The Effect of Probe Dynamics on Galactic Exploration Timescales

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June 22, 2018

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Abstract

The travel time required for one civilisation to explore the Milky Way using probes is a crucial component of Fermi's Paradox. Previous attempts to estimate this travel time have assumed that the probe's motion is simple, moving at a constant maximum velocity, with powered flight producing the necessary change in velocity required at each star to complete its chosen trajectory. This approach ignores lessons learned from interplanetary exploration, where orbital slingshot maneouvres can provide significant velocity boosts at little to no fuel cost. It is plausible that any attempt to explore the Galaxy would utilise such economising techniques, despite there being an upper limit to these velocity boosts, related to the escape velocity of the object being used to provide the slingshot.

In order to investigate the effects of these techniques, we present multiple realisations of single probes exploring a small patch of the Milky Way. We investigate 3 separate scenarios, studying the slingshot effect on trajectories defined by simple heuristics. These scenarios are: i) standard powered flight to the nearest unvisited star without using slingshot techniques; ii) flight to the nearest unvisited star using slingshot techniques, and iii) flight to the next unvisited star which provides the maximal velocity boost under a slingshot trajectory.

We find that adding slingshot velocity boosts can decrease the travel time by up to two orders of magnitude over simple powered flight. In the third case, selecting a route which maximises velocity boosts also reduces the travel time relative to powered flight, but by a much reduced factor. From these simulations, we suggest that adding realistic probe trajectories tends to strengthen Fermi's Paradox.

Keywords: Fermi Paradox, SETI, interstellar exploration, probe dynamics

1 Introduction

Fermi's Paradox remains an important cornerstone of modern thinking on extraterrestrial intelligence (ETI). It taxes most, if not all attempts to formulate an optimistic perspective on the frequency of alien civilisations in the Galaxy both in space and time.

Detailed reviews of the Paradox can be found in Brin (1983), Webb (2002) and Cirkovic (2009). The Paradox rests on the current absence of ETI in the Solar System (what Hart 1975 refers to as "Fact A"). This absence runs counter to estimated timescales for intelligent species to colonise of the Galaxy - what Cirkovic (2009) (and references within) refers to as the Fermi-Hart timescale (see e.g. Hart 1975; Tipler 1980):

$$t_{FH} = 10^6 - 10^8 \, \text{yr} \tag{1}$$

This is compounded by the fact that the age of the Earth is at least an order of magnitude higher, and the median age of terrestrial exoplanets is estimated to be a further 1 Gyr older than the Earth (Lineweaver, 2001). It appears the inexorable conclusion one must draw is that ETIs do not exist, otherwise we would have detected their presence in the Solar System.

It is common for attempts to resolve the Paradox to speculate on the motivation or sociological make-up of ETIs - for example, one solution suggests that the Earth has attained a protected status and must not be disturbed, often known as the Zoo Hypothesis (e.g. Ball 1973). While flaws can be exposed in these types of hypothesis (see e.g. Forgan 2011), there are many solutions that are simply unfalsifiable, and while they cannot be ruled out, they cannot be currently considered as scientifically meritorious. Until conclusive data is compiled on something as esoteric as extraterrestrial sociology, it is more worthwhile to focus on potential physical constraints for extraterrestrial contact.

Weaker formulations of the Paradox merely rest on ETIs practising interstellar communication rather than interstellar colonisation (e.g. Scheffer 1994)- stronger formulations use self-replicating Von Neumann probes to explore the galaxy at an exponential rate. It is this process of self-replication (or colonies carrying out subsequent autonomous colonisation) that allows t_{FH} to be small enough for the Paradox to be robust. While there have been many arguments for and against the use of self-replicating probes (e.g. Tipler 1980; Sagan & Newman 1983; Chyba & Hand 2005; Wiley 2011), we wish to focus instead on a more fundamental aspect of probe exploration that has not been addressed fully.

