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Simulating the characteristics of extra-terrestrial civilizations that encounter Earth

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Abstract. It is generally believed that it is unlikely that our civilization is alone in this galaxy. This belief is central to the premise of the Search for Extraterrestrial Intelligence (SETI), which has focused mainly on searching for radio signals originating from extraterrestrial communications, since it is believed that extraterrestrial craft visiting Earth would be an extremely unlikely event. However, the fact that we ourselves are currently working on developing probes to send to the Alpha Centauri system by 2069, strongly suggests that other civilizations may make similar, or more ambitious, efforts. Therefore, it is reasonable to inform our expectations by considering what characteristics and capabilities would be required for an interstellar civilization to find and visit Earth. In this paper, a physics-based analytic model of expanding interstellar civilizations is developed. A million civilizations that encounter Earth are simulated and their statistics are studied to determine their characteristics.

Keywords. extra-terrestrial, interstellar travel, interstellar colonization

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1. Introduction

Given what is known about the populations of planets (Traub 2011; Seager 2013; Batalha 2014; Kane *et al.* 2016), and the generation, prevalence and distribution of complex organic molecules in space (Ehrenfreund and Sephton 2006; Knuth *et al.* 2007; Salama 2008; Walsh *et al.* 2014; Cami *et al.* 2018; Ohishi 2019), it is generally believed that it is unlikely that our civilization is alone in this galaxy (Sagan 1963; Shklovsky and Sagan 1966; Drake 1980; Grosz 2013). That we are not alone is a central tenet of the Search for Extraterrestrial Intelligence (SETI) program (Tarter *et al.* 2010) and the more recent Breakthrough Listen program (Worden *et al.* 2017), which mainly focus on searching for extraterrestrial radio signals, since it is thought that extraterrestrial spacecraft visiting Earth would be an extremely unlikely event.

However, the fact that in the last decade we have observed three interstellar objects, the meteor CNEOS 2014-01-08 (Siraj and Loeb 2022), the asteroid 1I/2017 U1 (‘Oumuamua) (Meech *et al.* 2017), and comet C/2019 Q4 (2I/Borisov) (Guzik *et al.* 2020), and that we are currently working on developing probes to send to the Alpha Centauri system by 2069 (Clery 2016; Daukantas 2017; Litchford and Sheehy 2020), a century after the first Moon landings, suggests that other civilizations may make similar, or even more ambitious, efforts (Freitas 1983). It is therefore reasonable to utilize our current understanding of physics to precisely delineate our prior expectations of the possibility that an extraterrestrial civilization could visit Earth. These expectations can be made more precise by identifying which characteristics and capabilities such an interstellar civilization would have to possess.

We are relatively knowledgeable about the physics involved in interstellar travel, even if we are still naive about the requisite technologies and whether or not they can be created. In this paper, we use our knowledge of physics to create models of interstellar civilizations that expand their domains over time by traveling at potentially relativistic speeds in order to explore and occupy nearby star systems. The model we adopt is similar to the model recently investigated by Carroll-Nellenback *et al.* (2019) where a civilization experiences resource-limited exponential growth resulting in an expanding domain front. By modeling each civilization with several general parameters quantifying the basic capabilities for interstellar travel, we can identify which civilizations would have been capable of finding and visiting Earth. From this subset of civilizations we compile statistics on their parameter values thus objectively quantifying our prior expectations on the nature of such civilizations. In addition, we will learn which qualities and capabilities are critical for a civilization to successfully engage in interstellar exploration and occupation. Once identified, these qualities and capabilities could be nurtured and developed to enable our civilization to embark on interstellar exploration.

Since these models are constructed based on our current knowledge of physics, the results of these simulations ought to conform to our expectations. In this sense, we do not expect any dramatic surprises beyond those that could have been carefully reasoned. Although by simulating interstellar colonization, we can expect to add a layer of precision to our expectations by quantifying civilization model parameters with mean values and uncertainties.

