A brief analysis of the Fermi Paradox and the possible consequences on the study of intelligent life in the Milky Way

Author: Alejandro León Pérez*
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Advisor: Alberto Manrique Oliva
(Dated: June 21, 2021)

Abstract: A study on intelligent life in our galaxy is presented. By means of self-replicating probes, an attempt will be made to explain the Fermi Paradox, using random mutations that simulate the existence of a competition between two species: explorers (prey) and predators. We will model an observed and analyzed behavior on planet Earth: the survival of two species through competition between themselves. Furthermore, we will implement our study along a stellar weight graph that simulates the statistical distribution of stars in the Milky Way. Everything seems to indicate that it is highly unlikely that the human species will establish contact with an high technological development extraterrestrial civilization throughout its existence.

I. INTRODUCTION

Why are we unable to detect intelligent life? This question raises two equally complex philosophical questions. On the one hand, can we assume the existence of intelligent life outside of our planet? On the other hand, if these civilizations existed, why cannot we detect them? The following study will try to give a possible answer to the so-called Fermi paradox, in fact we cannot guarantee its uniqueness and so even raising it is completely bold. Trying to pose the study of extraterrestrial life in the Milky Way in a minimally serious way requires generating an open model that encompasses a set of degrees of freedom large enough for the modeling product to have a viable predictive range. To this day, we do not have an answer to these two great questions, not even an hypothesis with which the entire scientific community agrees. There are authors who, starting from the assumption of the existence of intelligent life in the Galaxy, consider that due to the presence of finite resources in their local environment of action, or their depletion, they cannot colonize or explore the Galaxy at an exponential rate: that is why we do not detect them [1]. Other authors firmly deny the hypotheses of intelligent life by means of the Special Earth Hypothesis [2]. Highly speculative hypotheses range from Planetary Zoos to simulations of life, and then we find others less controversial, which expose the existence of a direct relationship between a degree of advanced technological development as a precedent to the self-destruction of civilizations − among them Enrico Fermi [3].

At this point, and presenting the subjectivity on the nature of this study, we will use the following hypothetical framework that will support the motivation for this work.

- If there are a series of favorable conditions, the matter will be able to generate life, by life meaning the similar process observed on planet Earth.
- Life is a constant in this Universe, and therefore, life exists in other planets, at least within the limits of our galactic disk.
- We define Nature as a closed ecosystem constituted by a set of random dynamics that shape populations, environments, interactions and developments of the products and by-products derived from life.
- Since at the first signs of development, the resources to which the products derived from life can have access are limited, they have followed a process parallel to that developed by the species on planet Earth (that of free competition) causing intelligence to be a competitive advantage in the fight to obtain the resources of the system in which it exists.
- Due to the previous statement, different civilizations have been established throughout the galactic disk, and we can find at least one with a technological profile similar or superior to human species.
- A representative percentage of all galactic civilizations tend to seek answers to existential statements, therefore, among their motivations, we find exploration, contact and colonization of other worlds.

Related to the last statement, what is the most efficient way known to the human species for galactic exploration? The proposed answer to this question was motivated by the physicist-mathematician John Von Neumann, through the so-called Self-Replicating Probes. A civilization with sufficient technological degree should be able to generate self-replicating probes (explorers) which, using the local resources of the star system, could self-replicate in order to explore new systems. Neumann's hypotheses propose an exponential growth of explorers so that in less time than the galactic age our species

*Electronic address: alejandroleonperez1@gmail.com

should have had contact with these probes[4]. Since we do not see them, the literature propose other alternatives to this question: they have already visited planet Earth and left, they observe us and live with us but they are not detectable for our species, or they have not yet established contact with our star system.

We will start from the following assumption: a galactic civilization establishes (at least locally) contact with its environment through these probes. As we do not see them, we will assume that the following statements have occurred:

- The explorers have not yet established contact with the human species.
- Due to the above statement, the extraterrestrial civilization is not in a neighborhood of the galactic disk, centered on the Earth and with a radius considerably large.
- Initially, Nature has acted on the population of probes, causing a series of mutations (failures in the programming and configuration of the probes) that ultimately led to the existence of at least 2 sufficiently differentiated species with respect to the initial population[6].
- The hypothesis of life would have originated the competition between both species of probes, originating a population that will act as predators (predator) against a second population whose initial function is interplanetary exploration (prey). Both populations will compete with each other by shaping the behavior of the prey-predator phenomenology observed on Earth.