The Paradox leans heavily on the dynamics of interstellar flight, and the motivations of the extraterrestrial intelligences (or ETIs) that drive the exploration. Sagan (1963) expounds a framework for a cadre of civilisations visiting star systems using relativistic interstellar flight. Under these assumptions, the visiting rate for main sequence stars could be as high as once per ten thousand years (although it makes relatively optimistic assumptions about the number of civilisations forming the cadre). The associated problems of population growth and carrying capacity are also important drivers for continual exploration, as was explored by Newman & Sagan (1981) using nonlinear diffusion equations. The stipulation that ETIs practise zero population growth can alter t_{FH} by several orders of magnitude.

At a more fundamental level, Bjø rk (2007) investigated probe exploration in a schematic model of the Galaxy, with an exponentially declining stellar surface density distribution. Each host probe visits a subset of the Galactic stellar population, containing 40,000 stars. The host then releases 8 sub-probes, which explore this subset, and then dock with the host before travelling to a new Galactic sector. Each probe has a constant velocity of $0.1c$, and travels to its nearest unvisited star under powered flight. There is no attempt to optimise the trajectory of the sub-probes beyond this simple heuristic. Optimising its trajectory is an instance of the "travelling salesman" problem (Golden & Assad, 1988; Toth & Vigo, 2001), an NP-hard problem which is computationally prohibitive to solve for large node numbers, as is the case in interstellar exploration.

Cotta & Morales (2009) extended this work by using algorithms to improve the trajectory of the probes, reducing the tour length by around 10%. They subsequently carried out a probabilistic analysis assuming many ETIs were carrying out exploration in this fashion. This allowed them to estimate the maximum number of ETIs exploring the Galaxy (N_{ETI}) that could do so while ensuring contact with Earth remained statistically unlikely. In the parameter space explored, they estimate that the upper limit is approximately

$N_{ETI} < 10^3$.

What is common to all these simulations of probe exploration is that they ignore or neglect lessons learned from Mankind's unmanned exploration of the Solar System. Simple powered flight is an inefficient means of travel, especially for probes using chemical or nuclear propulsion methods. Using slingshots inside gravitational potential wells allows the probe to produce relatively large Δv and alter its trajectory without expending fuel, and potentially boosting its speed relative to the rest frame of its starting position. This has been utilised successfully by Mankind during its exploration of the Solar System, both in the ecliptic plane through the triumphal tour of the Voyager probes (see e.g. Gurzadyan 1996), and even out of the ecliptic during the Ulysses mission (Smith et al., 1991).

In principle, this behaviour can be scaled up to the Galactic level, where the potential well of stars can now be used to provide Δv and increase the probe speed relative to the Galactic rest frame (Surdin, 1986). While this requires probes to be able to navigate extremely accurately, this would not appear to be an insurmountable obstacle provided the probe possessed sufficient autonomous computing power, and retained enough fuel for judicious course corrections.

In this paper, we investigate the effect of individual probe dynamics on the visitation timescale of a population of stars. We run a series of Monte Carlo Realisations (MCRs), where in each realisation a single probe traverses a path through a population of stars. The stellar population has a number density and velocity field akin to that of the Solar Neighbourhood. We run three separate sets of realisations, focusing on three basic scenarios:

1. A single probe, visiting stars under powered flight, with each leg of the route determined by finding the nearest unvisited neighbour (which we label **powered**),

2. As 1., except utilising slingshot trajectories to boost the velocity of the probe (which we label **slingshot**),

3. A single probe which selects the next star to travel to such that the velocity boost derived from a slingshot is maximal, which depends on the destination star's velocity relative to the current star (which we label **maxspeed**).

