Eternity in six hours: intergalactic spreading of intelligent life and sharpening the Fermi paradox

Stuart Armstrong[a,*], Anders Sandberg[a]

[a] *Future of Humanity Institute, Philosophy Department, Oxford University, Suite 8, Littlegate House 16/17 St. Ebbe's Street, Oxford, OX1 1PT UK*

Abstract

The Fermi paradox is the discrepancy between the strong likelihood of alien intelligent life emerging (under a wide variety of assumptions), and the absence of any visible evidence for such emergence. In this paper, we extend the Fermi paradox to not only life in this galaxy, but to other galaxies as well. We do this by demonstrating that traveling between galaxies – indeed even launching a colonisation project for the entire reachable universe – is a relatively simple task for a star-spanning civilization, requiring modest amounts of energy and resources. We start by demonstrating that humanity itself could likely accomplish such a colonisation project in the foreseeable future, should we want to, and then demonstrate that there are millions of galaxies that could have reached us by now, using similar methods. This results in a considerable sharpening of the Fermi paradox.

Keywords: Fermi paradox, interstellar travel, intergalactic travel, Dyson shell, SETI, exploratory engineering

---

1. Introduction

1.1. The classical Fermi paradox

The Fermi paradox, or more properly the Fermi question, consists of the apparent discrepancy between assigning a non-negligible probability for intelligent life emerging, the size and age of the universe, the relative rapidity

*Corresponding author

Email addresses: stuart.armstrong@philosophy.ox.ac.uk (Stuart Armstrong), anders.sandberg@philosophy.ox.ac.uk (Anders Sandberg)

with which intelligent life could expand across space or otherwise make itself visible, and the lack of observations of any alien intelligence. Put more simply, why don't we see the aliens that should be out there [1]?

There are about $2.5 \cdot 10^{11}$ stars in the Milky Way and about $5 \cdot 10^{22}$ stars in the visible universe. Planetary systems appear to be relatively common. Assuming the mediocrity principle, which states that Earth is not special, but merely a typical planet, subject to the same laws, effects, and likely outcomes as any other world, it would appear that life and in particular intelligent life would have developed on some of these worlds. Even if a very small fraction such worlds developed intelligence, e.g. 10^{-9}, it would imply hundreds of intelligent species in the Milky Way. These civilisations would be likely considerably more advanced than us, since the Earth is a latecomer: the median age of terrestrial planets is 1.8–0.9 times greater than the age of the Earth [2, 3].

Even at a relatively slow spread using subrelativistic starships, such species could colonize the galactic disk within 50 million to one billion years [4], a very short time compared to the galactic age of 10^{10} years. However, we do not see any evidence of past or present visitations in the solar system, nor any signs of technological activities elsewhere. This is potentially worrying for the future of the human species. If the explanation for the Fermi paradox is simply that intelligent life is hard to evolve (an 'early Great Filter'), then there are no implications for us. But if the explanation is that intelligent life tends to destroy itself before becoming spacefaring (a 'late Great Filter), then we have reason to worry about our future [5, 6]. Gaining information about the relative weights of these possibilities is relevant for policy, for example whether to focus far more on reduction of existential risk.

1.2. Expanding the paradox

The contribution of this paper is to sharpen the Fermi paradox by demonstrating that *intergalactic* colonisation is a feasible task for a civilisation capable of interstellar colonisation – in fact, intergalactic colonisation is not far beyond our current capabilities today. So the apparently empty skies hold a much greater puzzle than before: not only are we not seeing all the alien civilisations that might exist in our galaxy, but we're not seeing all the alien civilisations that might exist in the millions of nearby galaxies and that could have crossed over to ours.

We will not speculate in this paper about resolutions to the Fermi paradox (beyond a discussion in Section 6.2 as to the potential motives for universal expansion). But this sharpening does increase the likelihood of some explanations (e.g. some sort of cosmic disasters typically wipes out intelligent or pre-intelligent life) while diminishing the likelihood of some others (e.g. alien life is quite common, but by chance we're living in a galaxy without any).