Starting from this scenario, we will study the dynamics of populations that try to answer why our species is unable to detect products or by-products of intelligent life beyond our planet Earth. We will assume the existence of two populations, which compete with each other for their own evolutionary and population development.

In Section II we will introduce the prey-predator behaviour. Next (Section III), we will develop a model based on stellar distributions in the Milky Way in which we translate the study of populations (Section IV), and following this, we will present a branch of conclusions and results (Section V) extracted from the model.

II. THE PREY-PREDATOR MODEL

The Lotka-Volterra model captures at first order the behavior of two populations that compete for finite resources in Nature: one predator and the other prey. We achieve this modeling by means of three response functions $g = g(P, D)$, $\phi = \phi(P, D)$ and $q = q(P, D)$ which help describe the evolution of populations and whose simplest form is governed by a linear dependency with the variables involved P (prey) and D (predator). In our case, beyond adopting a linearity in the response functions, we will try to model the behavior observed in terrestrial populations.

- There are finite resources with potential for exploitation on given timescales: for a fixed galactic time, a species has only had access to a finite amount of resources.
- Predation (the act observed on planet Earth called hunting) carries a quantized cost of time in searching for and handling prey.
- It is necessary to implement a saturation response in predators, interpreted as a necessary time for recycling materials for the construction of new predators.
- The death of predators is due to failures, impacts, shocks or deterioration in their operation (useful life) so we can express a mortality rate in predators.

Having stated all this, it is proposed to adapt a type II Holling function as a functional response, meaning $f(P, D) = \frac{P\phi(P,D)}{D} = \frac{cP}{a+P}$ (a,c constants explained below) and implies that once the predators are satiated, they do not increase the rate of prey consumption even though their number growths. A saturated dependency is assumed for $q(P) = \frac{bP}{a+P}$ and $g(P) = r(1 - \frac{P}{K})$, where K is the support capacity of the environment in which they evolve.

$$X_\mu(P, D) : \begin{cases} \frac{dP}{dt} = rP(1 - \frac{P}{K}) - D\frac{cP}{a+P} \\ \frac{dD}{dt} = D(-d + \frac{bP}{a+P}) \end{cases}$$

r: intrinsic growth rate of preys.
d: per capita predator kill rate.
K: bearing capacity of the prey medium (environmental load).
a: capture average saturation constant.
b: catch rate mean saturation constant.
c: conversion rate mean saturation constant.

The populations are collected by means of a positive definite parametric description $\mu = (r, K, d, a, b, c) \in E = \Re^6_+ \times] - K, K[$.

Due to the nature of the study, it is of interest to focus on those stable or asymptotically stable populations on time scales similar to the age of the Earth. Therefore, we will focus on periodic solutions or limit cycles that provide stability in terms of the dynamics of both populations. In particular, we find a single critical point inside the first quadrant of the phase diagram under the numerical conditions: $b > d$, $K > \frac{ad}{b-d}$. In this case, it will be defined by the expression:

$$(x^*, y^*) := \left[\frac{ad}{b-d}, \frac{abr}{(b-d)cK}(K - \frac{ad}{b-d})\right]$$

The condition of global numerical stability is achieved by means of the lower bound: $K \leq a + 2x^*$ [5]. As it can be seen in FIG.1, two different dynamics are presented. For both analyzes we start from the same numerical conditions: a = 4.8, c = 0.368, r = 0.5, d = 0.45, b = 1.258, P (0) = 0.9, D (0) = 1.5 but with a variant in the condition of the variable $K = a + 2x^* - 1.5$ (purple, stable) and $K = a + 2x^* + 15$ (green, unstable). Furthermore, analyzing in detail the stable dynamics, we can observe in FIG.2 the different oscillations of populations for prey and predators. As it can be observed, after $\sim$ 300 kyr the solution reaches convergence towards two numerical constants − an attractor in the phase diagram. .

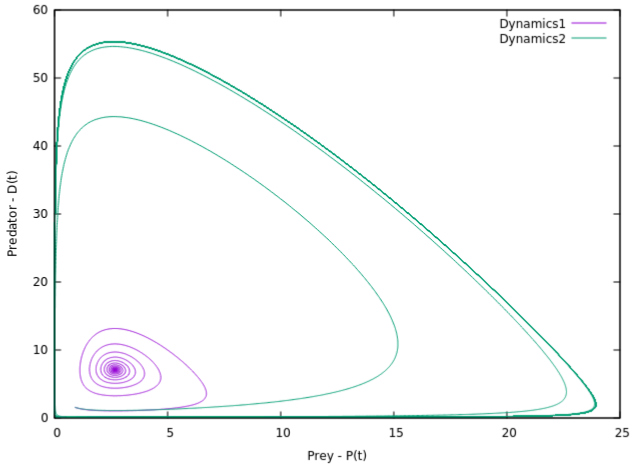

FIG. 1: Phase diagram for two different dynamics each one different to the other based on the numerical constant, K