In section 2, we describe the mechanics of the slingshot maneouvres employed in this paper, as well as the setup of the simulations; section 3 describes the results of the three scenarios, and in sections 4 and 5 we discuss and conclude the work.
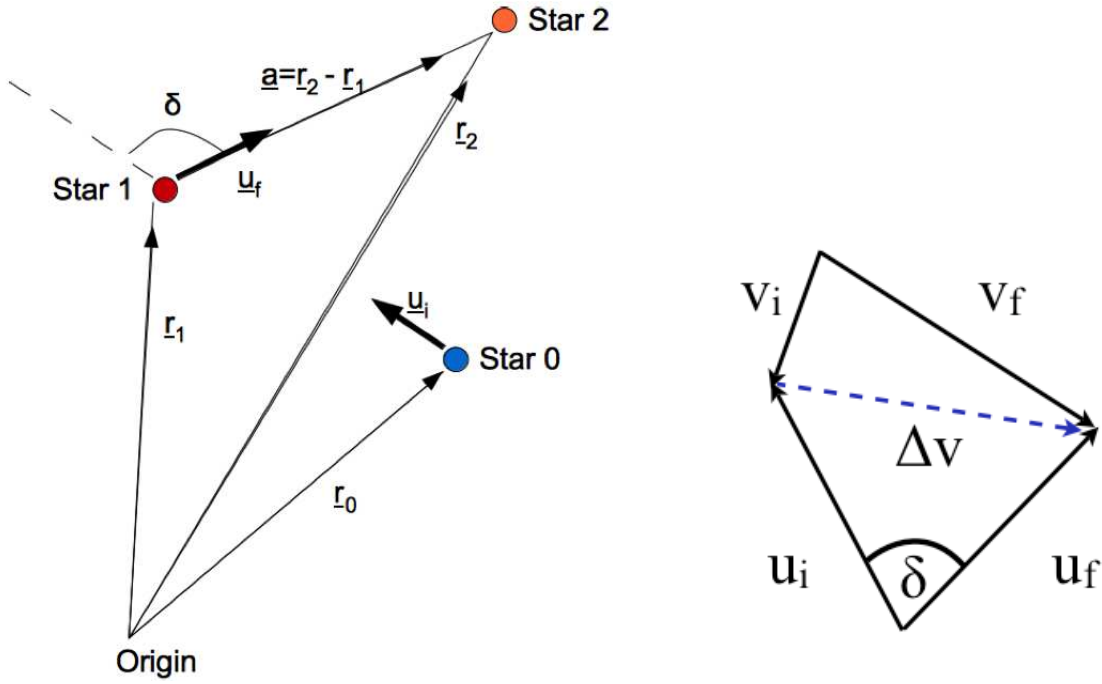
Figure 1: The vector diagram above shows he path of the probe from the stars reference frame, changing its direction by an angle δ but not the magnitude of its velocity.

2 Method

2.1 The Dynamics of Slingshot Trajectories

A slingshot trajectory uses the momentum of the star it passes to gain or lose velocity, depending on the incident angle of the probe's approach. The probe therefore does not need to expend additional energy that would otherwise be required to complete a similar trajectory under powered flight. We briefly describe the mathematics of slingshot trajectories here: for more detail the reader is referred to Gurzadyan (1996) (in particular to Chapter XIII, section 4, equations 29 to 31).

The left panel of Figure 2.1 describes one stage of the probe's trajectory when slingshots are used. The probe begins at Star 0, accelerating to velocity $\mathbf{u}_i$ (measured in the frame where Star 1 is at rest). For the probe to proceed to star 2 after the slingshot, its velocity must assume the vector $\mathbf{u}_f$, again in Star 1's frame. The angle between $\mathbf{u}_i$ and $\mathbf{u}_f$ is δ. In this manoeuvre, the probe follows a hyperbolic trajectory, and

$$|\mathbf{u}_i| = |\mathbf{u}_f|. \tag{2}$$

However, we are interested in the probe's velocity in the "lab" frame, i.e. a frame of reference where the Galactic Centre is at rest. The right panel of Figure 2.1 shows the vector diagram connecting the initial and final velocities in both frames. As a result of adding the star's motion to $\mathbf{u}_i$ and $\mathbf{u}_f$ to create the Galactic

frame velocities $\mathbf{v}_i$ and $\mathbf{v}_f$, we can see that there is indeed an increase in the probe's speed, Δv, which we can deduce simply:

$$\Delta v = 2|\mathbf{u}_i| \sin\left(\frac{\delta}{2}\right).$$

(3)

