *Therefore, not-(probably q).*
(5) *Therefore, not-p.*

Notice that the concept of *probability* is used uniformly for q and r. So, q would represent, with the same logical effect, 'probably q' and *mutatis mutandis* for r. It is thus irrelevant for the logical form of the argument occurrences of q or *probably* q (the same for r), and then only classical propositional logic is used. Departing from the set of premises

$$\{p \rightarrow q, q \rightarrow r, \neg r\}$$

Freitas shows that it is possible to conclude, first, $\neg q$ and, then, this sentence can be used to conclude $\neg p$. We know that this reasoning is classically valid and it is based in two applications of a truth-

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preserving rule called *modus tollens*. This argument is always valid, assuming the truth of the premises. The question of whether the premises are really true goes beyond the scope of logic, and Freitas argues that the inference is invalid taking into account that (3) has an indeterminate truth-value. But the argument above is valid, and if premises of the set $\{p \to q,\ q \to r,\ \neg r\}$ are true, then it follows, necessarily, $\neg p$. So, Freitas rejects the Great Silence based on the fact that he considers Fermi paradox as an invalid inference which shows that there are no ETI, but this is not what Fermi paradox is.

Robert Gray pointed out in Gray (2015) that the argument deducing that ETI do not exist because they are not detectable should be called Hart–Tipler argument, not Fermi paradox. According to Gray, the idea that Fermi paradox is an argument denying the existence of ETI has its origin in the work of Hart (1975) and has been improved by Tipler (1980). Notice, however, that Hart–Tipler argument (or Rare Earth arguments in general) should not be confused with Fermi paradox. Collapsing both concepts and arguments in a kind of straw man fallacy, Gray also states that Fermi paradox is not a paradox, but only a 'question about the feasibility of interstellar travel' (cf. Gray (2015), p. 197). A clear diagnosis of this inadequate approach has been sustained and well explained by Ćirković (2016).

Fermi paradox conceived as an inference rejecting existence of ETI is not an appropriate interpretation, given that the paradox is not ontological, but epistemic. Fermi paradox has nothing to do with proving sentences of the form $\neg p$. As a consequence, it is straightforward that the above argument suggested by Freitas is not a formalization of Fermi paradox. It is, instead, an argument concluding that ETI do not exist. So, in the form above, it can be viewed as a formalization of a solution to Fermi paradox, not as a formalization of the Fermi paradox itself. Ćirković shows in Ćirković (2018) that these referrals do not respect a very important philosophical option we should adopt while explaining the Fermi paradox, as this kind of approach to the paradox can be included in those Rare Earth arguments trying to prove that ETI do not exist and, as such, it violates Copernicanism (i.e. the assumption of mediocrity suggested by Shklovskii and Sagan (1966)).

The language L of classical propositional logic is enough to formulate Fermi paradox and there is not only one possible formalization of the argument. We could enrich our language to formalize different aspects of the paradox. For instance, in a combined modal epistemic logic with the knowledge operator K interpreted as *detection*, the so-called verification principle could be read as 'If ETI exist, then it is possible to detect that ETI exist' and from this it would follow, as a consequence of Fitch's knowability paradox (cf. in Salerno (2009) for a survey on Fitch's inference), that 'If ETI exist, then it is detected that ETI exist'. So, Fermi paradox could be read and studied inside the frontiers of Fitch's deduction. However, for now, as we do prefer Occam's Razor, dealing with only basic classical propositional logic is more than enough.

The *Silentium Universi set* and its paradoxical content

The concept of *detection* is epistemic: it deals with our ability to know something, our ability to recognize something as existent. To detect something is a guarantee that the object of detection do really exists according to some possible empirical or scientific explanation, and there is also a difference between detection and detectability. While detection means the current act of detection, detectability means the possibility of detection (these two notions appear very often on studies concerning Fermi paradox, and Ćirković (2018) argues (p. 17) that we should enlarge our comprehension of *detectability* to better reason about the Great Silence). Possibility here should be understood as what is logically possible and not simply empirically possible: something is logically possible with respect to a given logic if and only if it is consistent or compatible with a given underlying logic. So, there would be, at least, two distinct forms of Fermi paradox depending on our choice to formulate it using the notion of *detection* or *detectability*. Let's consider the paradox for the more general case of detectability: if something is detected, then it is detectable, while it can be detectable without being actually detected.

In order to provide an structural analysis of Fermi paradox by means of formal logic, now, let p be a formalization of 'ETI exist' and q be a formalization of 'ETI are detectable'. The expected inference is given by

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(1*) If p, then q.
(2*) p.
(3*) Therefore, q.

In natural language, the argument is the following: 'If ETI exist, then they are detectable. They exist. Thus, they are detectable'. This is a regular truth-preserving valid inference in classical propositional logic called *modus ponens*. This well-known logical inference preserves truth: assuming both premises as true, it follows necessarily that the conclusion is true. True premises imply a true conclusion. This is the essence of logical inference. What is expected concerning ETI is that they should be detectable – because their existence is highly probable – but they are not. So, the paradox gets stronger especially because the two considered premises are very plausible and seem to be true. It is supposed that the existence of ETI is concrete, plausible and real. For this reason, we expect that they should be not merely detectable but, in fact, detected.