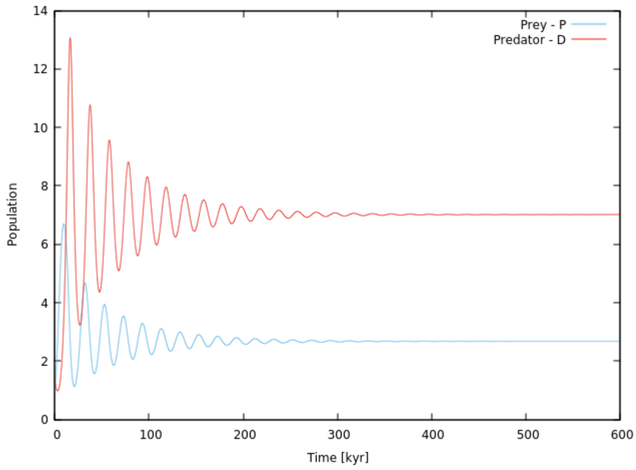

FIG. 2: Evolution of populations for prey and predator as a function of time (stable dynamics in FIG.1)

III. CONSTRUCTION OF THE MODEL AND STELLAR POPULATION

Initially it was thought to use a distribution of stars collected by the Gaia − ESA probe, however we have the problem that the catalog does not include the distance to the galactic center. In order to solve the problem, we consider a probabilistic function that adapts to the stellar statistical distribution of the Milky Way: $P(r_i) \propto e^{-r_i/r_s}$ where $r_s = 3.5$ kpc and r_i is the radial distance from the semi-major axis of the Galaxy. We normalized it, generate a population of 10,000 stars, and fix it. We will prepare our study based on this new population. It should be noted that we have taken the population considering radii in the galactic disk of: $r_1 = 4$ kpc and $r_2 = 10$ kpc which define what is known as the Galactic Habitability Zone (GHZ): the most probable region of the Galaxy in which may appear planetary systems capable of harboring some kind of life[2]. Beyond the outer radius limit, the metallicity of stars is low to allow the formation of telluric planets (such as Earth) and with a smaller inner radius, exposure to astrophysical cataclysms (gamma-ray bursts, high star formation rates followed by mass supernova explosions, jets that form in the accretion discs of black holes, ...) greatly hinder the formation of life.

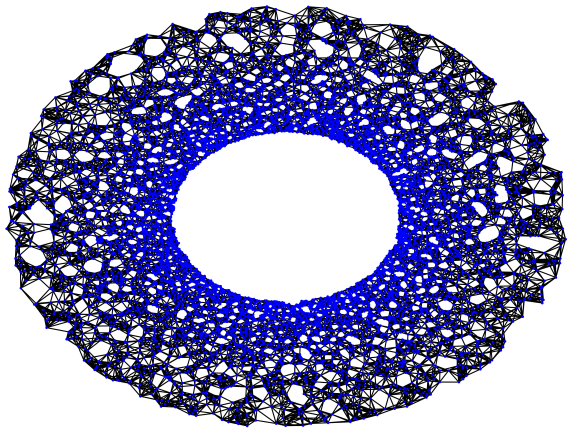

FIG. 3: The connected graph based on 10 conections for star.

We construct a weighted graph of 10,000 nodes connected by vertices whose weight is the coordinate distance with respect to the contiguous node. We find the minimum distance that allows us to travel the entire circuit in the shortest time possible − Kruskal's algorithm. To do this, we have to guarantee that our graph is connected: given a node n_i there is a connection with a neighbor other than the one from which it started. We solve the problem by considering that each node has a connection with its 10 closest neighbors (FIG.3). We program these algorithms (Kruskall's algorithm and a graph with 10 connections per node with weights equal to the distances between them). Once our minimal graph is obtained (FIG.4), we set it to convert it into what will be our object of study from now on.