The change in the probe's momentum in this frame is balanced by a change in the star's momentum relative to the Galactic Centre. The fractional decrease in momentum the star experiences is so small that we can effectively regard it as negligible. The angle δ is related to the inward velocity as follows:

$$\tan\left(\frac{\delta}{2}\right) = \frac{GM_*}{r_c u_i}$$

(4)

where r_c is the distance of closest approach to the star. This places an upper limit on the value of δ and consequently Δv (see Discussion).

We assume the probe has a maximum velocity it can attain under its own power. This defines the probe's initial velocity as it travels from Star 0 to Star 1. Henceforth, it can travel with increasing speed as it undergoes a series of slingshot maneouvres. The magnitude of the boost achieved by the slingshot maneouvre is increased if the star's own velocity runs parallel to the probe's trajectory. Therefore, it is possible that a probe could choose a course based on the spatial velocities of stars relative to each other, such that it carries out slingshots with maximal Δv.

2.2 Simulating Probe motion

We carry out three simulation scenarios, all in a small patch of the Galaxy containing one million stars, at a uniform density of 1 star per cubic parsec. The stars were set in a shearing sheet configuration to emulate the rotation curve of the Milky Way. For convenience, the stars were given velocity vectors for the slingshot calculation, but fixed in position. For each scenario, 30 realisations were carried out - this number represents a balance between reducing computational expense and maintaining a sufficiently small standard error arising from random uncertainties. As we will see in later sections, 30 realisations is sufficient to produce total travel times at accuracies of a few percent. In each realisation, the probe is allocated a different starting star.

The three scenarios are:

1. Powered flight to the nearest neighbour (**powered**). The probe travels from the starting star to the closest neighbour at its maximum powered velocity. The Δv is therefore fixed by the repeated deceleration and acceleration the probe makes at every stage of the trip.

2. Slingshot assisted flight to the nearest neighbour (**slingshot**). Here the path is identical to that taken when using powered flight due to the same method of choosing the next star. However, the probe need only expend Δv to accelerate to maximum velocity once, and does not need to decelerate,

instead using the slingshot manoeuvre to repeatedly boost its maximum velocity. We assume that the δv expended by the probe to make course corrections to adopt a slingshot trajectory is negligible.

3. Slingshot assisted flight seeking the maximum velocity boost (**maxspeed**). This selects a different path entirely to the other two scenarios, seeking instead the course such that the relative velocity vector between the current and destination stars is large and negative, i.e. the destination star is moving toward the current star. This will give a larger velocity boost, but will in general require a longer path length to achieve it.

We select a relatively low maximum velocity of $3 \times 10^{-5}c$, where c is the speed of light *in vacuo*. This is comparable to the maximum velocities obtained by unmanned terrestrial probes such as the Voyager probes[1]. Admittedly, the Voyager probes achieved these speeds thanks to slingshot trajectories, so the top speed of human technology under purely powered flight is unclear. To some extent, the maximum powered speed of the probe is less important - increasing or decreasing this maximum will simply affect the absolute values of the resulting travel times in a similar fashion. What is more important is the *relative* effect of changing the propulsion method and/or the trajectory.

3 Results

In Table 1 we summarise the three scenarios in terms of the total travel time to traverse all stars in the simulation, averaged over all 30 realisations. As the probe velocity we have selected is particularly low, the total travel times are quite large. In fact, two scenarios (powered and maxspeed) have travel times longer than the current age of the Universe (1.37×10^{10} yr), despite the standard error on the mean (which is generally a few percent of the mean). Therefore, it is unlikely that probes travelling at maximum velocities for current human technology can explore even a small fraction of their local neighbourhood in a timely fashion. We will investigate the reasons for this in more detail in the following sections.