2. The Milky Way Galaxy

The Milky Way Galaxy is believed to be a barred spiral galaxy with a diameter estimated to be about 150 000 ly to 200 000 ly containing about 100 to 400 billion stars with at least as many planets (Villard and Sahu 2012). In addition to the spiral disk, the Milky Way has a central elliptical bulge and is surrounded by a spheroidal halo of stars. The Milky Way is dynamic and is in the process of evolving in a complex manner as small neighboring galaxies continue to merge with the Milky Way forming streams of stars within the galaxy (Newberg *et al.* 2002; Ivezić *et al.* 2008). The stellar density of the galaxy is neither uniform nor smooth with density structures ranging from the more familiar spiral arms to the more recently discovered corrugation of the galactic disk (Xu *et al.* 2015). The limits in our knowledge about the galactic structure precludes the utility of a detailed galactic model in this study.

For these reasons, we adopt a simplified picture of the galaxy as a 900 ly thick disk of stars with uniform stellar density equal to that of the local stellar density. Given that there are approximately 317 stellar neighbors within 10 pc $\approx$ 32.6 ly of the Sun (Henry *et al.* 2018), the stellar density is approximately $\rho \approx 0.0022$ systems/ly^3. The stars in the galaxy are assumed to be stationary over the times scales of a civilization. This neglects the rotation of the stars about the galactic center, which given proper velocities ranging from around 200 to 250 km/s (Mróz *et al.* 2019) result in displacements on the order of 10 000 ly over a period of 10 million years, which would be relevant for older civilizations. By not modeling stellar motions, we restrict this study to civilizations with lifetimes less than 10 million years.

Our stationary approximation also neglects random, or thermal, stellar motions, which have been modeled by Carroll-Nellenback *et al.* (2019) as a Maxwell-Boltzmann distribution with an average speed of 10^{-4} c. These thermal motions, which would introduce a small diffusive component, become relevant in the low stellar density limit where some civilizations would have to wait for a settleable star systems to come into range (Carroll-Nellenback *et al.* 2019).

Limiting our study to situations we are familiar with, such as terrestrial, icy, or ocean-bearing worlds, places constraints on where in the galaxy such life might evolve. To form terrestrial planets the stellar environment must have a sufficient supply of heavy elements, or metallicity (Wang and Fischer 2014). In addition, the local environment must be relatively calm for the length of time required for the evolution of complex life. This means that both nearby supernovae and stellar interactions need to be relatively rare. This results in a Galactic Habitable Zone (GHZ) that is expected to be an annular disk-shaped region with an inner radius of 4 kpc $\approx 13,000$ ly and an outer radius of 11 kpc $\approx 36,000$ ly (Lineweaver *et al.* 2004). Stars close to the galactic center will be older generation stars with high metallicity and a commensurate tendency to have large close-orbiting massive planets (Wang and Fischer 2014), which may disrupt smaller terrestrial worlds (Raymond *et al.* 2006; Haghighipour 2007). More importantly, the greater density of stars near the galactic center will result in more frequent stellar interactions, which threaten the stability of planetary systems, as well as a significantly higher supernova rate resulting in more frequent sterilizing events. On the other hand, stars in the outer reaches of the galaxy tend to be earlier generation stars with low metallicity, which is expected to result in terrestrial planets being more rare (Lineweaver *et al.* 2004).

3. Model Parameters Describing a Civilization

A civilization's **origin** (x_o, y_o, z_o) is sampled uniformly from the GHZ, and its **lifetime** T is sampled from the range $[1, 10 \times 10^6]$ y. Table 1 lists the civilization's model parameters, ranges, and the prior probability distributions from which they are sampled. Parameters are either uniformly distributed, or distributed with a Jeffrey's prior, which is invariant with respect to the choice of units (and thus greatly favors smaller values).

Civilizations are modeled independently (no interactions) and it is assumed that the civilization's parameters do not change over their lifetime. This way we can more effectively model what one expects from a civilization with a given set of parameters. A civilization's dispersion across interstellar space will be highly species and culture dependent. It will also depend greatly on the type of occupation, which could range from setting up small bases or research stations to exoforming planets to support large populations (colonization). To model these possibilities, we employ a parameter called the **resilience**, $\mathscr{R}$, which is the probability that a given system will have a suitable world to occupy, and the **colonization time**, t_{col}, which describes how long it takes to establish a presence before moving on to another star system.

Table 1. Civilization Parameters and their Prior Probabilities.