Premisse (1*) states that 'If ETI exist, then they are detectable'. This is, indeed, a particular instance of a more general hybrid metaphysical and epistemic law according to which 'if an object o exists, then o is detectable'. It is clear that one could find many counterexamples to (1*), formulated for ETI or for general objects, because it is trivially true that something can exist without being detected. There are naturally non-detectable black holes, exoplanets, galaxies and other astronomical objects which certainly exist though they are not detected. However, given the high probability of truth of (2*), (1*) becomes interesting in the case of ETI. If we accept Copernicanism, the pattern we find on Earth and in the Solar System should appear everywhere in the universe, and so ETI should be very common. Therefore, they should be easily detected (or detectable).

Premise (2*) is contentious, despite Copernicanism and the fact that there are many arguments which can be used to state that (2*) is true: The size and the age of the universe (it is too large and too old, at least from our perspective), the development of life on Earth which leaded to a technological civilization, the Drake equation (with reasonable parameters) could be mentioned as a non-exhaustive list favouring the truth of (2*). So, the sentence 'ETI exist' is here taken as sentence with precise truth-value (i.e. truth), considering that it is highly probable, but notice that this probability is not captured by the formalization. Nonetheless, there are those who argue that (2*) is a false sentence. Rare Earth arguments deny the truth of (2*) and conclude that ETI do not exist, but this kind of argument does not affect the formal analysis, as the falsitity of p can be viewed only as a solution to Fermi paradox, not as the Fermi paradox itself.

Combining premises (1*) and (2*) generates a somewhat paradoxical situation because q is not the case (i.e. q is false assuming they are not currently detected). So, it holds $\neg q$. Given premises (1*) and (2*), we expect q (we had expected their easy detectability), but what we do have is $\neg q$. In this precise sense, the following set of propositions

$$F = \{p \to q, p, \neg q\}$$

leads to a contradiction using classical propositional reasoning. Let's call a given set X a *Silentium Universi set* if and only if it contains sentences about extraterrestrial intelligence (or life) and it leads to an inconsistency or contradiction. So, the set F above is a *Silentium Universi set* and it has as consequence a set of contradictory propositions:

$$\{q, \neg q\}$$

which means that ETI are detectable but they are not, in fact, detected (i.e. detectable). This is precisely what Fermi paradox is. The set $\{q, \neg q\}$ contains a contradiction. It is an inconsistent and paradoxical set, assuming premises (1*) and (2*) as true statements. So, a *Silentium Universi set* is any set on ETI which implicitly contains a contradiction. In this way, from a *Silentium Universi set* a contradictory situation can be derived.

Consistent explanatory hypotheses

In the current framework, it does not count as a solution to the Fermi paradox explanations of the reason why there is a situation of non-detection (or non-detectability), because only explaining the non-detection would still allow room for the contradiction and the contradictory set would still be derived. In this sense, for example, one could mention explanations of the paradox such as the Zoo Hypothesis proposed by Ball (1973) and the Transcension Hypothesis of John Smart introduced in Smart (2012). Though they are pretty good explanations for the entire situation, they are not properly solutions, because nothing is changed in the *Silentium Universi* set. A solution to the Fermi paradox should eliminate the contradictory context raised by forms of the *Silentium Universi* set. Only explaining the situation of non-detectability is not enough to guarantee a solution. Paradoxes are solved whenever we have a counterexample showing a new environment in which we have true premises, and a false conclusion.

Fermi paradox can be thought as an inconvenient contradiction raised by types of *Silentium Universi* set. A genuine solution should provide reasons to eliminate some sentence from the *Silentium Universi* set. In this category, Rare Earth solutions such as those initially advanced by Hart (1975) would figure as truly solutions, but they have the insurmountable gap concerning the main argument: it is not possible to prove (with certainty) that something (i.e. ETI) does not exist, given that it is impossible to go through the totality of the universe and show that there are no ETI. It seems, therefore, there are only two possible routes to solve Fermi paradox: or to show that ETI do not exist (which is impossible) or to provide a way to detect them, in fact, detecting them. So, if it would be possible to show that ETI do not exist, then a sentence of the form p would be deleted from the set and the contradiction would be eliminated. Otherwise, if we detect them, then a sentence of the form $\neg q$ would disapper and then the inconsistency would be dissolved. Therefore, if for some reason, ETI are not detected, we will have to live with the inconvenience of the *Silentium Universi* set and, thus, the Fermi paradox persists.

Let's illustrate the above analysis with some examples which can be found in the literature on the Fermi paradox (cf. Ćirković (2018) for a detailed exposition and reflection on the explanatory hypotheses considered below). Suppose a situation in which two proposed explanations to the Fermi paradox are consistent with a plausible working hypothesis (H*) according to which *there are supercivilizations* in the sense of Kardashev (1964) and Kardashev (1985). A supercivilization (or a Kardashev type III civilization in the regular scale) is a civilization able to operate, manage and control technologically, at least, the environment of a whole galaxy. By the way, this kind of civilization would have enough technology to perform transformations in the physical structure of reality. These supercivilizations can have other forms of intelligence and other types of manifestation: they could have deep, substantial and old technology in order to overcome what is physical. If this occurs, then they would not be detectable and, therefore, it is meaningless to argue that there is no supercivilization in our Galaxy or in the universe in general. So, let's take into account two explanatory hypotheses.