Generally one can argue for a likely expansion by going into details about some particular design for how it could be accomplished [7, 4, 8], and showing that that method would produce a galaxy-wide colonisation on a time-scale far shorter than evolutionary or astronomical time scales. Our paper takes a similar tack, but using a far higher fan-out than is usual and intergalactic colonisation instead. We argue that it is rational and possible for a civilisation to send a large number of replicating probes to great distances, and that the resources demanded (time, cost and energy) are small on an astronomical scale. It is very much in a "Dysonian SETI" vein , using exploratory engineering to study possible macroscale projects and their SETI implications [9].

Extragalactic SETI has not been studied much [9] (with the exception of [10]), perhaps due to a bias towards radio communications and against the Kardashev Type III civilizations that would be the only observable intelligences at this scale. Similarly there is limited prior studies on intergalactic colonisation (the exception may be [11]), likely because interstellar colonisation is deemed sufficiently challenging. Expansion timescale arguments are hence content to deal with just a single galaxy to show there is a timescale discrepancy. However, the main difference between interstellar and intergalactic travel is merely a longer time until the destination is reached. If the contents of the colonizing probe are inert over long timescales (as they would need to be for many forms of interstellar travel) it is likely that they can be made inert over the longer flights to other galaxies. Given recent advances in our understanding of the large-scale structure of the universe it behooves us to investigate its feasibility and implications.

Initially, we will look at whether humanity (as a whole) could attempt a mass colonisation of the universe, and on what time scale. Socially, we are unlikely to see such an extraordinary focus on a single goal – but an expanding human civilisation will certainly produce excess resources, some which could be diverted for this purpose. To this end we will first delineate a potential replicator probe design, and tackle how such probes could decelerate upon arrival. We will see what speeds these probes could move at, and how many duplicates need to be sent out to avoid collisions with intergalactic dust particles.

Then we will consider the launch system – due to the great inefficiency of the rocket equation, it would be much more effective to use fixed launch systems than to count on the probes to power themselves. We will analyse these launch systems, and delve into some details as to how they could be powered (four different scenarios will be considered, from speculative anti-matter drives to reasonable fission engines). It will turn out that only about six hours of the sun's energy is needed to commence the colonisation of the entire universe! And this is the kind of energy that a future human civilisation could quite easily aspire to, as we shall demonstrate.

The whole procedure is presented as a conjunction of designs: this technology will be needed, then this one, then the probe must be built in this way, and so on. However, most of these requirements have alternative pathways (instead of constructing a very fine rocket, we could figure out ways of shielding it from collisions, etc. . .) so the whole construction is robust. We will seek to use conservative assumptions throughout.

Of course, this human-based speculation serves simply to illustrate the potential ease with which putative alien civilisation could have reached the Milky Way in time for us to have noticed them today. Thus we will look back into time, and see how many galaxies could have reached us by the present time. These number in the millions, making the Fermi paradox that much more potent.

We'll end with a discussion of the motivations that could cause us or some other civilisation to embark on a colonisation of the universe, and on the implications of this model for SETI.

2. Exploratory engineering

Our paper will by necessity consider technologies that do not exist yet: what is the rational approach to analyse them?

Exploratory engineering is the art of figuring out what techniques are compatible with known physics, and could plausibly be reached in the future by human scientists [12]. Figure 1 illustrates this: there are known physical limits, and known engineering techniques quite far off from them. Exploratory engineering looks at results that are beyond what is currently possible, but that are likely to be achieved by future civilisations.

That is the aim; but in practice it is much easier to solve 'compatible with known physics' that 'could plausibly be reached'. For instance, there are designs of nanotechnological devices that could in theory perform a wide