Model Parameters				
Symbol	**Parameter**	**Prior Range**	**Units**	**Prior Type**
x_o	galactic x-coordinate	within the GHZ	ly	Uniform
y_o	galactic y-coordinate	within the GHZ	ly	Uniform
z_o	galactic z-coordinate	$[-450, 450]$	ly	Uniform
$\mathscr{R}$	resilience	$[0, 1]$	unitless	Uniform
T	civilization lifetime	$[1, 10 \times 10^6]$	years	Jeffreys
t_{col}	colonization time	$[1, 5000]$	years	Uniform
$\tau_{\max}$	endurance	$[1, 1000]$	years	Jeffreys
$a_{\max}$	max. acceleration	$[1, 25000]$	g	Jeffreys
$v_{\max}$	max. velocity	$[0.001, 1)$	c	Jeffreys
Derived Parameters				
Symbol	**Parameter**	**Units**	**Constraints**	
δ	interstellar reach	ly	$\delta > 7.37$ ly	
R	characteristic domain radius	ly		
v_{dom}	domain expansion velocity	c		
d_e	distance to Earth	ly		
t_e	time of first contact	y		

Note: Jeffreys priors were handled by working with uniformly-distributed logarithms of the parameters.

Their capability for space travel is modeled by describing the **maximum acceleration**, $a_{\max}$, and **maximum speed**, $v_{\max}$, of their spacecraft along with their **endurance**, τ, which describes how long they are able to travel in their spacecraft. Using the spacecraft parameters, $a_{\max}$ and $v_{\max}$ along with their endurance τ, relativistic rocket equations can be used to compute the maximum distance that they can travel, called their **reach**, δ. Using the reach, δ, we can compute the speed, v_{dom}, at which the civilization's domain radius R grows. This allows us to compute the civilization's distance from Earth, which is located at $(x_e, y_e, z_e) = (0, -26000, -45)$ ly.

4. Diffusion and Growth Models

While we can expect that nearby systems will be favored over distant ones, the unpredictable nature of the selection process will make colonization a relatively random process, well-described as a diffusion process. The probability that a given star system is occupied will evolve according to Fick's second law

$$\frac{\partial}{\partial t} p(r,t) = D \nabla^2 p(r,t), \tag{1}$$

where D is the diffusion constant. However, the fact that colonies are growing, maturing, and venturing out on their own adds a source term to the evolution of this probability. Since each colony is a potential colonizer, the rate of growth will be proportional to the occupation probability $p(r,t)$. However, the rate of growth will also be proportional to the probability of the opportunities for occupation, which is given by $\mathscr{R} - p(r,t)$. This results in the addition of a source term on the right

$$\frac{\partial}{\partial t} p(r,t) = D \nabla^2 p(r,t) + \rho \left(\mathscr{R} - p(r,t)\right) p(r,t), \tag{2}$$

where ρ is the constant of proportionality amounting to a growth rate. The resulting partial differential equation is known both as Fisher's equation (Fisher 1937) and the Kolmogorov-Petrovsky-Piskunov (KPP) equation (Kolmogorov *et al.* 1937).

To get some idea of what the solutions to this partial differential equation look like, we first consider the case where there is no diffusion, so that $D = 0$ and r is not a function of time t. This gives us the differential equation

$$\frac{d}{dt} p(r,t) = \rho \left(\mathscr{R} - p(r,t)\right) p(r,t), \tag{3}$$

which is the logistic differential equation (Verhulst 1838) where ρ is the growth rate. Unlike (2), this differential equation is easily integrated resulting in

$$p(r,t) = \frac{\mathscr{R}}{1 + \left(\frac{\mathscr{R} - p_o}{p_o}\right) e^{-\rho(t - t_o)}} \tag{4}$$

where $p_o = p(r,t_o)$ is the occupation probability at 'initial' time t_o. The logistic equation is a sigmoid function which initially grows exponentially and then saturates at an occupation probability given by the resilience, $p(r,t) = \mathscr{R}$, due to the fact that colonization options are limited by their resilience.