The first one is the Transcension Hypothesis elaborated by Smart (2012). He states that supercivilizations (i.e. 'sufficiently advanced civilizations') execute a reduction of space, time, energy and matter while enlarging density up to the level where these civilizations go to the inner space or black holes in such a way that they leave the universe and, for this reason, they cannot be detectable (a supercivilization in the context of transcension is more easily adapted and thought inside the realm of a divergent scale such as the Barrow scale established in Barrow (1998)). Smart correctly points out that this hypothesis explains Fermi paradox. If Transcension Conjecture is right, then it provides only an explanation to Fermi paradox, not a solution.

The New Cosmogony Hypothesis, developed by Lem (1999) and widely studied and evaluated by Ćirković (2018), states that supercivilizations are very old and had enough time to develop technological devices that, for us, looks like laws of nature: the technological byproduct of advanced civilizations. So, we confuse both levels given that there is a collapse between what is natural and what is artificial. If the New Cosmogony Conjecture is correct, like Transcension, then it provides only an explanation to Fermi paradox, not a solution.

If these hypotheses are only explanations, not real solutions, we need some extra criteria to check whether they are feasible. One plausible criterion would be that of consistency. Let H_1, ..., H_n be explanatory hypotheses for the Fermi paradox. We say that a hypothesis (H_i) is consistent with a hypothesis (H_j) if and only if

$$H_i \cup H_j \nvdash \perp$$

where $1 \leq i, j \leq n$ and $\perp$ means an inconsistency in a given underlying logic. Consistency here means that it is possible to combine explanations to the Fermi paradox without raising or generating contradictions. In this sense, many explanations are compatible and can coexist.

It seems that Transcension Hypothesis and New Cosmogony are both cases of transcendence and they are consistent with (H*). They are forms of transcendence because, in the case of Transcension, the transcendental aspect is to leave the universe and go towards a new form of reality, while in the case of New Cosmogony there is a transcendence because highly developed civilizations are not recognizable, but they are here, they are displayed by the laws of nature. These two hypotheses require the existence of advanced civilizations, and so they are consistent with (H*). The Zoo Hypothesis (cf. Ball 1973) is also consistent with (H*), and it is also consistent with Transcension and New Cosmogony. Indeed, the Zoo Hypothesis could be easily figured out as a corollary of both, for instance. It is interesting to note these explanations do not solve the Fermi paradox. They are solely theoretical explanations for non-detectability, and the inconsistency deduced from the *Silentium Universi* set is still there.

Differently, Rare Earth hypotheses (cf. Hart 1975; Tipler 1980 and many others), especially those arguing that there is only one intelligence in the universe (i.e. human intelligence), for instance, are not consistent with the existence of supercivilizations (H*). These local consistencies entail an explanation of the paradoxical context of the inference, but in no case one is allowed to say that there are solutions, because the *Silentium Universi* set can still be constructed.

If one now attempts to combine Rare Earth explanations with, let's say, Transcension and New Cosmogony, then a contradiction follows. These hypotheses would not be combinable and, therefore, cannot exist together into a single powerful consistent explanation. Without any detection all we can do is try to find plausible, feasible and consistent explanatory combined hypotheses.

Conclusion

This article showed that Fermi paradox is a problem concerning epistemic capabilities of human intelligence and our detectability competence. In this way, it can be really introduced and presented as a typical paradox containing a form of inconsistency or contradiction. Some analyses of the paradox have been improved by this framework inside classical propositional logic and a formalization of the paradox has been conducted showing in which sense some available hypotheses are solely explanations, and not solutions to the trouble.

Despite the fact that only classical propositional logic has been used, other forms of Fermi paradox could be introduced by means of other languages with enriched expressive powers. This could be done, as a matter of fact, also in the domain of modal logic. If we interpret the notion of *detection* as *knowledge*, then a whole new family of modal logics could be used to reason about Fermi paradox. Moreover, Fermi paradox could also be systematically studied in the domain of probability calculus and probability statements.

Without any kind of detection of ETI, or without any proof that they do not exist (and to provide this evidence seems to be virtually impossible), there is no way to solve Fermi paradox. Then, Fermi inference can be viewed as an unsolvable problem, if there is no detection. This is the case because if there is no detection, then kinds of *Silentium Universi* sets can always be generated, no matter how good these explanations are: they are only hypotheses explaining why the non-detection situation occurs.

The unique way to eliminate Fermi paradox is by means of a pure detection of ETI or by proving that they do no exist. But proving non-existence is not feasible because we cannot sweep and go through the whole universe in order to really realize that there are no ETI around. If our detectability competence does not suffer any substantial transformation over time in order to change in some essential way the content of the *Silentium Universi* set, then, we have to get familiar and accept all the implications of the Fermi paradox.

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