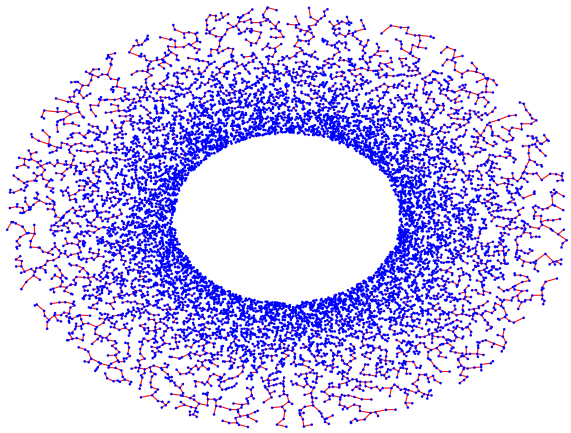

FIG. 4: Minimal Graph

IV. RESULTS

Since our motivation is to find how populations behave when, starting from a star, they interact with their neighbors, we have made an adaptation of the $X_\mu(P, D)$ system by adding two new linear variations to each population: $I_p(v, d, \alpha_p)$ (inputs) and $O_p(v, d, \alpha_p)$ (outputs). The inputs and outputs will define the flow of individuals that will arrive from each star i to its neighbor j, and will be defined as: $O_{p,ij} = \frac{\alpha_p v P}{D_{ij}}$ where P is the population of prey, α_p the percentage of prey P leaving the neighboring system, D_{ij} the distance from the star i to its neighbor j, and v the speed of the probes (taken equal to $0.3c$). Note that $I_{p,ij} = O_{p,ji}$. The definitions are similar for predators.

We used a first local study with 3 stars to check the feasibility in terms of convergence: fixed 3 stars at the nodes of an 1 kpc equilateral triangle we will carry out a study of the stability of each population. The conditions of each population are as follows: $S_1 := \{P(0) = 0.9, D(0) = 1.5\}$, $S_2 := \{P(0) = 0, D(0) = 0\}$, $S_3 := S_2$ and $\alpha_p = 0.1, \alpha_d = 0.99$ for the respective input/output flow. The results confirm the stability of this system, while also having analyzed variations in the population model as we can collect in FIG.5 and what corresponds to the same time evolution as of FIG.2, with variations in the initial populations $S_1 := \{P(0) = 0.9, D(0) = 1.5\}$, $S_2 := \{P(0) = 0, D(0) = 0\}$, $S_3 := \{P(0) = 0.1, D(0) = 0.2\}$. Due to the brevity of this study, instead of using a mathematical analysis based on parameter conditions once the introduction of flows has been established, we have focused on showing that there are solutions that continue to satisfy the convergence of the equations.

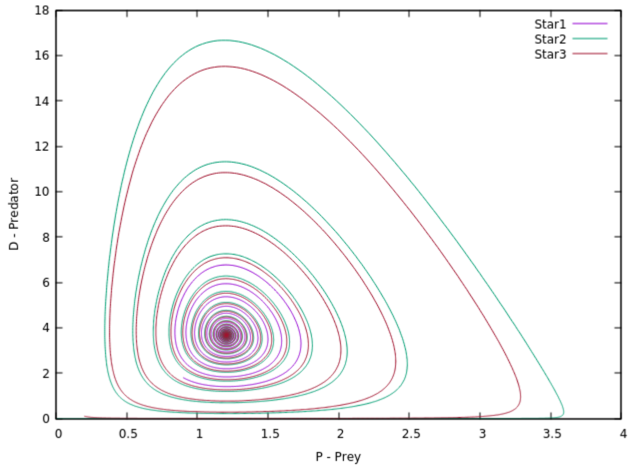

FIG. 5: Phase diagram with convergence for 3 star systems with different initial conditions.

At this point, we proceed to carry out a stability study on the population system of 10,000 stars with the same parametric description as follow FIG.2, but adding in this case: $\alpha_p = 0.1, \alpha_d = 0.99$ and for the initial star populations $P(0) = 0.9, D(0) = 1.5$. We will place it in te inner region of the graph, where we have distances between stars of the order $(10^{-3} - 10^{-4})$ kpc to observe the numerical feasibility in terms of the convergence of the model. We impose a numerical time step of 1000 years that will define the flow of incoming and outgoing populations in each star. It has been possible to observe the numerical convergence of the model accompanying in this case the population of the preys. By comparing FIGs. 6 and 7, we can see that the rate of expansion is quite representative and in scarce Myrs the probes have reached a sizeable area of the galactic disk (FIG.7).