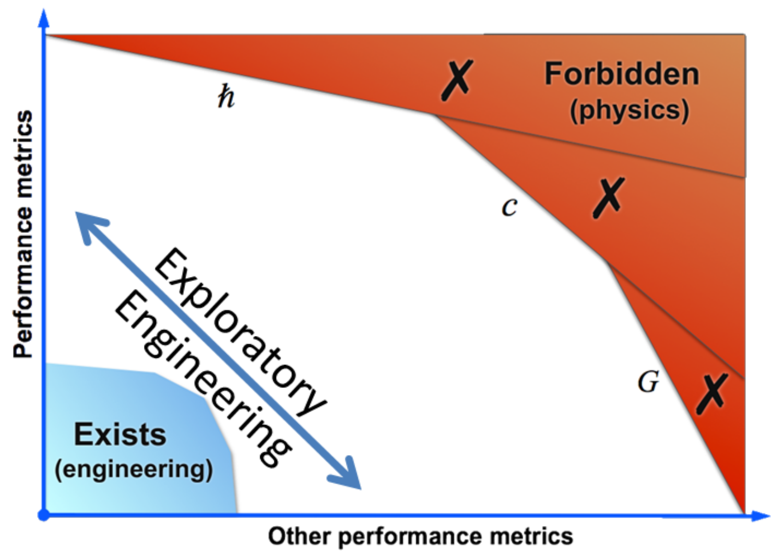

Figure 1: Symbolic representation of exploratory engineering. Courtesy of Eric Drexler.

variety of roles [13]. Seeing that these are possible according to our current models of physics is the easy part; estimating when, how and if such machines could ever be built is a far more subtle task. We shall need some assumptions to separate the plausible from the merely possible.

Humans have generally been quite successful at copying or co-opting nature. Hence our first assumption will be that, over the long term, anything possible in the natural world can also be done under human control.

This means that we will take self-replicators and artificial intelligence (AI) as technologies plausibly available to humans over the next few millennia, one way or another. Note that we don't necessarily mean the standard robotics conception of these; biological cells "programmed" by humans using synthetic biology techniques or modified animal brains could be other routes. It seems likely that through new technology and/or making use of existing natural processes, we will be able put together entities of this type.

Humans have proved adept at automating processes; with advances in AI, we would become even more so. Hence the second assumption is that any task that can be performed, can be automated. This includes the construction of new machinery and new factories (NASA had a design for a self-replicating lunar factory in 1980 [14], and we expect future generations to be able to surpass 1980s NASA). What this means is that sheer scale is not, in and of itself, an insurmountable obstacle: if we have the time, the equipment to build more equipment, and the necessary energy, then even tasks such as disassembling a planet (see Section 4.2) become possible.

These two assumptions – copying natural phenomena and full automation – are what we will be using to model the technologies in this paper.

In the next phase of the paper, we will assume that the human race has a collective burning desire to colonise the universe through replicating probes. This model will allow us to see that such a task is possible in time-frames that are trivial on the cosmic scale, requiring small amounts of the energy that a star-spanning civilisation could acquire. In Section 6.2, we'll turn again to motivation, asking what would induce a generic species to start such a colonisation project. But for now, let us lay aside the question of motives, and focus all attention on the practicalities of the project.

3. The probe and replicator design

Before any other considerations, we need to look at the design of the probe itself: the colonisation machine that will be sent out to the other galaxies.

3.1. Replicators

It would be ruinously difficult to send over a large colonisation fleet; a much more efficient idea is to send over a small payload that then builds what is required *in situ*. This is the concept of von Neumann probes: entities capable of constructing copies of themselves from the resources they find [15, 7]. More specifically, we would want them to be universal constructors: capable of constructing many things, including other universal constructors (which need not be identical).

These objects can certainly exist; indeed, a spaceship with a variety of human couples, life support systems, large databases and an onboard factory would count as a von Neumann probe, capable of building more copies of itself through manufacturing and reproduction. This is not the most practical design, though; it would weigh thousands of tons, would have limited acceleration, and would have whole host of social problems to contend with. What can the techniques of exploratory engineering tell us about more reasonable designs?

In the rest of this paper, we will draw a distinction between the 'replicator', the self-copying piece of the system (the payload to arrive in other galaxies), and the 'probe', the whole object that gets launched (replicator plus rockets and other equipment).