When diffusion is included, we expect that the population density will expand outward from their homeworld while the population density of the interior of their domain increases logistically saturating at $p(r,t) = \mathscr{R}$. The domain boundary, or frontier, will be an expanding wave with a shape related to both the logistic function and a three-dimensional Gaussian.

However, the fact that the partial differential equation (2) cannot be solved analytically means that we have to make some simplifications. Since we are mainly interested in whether the civilization finds Earth, we are going to ignore the growing population density of the interior, modeling the civilization as a three-dimensional Gaussian distribution, and focus on rate at which the domain boundary grows. The domain velocity is expected to be bounded by

$$v_{\text{dom}} \leq \frac{\delta}{\tau + t_{\text{col}}}. \tag{5}$$

However, one would expect that expansion will not be radial to the boundary, but that spacecraft will zig-zag from system to system resulting in (Bennett and Shostak 2007; Maccone 2012)

$$v_{\text{dom}} = \frac{\langle z \rangle}{\tau + t_{\text{col}}} = \frac{k\delta}{\tau + t_{\text{col}}}. \tag{6}$$

Computing the expected value of z by treating the domain as having a hard boundary results in $\langle z \rangle = 3/8\delta$. However, using a Taylor-series approximation of the Gaussian population profile across the domain reveals that k is not a constant, but that

$$\langle z \rangle = \frac{\delta^2}{5R} (\mathscr{R}^{-1} e^{1/2} - 1)^{-1}. \tag{7}$$

Substituting into (6) we see that the domain expansion velocity depends on the resilience, $\mathscr{R}$, and decreases as the domain radius, R, increases, since the volume to occupy goes as R^3.

Carroll-Nellenback *et al.* (2019) found that to maintain spherical expansion, the normalized density of settleable systems, η, must be greater than a critical value

$$\eta = \mathscr{R} \rho \delta^3 > \eta_c = 0.88, \tag{8}$$

where ρ is the stellar density, which places a constraint on the reach

$$\delta > \left(\frac{0.88}{\mathscr{R} \rho} \right)^{1/3}, \tag{9}$$

so that for lower resilience, one must be able to travel further. A resilience of $\mathscr{R} = 1$ results in a minimum reach of $\delta_{\text{min}} \approx 7.37$ ly.

5. Sampling from the Prior Probabilities

By sampling from the prior probabilities, listed in Table 1, one can evaluate our expectations for the capabilities of interstellar civilizations. For example, by sampling ten million spacefaring civilizations from the priors, we found that 2 219 792 civilizations were capable of interstellar colonization. Therefore the probability that a spacefaring civilization will be interstellar-capable is roughly 22.2%. Of those interstellar-capable civilizations, we found that 9 of those civilizations encountered Earth. Thus the probability that an interstellar-capable civilization will visit Earth is about $\frac{9}{2\,219\,792} \approx 0.000405\%$. That means that out of all of the spacefaring civilizations in the galaxy, only about 0.00009% of them encounter Earth. If we ever learn that someone had visited Earth, these results serve as a sort of Drake equation to estimate that there are about 1.1 million spacefaring civilizations and about 250 000 interstellar spacefaring civilizations in the galaxy.

6. Sampling Civilizations that Found Earth: Nested Sampling

The goal of this paper is to study the statistics of physics-based simulations of interstellar civilizations that encounter Earth. The fact that about only 1 out of 10^6 spacefaring civilizations find Earth, means that to sample 10^6 civilizations that find Earth, we would have to sample 10^{12}, or a trillion, civilizations from the prior. We are going to have to be a bit more clever if we want a million prior-distributed samples of civilizations that find Earth.

To accomplish this, we rely on the nested sampling algorithm (Skilling 2004, 2006), which is a stochastic (Lebesgue) integration algorithm to compute the Bayesian evidence by integrating the likelihood over the prior space. By performing a change of variables so that the prior probabilities are all uniform, the algorithm works by managing a population of N samples drawn uniformly from within a set of nested increasing-likelihood contours.

Instead of a likelihood function, we define a cost function based on the distance between the civilization's domain boundary and Earth. The algorithm then sorts civilizations based on this distance. At the end of the process, we are left with a prior-distributed (uniformly-distributed) population of $N = 10000$ civilizations all of which contain Earth within their domain. By running this algorithm 100 times (with $N = 10000$ samples), we obtain one million prior-distributed civilizations, which have found Earth. The statistics of these one million civilizations describe our best expectations given our current knowledge of physics.