On the other hand, the slingshot scenario has a significantly shorter travel time than the others. Of course, this travel time is only for 10^6 stars, and the Galaxy itself contains around 10^{11} stars, so it still remains unlikely that probes of this type could explore the entire Galaxy before Mankind began to construct devices that could detect them. For the Fermi Paradox to hold, the initial probe velocity would need to be much larger, a fact that has long been obvious (Sagan, 1963).

3.1 Powered Flight Only, Nearest Neighbour (powered)

Figure 2 shows the travel time between each star in the powered case. Here we average over 30 realisations, with the mean drawn in black and the standard error on the mean plotted in grey. Note that as the density of stars is roughly constant throughout the box, and the Δv achievable by the probe is fixed by its own engines,

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[1]http://voyager.jpl.nasa.gov/mission/weekly-reports/index.htm

Table 1: Summary of the three scenarios investigated in this work.

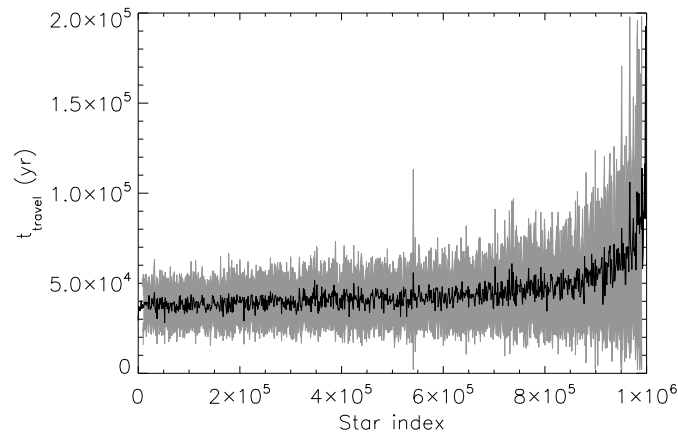| Simulation	Average Total Travel Time (yr)	Standard Error (yr)
powered	4.51×10^{10}	2.82×10^{7}
slingshot	3.99×10^{8}	3.51×10^{5}
maxspeed	1.99×10^{10}	1.23×10^{7}

Figure 2: The mean travel time between each star for probes in the *powered* simulations, averaged over 30 realisations. The grey shaded area represents the standard error on the mean.

the travel time between nearest neighbours is also reasonably constant. As the number of unvisited stars drops below a hundred thousand or so, the probe must travel longer distances to find an unvisited star, and hence the travel time increases towards the end of the simulation.