3.1.1. Data storage

It should be noted that data storage does not seem to offer much of restriction here. The most compact method of data storage reasonably imaginable would be a diamond constructed of carbon 12 and 13, with the two types of atoms serving as bits. This would have a storage capacity of 5×10^{22} bits per gram. By comparison, the total amount of data in the human world has been estimated at 2.4×10^{21} bits [16]. If human brains could be instantiated inside a computer [17], then 100 Terabytes is a reasonable estimate for the number of connections in a human brain, meaning one gram of diamond could contain about all the world's data and the (uncompressed) population of Britain.

A more physically plausible data storage level would be that of DNA, which averages one bit per 1.10×10^{-24} kg, or 9.13×10^{20} bits per gram. Storage of 5.27 megabits at a density of 6×10^{20} bits per gram has been demonstrated [18]. That is not to say that such limits will be readily achieved; still, they suggest that Kryder's law ('Moore's law' for hard drives storage [19]) has a lot of time still to run, and that whatever data is required to run the AI in the replicator and its blueprints would not take much more than a few grams.

3.1.2. Size upper limits

Freitas designed a self replicating probe in 1980 [15], building on earlier designs for the Daedalus project [20] and NASA's self-replicating lunar factory design [14]. It was fusion powered, and required basic AI; apart from that its assumptions were extraordinarily conservative in all respects, and all stages of the replication were detailed. It had a replication time of 500 years (largely due to slow fuel accumulation), and the replicator (the relevant part for our studies) weighed 500 tons. Because of its conservative assumptions, we can thus take 500 tons as a reasonable upper bound on the size of a viable von Neumann replicator.

3.1.3. Size lower limits

One of the smallest self replicating designs would be the Merkle-Freitas HC molecular assembler, at 3.91×10^{-18} kg [21]. Even rounding this up by a factor of ten, to give it something akin to a bacterial membrane allowing interactions with its general environment, its mass remains insignificant.

We currently have no engineering pathways that would lead to such a tiny assembler, so this can only be taken as a lower bound.

3.1.4. Building on examples in nature

As per our exploratory engineering assumptions, we will turn to nature to guide our estimates. Table 3.1.4 presents some terrestrial self-replicators [21]. Vibrio comma is the smallest replicator in a general environment, with the slightly heavier E. coli being a very robust replicator. The smallest seed weighs in at a millionth of a gram, yet can assemble a macroscopic structure (the resulting plant). The smallest acorn has a mass of a gram – and an acorn is in essence a solar powered machine that constructs a giant factory to produce more acorns.

Description	Size	Properties
Vibrio comma	10^{-16} kg	General environment replicator
E. Coli	5×10^{-16} kg	Robust replicator
Smallest seed	10^{-9} kg	Creates macroscopic structure
Smallest acorn	1 gram	Creates large structure

Table 1: Selected natural self-replicators.

Of course, the replicator would likely be in a less hospitable environment than an acorn on Earth. It may have to move about to position its initial solar captors (the easiest source of energy), and, assuming it landed on an asteroid (the most generally available landing target), it would have more difficulty leeching materials from the rocks around it. But nature has solved these problems quite well already; a centipede-like structure would provide easy movement, and roots are already capable of extracting all sorts of materials in all sorts of environments. Moreover, the replicators would have access to technology far beyond those in nature, such as lasers, mass spectrometry and detailed knowledge of chemistry.

All in all, it does not seem unreasonable to assume a final replicator with a mass of 30 grams, including the AI and the manipulator arms. This will be taken as the model, though the upper limit of 500 tons should be kept in mind as well.

3.2. Deceleration

A replicator can't just barrel through a galaxy, crashing into stars and shooting out the other side. It needs to slow down and eventually land on a planet or asteroid to get the raw material and resources to create more probes. Thus deceleration is a crucial step, and unlike the launch phase (see Section 4.3), the probe will have to carry on board the means of stopping itself (and that precisely is what distinguishes the probe from the replicator).

3.2.1. Magnetic sails and other exotica

Using rockets to decelerate (see Section 3.2.2) is a very inefficient process, in terms of the reaction mass that must be carried. A more efficient method would be to use properties of the target galaxy to slow down. One could use a magnetic sail [22], using reactions with the galaxy's magnetic field to lose velocity. A cunning trajectory might allow the use of gravitational gravitational assist to slow down effectively. More exotic methods such as a 'Bussard ramjet' [23] could be attempted, and other methods are certainly conceivable and possible.