V. CONCLUSIONS

The time step per iteration used, about 1000 years, is insignificant compared to the age of the Galaxy. The stability studies have a numerical development around 10 Myrs. This fact is based on the following aspects: (1) poverty in the computing capacity of the machine with which the study has been arranged, (2) error in the established numerical approximation, (3) stellar distribution with distances for interior stars to the galactic disk of the order $(10^{-3} - 10^{-4})$ kpc and what it means to express the flow in temporal terms greater than 1000 years (among others, the convergence to zero in the machine). Despite the competition, it has been proven that the populations of prey and predators can converge and stability in the entire system can be achieved, so the hypothesis of galactic exploration based on replicating probes with mutations is viable. On the other hand, the analyzed galactic exploration method may involve a great cost of

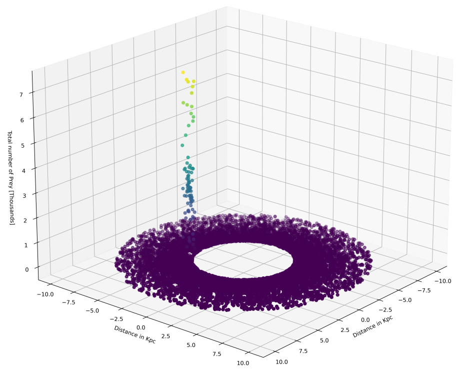

FIG. 6: Evolution of prey population for 4 Myr: x-axis (distance in kpc), y-axis (distance in kpc), z-axis (total number of prey)

time and resources beyond finding stabilities in the populations of the fixed star system. Presumably, the ultimate purpose of such exploration is not rewarded on timescales comparable to the existence of a civilization. Therefore, it is a method of exploration for local scales (or neighborhoods) in terms of obtaining results on the timescale of existence of a galactic civilization. For the purposes of the latter and following a subjective exposition, it can be determined that even if there are extraterrestrial civilizations in the Galaxy, it is highly unlikely that the human species (in its timescale of existence) can detect traces of contact with other civilizations through probes of this nature. Finally, and in accordance with the temporal fraction of existence of the human species in the Galaxy (estimated at 0.00315% over the total age of the Galaxy) we can conclude the following statement: there is no extraterrestrial civilization with the sufficient technological degree as to implement a survey of this nature, at least in a neighborhood of 10 Myrs traveling at a speed of 0.3c with center in planet Earth. This fact and under the premise of not denying the Copernican Principle, seems to indicate that intelligent life with this degree of technological development is something widely rare and supposes on the one hand: (a) limits in the technological development of civilizations, or (b) the self-destruction or extinction of civilizations; so the hypothesis of a succession of cyclical cataclysms in the Milky Way that were capable of periodically prescribing life before having reached this technological development is plausible and must be taken into consideration.

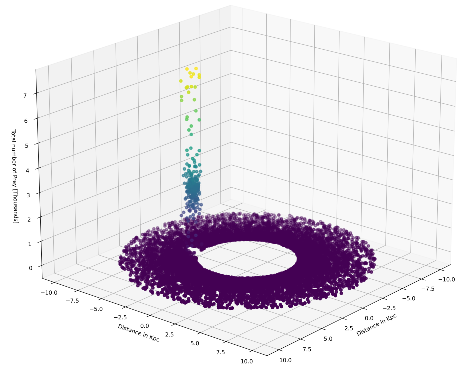

FIG. 7: Evolution of prey population for 9.5 Myr: x-axis (distance in kpc), y-axis (distance in kpc), z-axis (total number of prey)

Acknowledgments

To my parents, who always supported my curiosity to understand how the world in which I lived worked. To my friend Miguel for having encouraged me from the first moment. To Dr. Alberto Manrique for having guided me in the elaboration of a work of this nature and to my high school teacher and friend Celina Morán Moltó: thank you for having introduced me to this beautiful world that is Astronomy.

[1] Duncan Forgan, 2019, *International Journal of Astrobiology*, Volume 18, pp. 552
[2] Peter D. Ward, Donald Brownlee, 2000, *Rare Earth: Why Complex Life is Uncommon in the Universe*, (1st ed; Copernicus Books)
[3] Jacob D. Haqq-Misra, Seth D.Baum, 2009,*Journal of the British Interplanetary Society*, Volume 62, pp. 2
[4] Arwen Nicholson, Duncan Forgan, 2013, *International Journal of Astrobiology*, Volume 12, pp. 337
[5] Jean Jules Tewa, Valaire Yatat Djeumen, Samuel Bowong, 2013, *Applied Mathematical Modelling*, Volume 37, pp. 4825
[6] Charles Darwin, 1859,*On the Origin of Species* (1st ed; Quarto Publishing Group; August 2019)