3.2 Slingshot Trajectory, Nearest Neighbour (slingshot)

If we now allow the probe to make slingshot maneouvres to its nearest neighbour (slingshot), then we can see that the probe's behaviour changes significantly (Figure 3). It follows the same course as before, but it can now boost its velocity at every stage of the journey (right panel), significantly reducing its travel time (left panel). As a result, it has increased its velocity by almost a factor of 100 throughout the simulation (a fact borne out by its total travel time being approximately 100 times smaller than the powered case). Even towards the end of its path, where the unvisited nearby stars reside at larger distances, the increased speed as a result of the slingshots allow the probe to cover these larger distances in a short time span. Note the large standard error on the mean - Δv is now a sensitive function of the probe's path (more specifically, the angle δ in Figure 2.1). As the probe begins from a different starting star in each realisation, the probe's path is significantly different, resulting in a large spread of Δv at each stage of the journey. The probes maximum velocity is eventually limited by the minimum value δ can take (see Discussion).
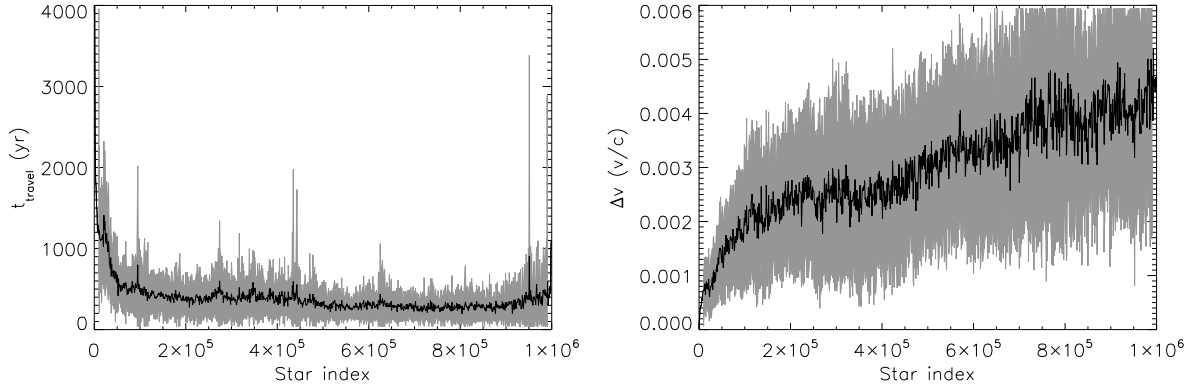
Figure 3: **Left**:The mean travel time between each star for probes in the *slingshot* simulations, averaged over 30 realisations. The grey shaded area represents the standard error on the mean. **Right**: the mean Δv generated as a result of each slingshot maneouvre, with standard error on the mean shaded grey.
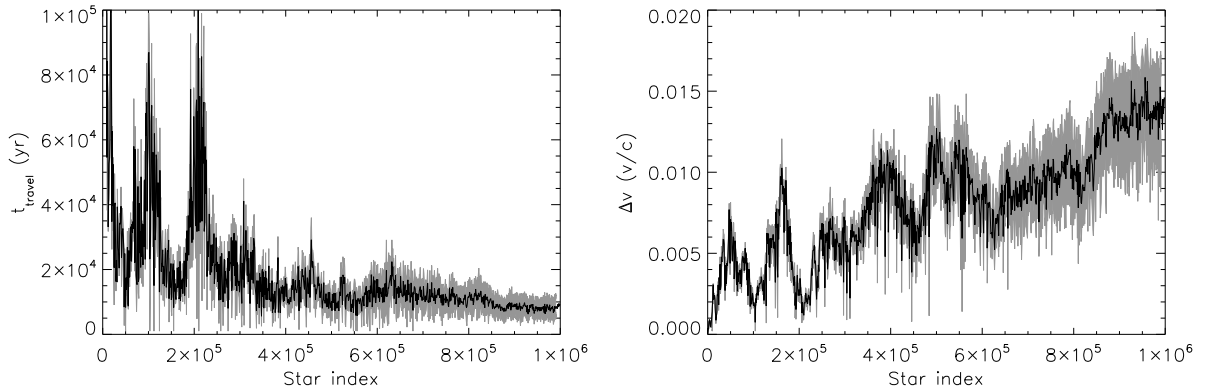

Figure 4: **Left**:The mean travel time between each star for probes in the *maxspeed* simulations, averaged over 30 realisations. The grey shaded area represents the standard error on the mean. **Right**: the mean Δv generated as a result of each slingshot maneouvre, with standard error on the mean shaded grey.

3.3 Slingshot Trajectory, Highest Δv (maxspeed)

With the probe now attempting to maximise its Δv, it pursues a fundamentally different trajectory to the other two cases. The selection criterion for the next star of the journey is purely to maximise Δv - the distance to the next star is not considered. The left hand panel of Figure 4 demonstrates the consequences of this. The travel time indicates protracted journeys between stars in the early stages of the probe's trip. The spikes in travel time are of high significance, and represent the extent of the simulation box. No periodic boundary conditions are applied - as a result, the probe commonly selects destinations that are at the opposite end of the box, and as a result must traverse the box's entire length frequently. The amplitude of these peaks decreases as the probe begins to boost its speed strongly (right hand panel of Figure 4). By selecting for maximal Δv, the probe can achieve velocity increases 2.5 times larger than the slingshot case.