The low mass of the replicator as compared with galactic objects would make these deceleration methods easier; but the extremely high velocity would make them harder. Since we are trying to stick with conservative assumptions, we will thus not make use of any of these exotic methods, and restrict ourselves to conventional rocket-based deceleration.

3.2.2. Rockets

The relativistic rocket equation is

$$\Delta v \quad = \quad c \tanh\left(\frac{I_{sp}}{c} \ln \frac{m_0}{m_1}\right), \tag{1}$$

where Δv is the difference in velocity, m_0 is the initial mass of the probe, m_1 the final mass of the replicator and the I_{sp}/c term denotes the specific impulse of the fuel burning process. The I_{sp}/c term can be derived from η, the proportion of fuel transformed into energy during the burning process, $I_{sp}/c = \sqrt{2\eta - \eta^2}$ [24].

We will consider three putative modes of deceleration, in decreasing order of speculativeness: antimatter-matter annihilation, nuclear fusion, and nuclear fission. Antimatter rockets could in theory have an I_{sp}/c of 1; in practice, we turn to the results presented in [25], which give an I_{sp}/c of

0.58 (confirming earlier work by Vulpetti [26]). Crucially, the paper explains methods of getting higher specific impulse (for instance through capturing gamma rays emitted during the reaction), which means that we can reasonably take $I_{sp}/c = 0.58$ as a middle of the road estimate for the specific impulse of possible antimatter based rockets. This corresponds to an efficiency of $\eta = 0.185$.

As for nuclear fusion, the standard fusion reaction is

$$^{3}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + n + 17.59\,\mathrm{MeV}.$$

In MeV, the masses of deuterium and tritium are 1876 and 2809, giving an η of $17.59/(1876+2809) = 0.00375$. We will take this η to be the correct value, because though no fusion reactor is likely to be perfectly efficient, there is also the possibility of getting extra energy from the further fusion of helium and possibly heavier elements.

For nuclear fission, the standard reaction is

$$^{235}\mathrm{U} + n \rightarrow {}^{141}\mathrm{Ba} + {}^{92}\mathrm{Kr} + 200\,\mathrm{Mev}.$$

The mass of uranium 235 is 218943 Mev, giving an η of $202/218943 = 0.000922$. We will – somewhat arbitrarily – assume that this reaction can in practice be made 90% efficient, giving a total efficiency of 0.000828, possibly through some 'in situ' re-enrichment of spent fuel – the kind of precise chemical engineering that cells carry out very naturally. For comparison purposes, current reactor designs could reach efficiencies of over 50% of the theoretical maximum [27].

This may be the area in which our claims to be making 'conservative' designs is weakest – any fall-off in fission efficiency results in a dramatic decrease in deceleration potential. To make this position more credible, we must appeal to the other conservative assumptions we have made – especially assuming that the probe possesses no 'magnetic sail' or other ways of decelerating using its target galaxy (see Section 3.2.1) and that we are ignoring the deceleration caused by the expansion of the universe (see Section 3.2.3).

So for the three types of rockets, we have efficiencies of 0.185, 0.00375, and $0.00092 \times 0.9 = 0.000828$. But the rocket does not consist of pure fuel; the reactors and other components must be included as well. Since the rocket will be optimised for maximal efficiency, we assume that 95% of the rocket mass will be fuel, the remaining 5% being infrastructure, and that the infrastructure is gradually cannibalised to serve as reaction mass. Hence the real efficiencies are 95% of the above, giving actual efficiencies of 0.176, 0.00356, and 0.000787, and consequently the I_{sp}/c's as given in Table 2.

	Matter-antimatter	Fusion	Fission
I_{sp}/c	0.567	0.0843	0.0397

Table 2: I_{sp}/c of different types of rockets.