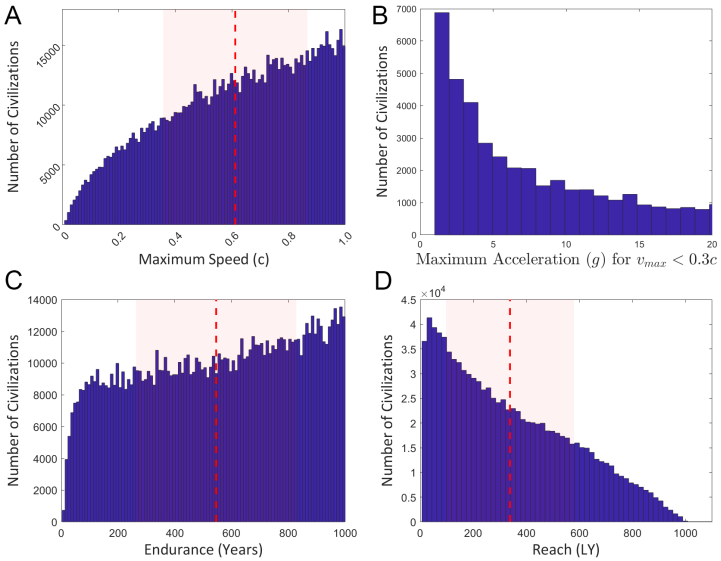

Figure 1. A. The maximum velocities, $v_{\max}$, of the spacecraft reveal that it is better to go faster, but interstellar travel is possible at 10's of percent of the speed of light. Mean $v_{\max} = 0.61 \pm 0.25$ c is displayed with a dashed line and shading. B. Accelerations of spacecraft with $v_{\max} < 0.3$ c reveal that accelerations between 1 to 2 g are in many cases sufficient. C. Endurances, $\tau_{\max}$, are widely distributed. Mean $\tau_{\max} = 545 \pm 282$ y. D. The civilizations' reach, δ, peaks around 26 to 44 LYs, with a mean of 340 ± 240 ly.

7. Characteristics of Interstellar Civilizations that Encounter Earth

Figure 1A illustrates that maximum speeds, $v_{\max}$, a fraction of the speed of light are sufficient for interstellar exploration and colonization. Over 21 600 civilizations ($\sim 2\%$) were able to find Earth by traveling at speeds less than 10% the speed of light (0.1 c), 75 000 ($\sim 7.5\%$) at speeds less than 0.2 c, and 146 000 ($\sim 15\%$) at speeds less than 0.3 c. Resulting accelerations, $a_{\max}$, remained roughly prior-distributed, so that low accelerations are more probable (Fig. 1B), and reasonable accelerations between 1 to 2 g are in many cases sufficient.

Relatively slow speeds require greater endurance, $\tau_{\max}$, which is widely distributed from tens of years to 1000 years (Fig. 1C). Endurance, along with $v_{\max}$ and $a_{\max}$, affect the civilizations' reach, δ, which was found to be most probably around 26 and 44 LYs, with a mean of 340 ± 240 LYs (Fig. 1D). While clearly challenging for organisms with human tolerances and lifespans, these capabilities are possible for AI-controlled space probes.

To get an understanding of how large these civilizations are, Figure 2 illustrates the distribution of domain radii (A), R, and the distances between their origin and Earth (B). The most probable domain radius, R, was found to be 260 ly, and the distribution has a mean of 500 ± 330 ly. B. The most probable distance between the civilization's origin and Earth was 248 ly with a mean of 560 ± 410 ly, so that Earth is often well within their domain.

The distribution of lifetimes, T, had a short lifetime spike, due to the Jeffrey's prior, followed by a rather uniform distribution up to 10 million years. The age of the civilization when it found Earth had a similar spike followed by a linear decreasing distribution approaching zero at 10 million years. The time of first contact ranges from 0 (present) to the difference between the lifetime and the age at which they found Earth. Uniformly sampling over this range gives the distribution of first contact times (Fig. 2C), which shows that if we find that extraterrestrials have visited Earth, then it is possible that Earth was found long ago with a mean first contact time of about $1.17^{+2.44}_{-1.02}$ million years ago.