4 Discussion

4.1 Limitations of the Analysis

Before discussing the implications of these results, we should first note some simplifications made to expedite the analysis.

Probably the most important simplification made was to fix the stars in position. While all stars possessed a velocity vector, the position vectors were never updated. As the aim was to create a large number of realisations at modest computational expense, it was felt that this assumption was reasonable. However, it does force us to jettison important dynamical aspects. For example, in the maxspeed case, the probe will select destination stars with relative velocity vectors which are large and negative, i.e the destination star and the current star are moving towards each other. This will reduce the travel time (just as positive relative velocity will increase the travel time). Future work in this area should investigate this effect.

The probe's motion was also simplified in several ways. The maximum Δv achievable by the probe is limited by the distance of closest approach that a probe can make to the star. From equation (4), for a star with mass M_* and an effective radial boundary R_{eff} that the probe cannot cross, there is a maximum value of rotation angle δ dependent on the inward stellarcentric velocity, u_i (Gurzadyan, 1996):

$$\tan \frac{\delta}{2} = \frac{\sqrt{GM_*}}{R_{\mathrm{eff}} u_i} \tag{5}$$

Substituting this into equation 3, we obtain:

$$\Delta v_{\max} = \frac{u_{esc}^2}{\frac{u_{esc}^2}{2u_i} + u_i} \tag{6}$$

where u_{esc} is the escape velocity at the radial boundary of the star:

$$u_{esc} = \sqrt{\frac{2GM_*}{R_{\mathrm{eff}}}} \tag{7}$$

The maximum Δv achievable becomes quite negligible as u_i exceeds $\sim 0.01c$ - for example, a star of mass $1M_{\mathrm{odot}}$ and $R_{eff} = R_\odot$ gives a maximum Δv of $\sim 10^{-11}c$. To improve this value, the probe would have to risk very close approaches with massive, compact objects such as neutron stars and black holes (Dyson, 1963), which could present hazardous tidal forces upon the craft's hull.

We have ignored relativistic effects in this analysis. The probe achieves velocities of $\sim 0.01c$, which gives a Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} = 1.00005, \tag{8}$$

indicating that classical physics is an acceptable approximation for this work. However, future studies that use a higher initial velocity should be cognisant of this.

4.2   Implications for Fermi's Paradox

Let us now investigate possible constraints on Fermi's Paradox, and in particular, the Fermi-Hart timescale t_{FH}. If we assume a constant number density of stars, then we can estimate t_{FH} from the average total travel times calculated in this study:

$$t_{FH} \sim \left(\frac{3 \times 10^{-5}}{\frac{v_{\text{initial}}}{c}} \right) \left(\frac{N_{star}}{10^6} \right) t_{\text{travel}}. \tag{9}$$

Assuming that the number of stars in the Galaxy, $N_{star} = 10^{11}$, then at $v_{\text{initial}} = 3 \times 10^{-5}c$:

$$t_{FH} \sim 10^5 t_{\text{travel}} \sim 10^{13} - 10^{15} \, \text{yr}. \tag{10}$$

This confirms that given the low initial velocity we selected, motivated by current speed records of human-manufactured probes, we are currently incapable of exploring the Galaxy inside the Hubble time with a single probe. However, we should still note that we are much stricter than we might need to be when imposing the maximum powered velocity of a spacecraft, and the relative decrease in travel time depending on probe dynamics is significant (as shown in Table 1). As is well known, if higher initial velocities are indeed possible, then the Fermi-Hart timescale becomes amenable. We can estimate the minimum velocity by rearranging equation (9) for v_{initial}/c:

$$\frac{v_{\text{initial}}}{c} \sim 3 \times 10^{-5} \left(\frac{t_{\text{travel}}}{t_{FH}} \right) \left(\frac{N_{star}}{10^6} \right) = 3 \left(\frac{t_{\text{travel}}}{t_{FH}} \right), \tag{11}$$

i.e. even if $v_{\text{initial}} \sim c$, then

$$t_{FH} \sim 3 t_{\text{travel}} \sim 10^9 - 10^{11} \, \text{yr} \tag{12}$$

which is still quite high (except for possibly the slingshot case, and even then the velocity boosts possible will be much smaller than those achieved at low speeds). From this, we appear to confirm previous calculations that even when probe dynamics are considered in more detail, one of two conditions must be satisfied for t_{FH} to be sufficiently low:

1. Faster than light travel is possible, or

2. multiple probes are required Tipler (1980); Wiley (2011).

While option 1 has been explored theoretically and found to be possible for massless particles and for civilisations that can correctly manipulate space-time (see e.g. Crawford 1995 for a review of these concepts), it requires the existence of exotic matter and energy sources, not to mention staggering technological prowess we do not yet possess. Option 2 would therefore appear to be the most plausible choice. Indeed, probes which carry out a series of stellar flybys without leaving significant evidence of their passage would not affect Fermi's Paradox at all, as individual star systems would only be able to detect these probes briefly

(if at all). It would seem reasonable then to require that probes leave some sort of beacon or artifact in their wake as they pass through a system, to signal their existence and to strengthen Fermi's Paradox. The manufacture (or replication) of many beacons becomes an industrial problem on a scale similar to that of manufacturing multiple probes.

Given our current ability to manufacture large numbers of similar sized craft for terrestrial uses, it is not unlikely that we can adopt a similar approach to building probes. A simple calculation shows that producing 10^{11} Voyager-esque probes would allow humankind to explore the Galaxy in 10^9 years. Given that around 5×10^7 automobiles are produced each year globally[2], it seems reasonable to expect a coordinated global effort could produce the requisite probes within a few thousand years. If the probes are made to be self-replicating, using materials en route to synthesise copies, the exponential nature of this process cuts down exploration time dramatically (Wiley, 2011).

Whether ETIs create a static fleet of probes launched from one source, or an exponentially growing fleet of probes replicated in transit from raw material orbiting destination stars, we argue that these measures strengthen the Fermi Paradox further when slingshot dynamics are included, but the relative strength of dynamics versus numbers are currently unclear. To answer this, we are repeating the analysis made in this paper with self-replicating probes to investigate whether optimised slingshot dynamics are even worthwhile in a cost-benefit scenario (Nicholson et al, in prep).

Having said this, probes carrying out slingshot trajectories in a larger, more realistic domain will be able to produce more realistic trajectories. This is another important avenue for further investigation.

5 Conclusions

We carried out Monte Carlo Realisation (MCR) simulations of a single probe traversing a section of the Galaxy, exploring the effect of slingshot dynamics on the total travel time. Three scenarios were explored: the standard scenario where probes travel under powered flight to their nearest neighbour (powered); traversing the same path, but utilising slingshot trajectories to boost the probe's velocity (slingshot); and a third scenario where the probe selects its next destination in order to maximise the probe's velocity boost (maxspeed).

We find that allowing the probe to make slingshots can reduce the probe's total travel time by two orders of magnitude. The velocity boost is typically additive, and as a result this velocity boost could presumably be marginally increased by allowing the probe to explore a larger domain and a higher quantity of stars.

The speed of the probe was selected to represent current human ability in unmanned spaceflight. The exploration time of probes moving at this speed is sufficiently large that humans would struggle to explore the Galaxy inside one Hubble time without mass production of probes. Our work shows that even when optimising probe trajectories are taken into account, the travel time remains quite large.

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[2]http://www.oica.net/

6 Acknowledgements

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