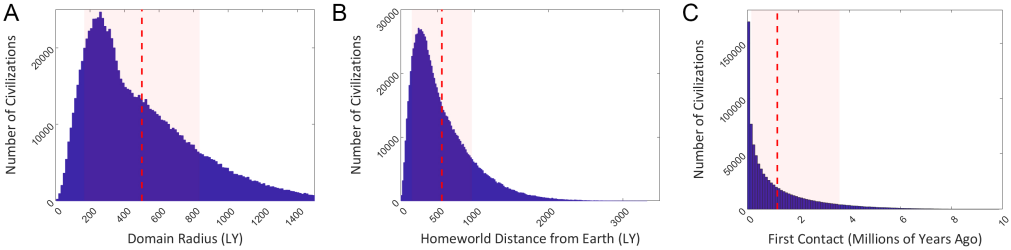

Figure 2. A. The distribution of domain radii, R. Mean $R = 500 \pm 330$ ly. B. The distribution of distance, d_e, between the civilization's origin and Earth. Mean $d_e = 560 \pm 410$ ly. C. The distribution of Earth first contact times, which have a mean of $1.17^{+2.44}_{-1.02}$ million years ago.

8. Discussion

By explicitly stating our expectations of characteristics of spacefaring civilizations as prior probabilities, we have sampled from these priors to determine what our expectations ought to be for interstellar civilizations to spread out throughout the galaxy and encounter Earth. Based on these prior expectations, we have found that only 22.2% of spacefaring civilizations are capable of interstellar travel and sustainable occupation of other star systems. As one would expect, the probability of a civilization finding and visiting, or occupying, Earth is much lower at only about a 0.0004% probability, and that there is an overall probability of 0.00009% that any spacefaring civilization could encounter and visit Earth. If we ever learn that an extraterrestrial civilization had visited Earth, these results serve as a variation of the Drake equation to estimate that there are about one million spacefaring civilizations and about 250 000 interstellar spacefaring civilizations in the galaxy. Practically, what is important is the number of interstellar-capable civilizations within 560 LY of Earth (mean distance between a civilization's origin and Earth), which includes around 1.7 to 3 million star systems ($N = \rho V$).

This analysis is not without faults, and should be treated as a rough (hopefully conservative) estimate. Ignorance about the galactic structure required that we make simplifying assumptions about the galaxy. Unlike Carroll-Nellenback *et al.* (2019), we neglected stellar motions, which they demonstrated could significantly aid domain expansion over extremely long time scales. We employed an average stellar density of $\rho \approx 0.0022$ systems/ly^3, which is about half as large as other estimates of 0.004 systems/ly^3 (Gregersen 2010).

We worked to keep the ranges of the civilization parameters broad so that we could observe their importance, and accommodate the potential diversity of civilizations. Since we worked to establish our expectations based on known physics, we considered spacecraft speeds up to, but not exceeding, the speed of light. Since ideas about warp drive have only begun to be explored (Alcubierre 1994; Davis 2009; Bobrick and Martire 2021), it is premature to attempt to model that physics, especially since the speeds of potential warp drives are not yet widely established (Smolyaninov 2011). We used a lower speed limit of $0.001c \approx 1.8 \times 10^6$ km/hr, which is about 3 times faster than our current capability (Parker Solar Probe). The accelerations were set with an upper limit of (an admittedly high) 25 000 g, which is two to five times higher than the estimated accelerations in some well-documented UAP cases (Knuth *et al.* 2019; Coumbe 2022), so that we could explore the consequences of such high accelerations. As one would expect, higher accelerations significantly reduce travel times. For example at a 1000 g acceleration a ship can reach a speed of $0.9c$ in only 17.5 hrs (Knuth *et al.* 2019). However, we found that sustained lower accelerations are also effective. When one considers that a 1 g acceleration is approximately 1 (ly/year)/year, it becomes clear that relativistic speeds are attainable at sustained human-friendly accelerations. Of course, much of this relies on what can actually be engineered, which is expected to be civilization-dependent up to a limit.

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