Plugging these numbers into the relativistic rocket equation (1) for Δv's of $50\%c$, $80\%c$ and $99\%c$, and a replicator with a final mass of 30 grams, we get initial masses for the probes as given in Table 3.

Δv	Matter-antimatter	Fusion	Fission
$50\%c$	0.0791 kg	20.2 kg	**31100** kg
$80\%c$	0.208 kg	**13600** kg	3.23×10^{10} kg
$99\%c$	**3.20** kg	1.28×10^{12} kg	2.90×10^{27} kg

Table 3: Initial masses needed for decelerating from various speeds.

The values in bold are those we will be considering in this paper, rounding them up. Thus we will consider matter-antimatter probes of total launch mass 5 kg launched at $99\%c$, fusion-powered probes of mass 15 t launched at $80\%c$, and fission-powered probes of mass 35 t launched at $50\%c$.

3.2.3. No deceleration

Because of the expansion of the universe, some of the probes sent to more distant galaxies might arrive at their destination with very little kinetic energy – even, in the limit, with none at all. If there we no time pressure whatsoever, we could launch probes at each galaxy at speeds calculated to ensure they coasted into that galaxy with no velocity. This is unlikely to be the best way of expanding, as it takes much longer to reach anything (infinite time in the theoretical limit, but still a long time if we allow the probe to arrive with *some* speed).

But this approach might still be interesting for the most distant galaxies; we could for instance imagine using fission rockets for reaching nearby galaxies, and aiming rocketless probes towards the rest. Some reaction mass would still be essential for fine maneuvering - we'd therefore imagine these probes having a mass of 1 kg, and being fired at 99%c, similarly to the matter-antimatter probes.

A coasting probe will also be slowed by collisions with intergalactic gas and dust, but for speeds below 99% c interaction with the cosmic microwave background will dominate [28]. The CMB ahead of the probe will be blue-shifted, producing drag [29]. However, for the probe sizes and velocities considered in this paper the slowing will be negligible ($< 10^{-10}$ over a billion years).

3.3. Collisions, interstellar dust and redundancy

Nature may not abhor a vacuum, but intergalactic space is not empty. At the speeds the probe is moving (up to 99% of the speed of light), the slightest collision could cause an explosion. There are potentially innovative ways of shielding the probe (one suggestion being a disposable low mass shield traveling ahead to ionize incoming particles, backed up with a strong magnetic field on the probe itself to deflect them), but we'll ignore them here and imagine the probe hurtling, unshielded, through the void.

We'll assume that our probe is of sturdy enough construction to survive a grenade blast (about 800 kJ), and that it is capable of repairing itself from sub-critical damage. This critical impact energy would correspond to the collision with a particle of mass:

$$M_{crit} = 8 \times 10^5 \frac{1}{c^2(\gamma - 1)} = 8 \times 10^5 \frac{1}{c^2 \left(\frac{1}{\sqrt{1 - v^2/c^2}} - 1 \right)}$$

In the worst case scenario, traveling at 99%c, this would correspond to a particle of mass 1.46×10^{-12} kg. The redundancy – the number of probes we would need to launch so that we would expect one of them to reach their target galaxy – is

$$R = \exp(dA\rho), \tag{2}$$

where A is the area cross-section of the probe, d the distance to be traveled (in comoving coordinates), and ρ the density of dangerous particles. As we shall see in Section 4.4.2, d is at most 4.09 megaParsecs. We'll assume that the probe has an area of only 1 cm^2, as this minimises the chance of collision. Of course, we won't assume that there would be a working rocket of only this diametre, just that the probe can be packed that tightly for the coasting part of the journey, deploying itself subsequently for the (much shorter) deceleration phase.

To calculate ρ, we'll make use of the Mathis-Rumpl-Nordsieck model [30], under which the distribution of dust particles follows a power law with exponent -3.5. This is likely an overestimate, since most interstellar dust models assume a cutoff near 1μ. [31] gives the mass density of particles of size at least one micron as 2×10^{-6} times the critical density, hence 10^{-35} gm/cm^3. Plugging the power law into this, and assuming cutoffs at 1 micron to 1 cm in dust particle size, we get a ρ of 2.79×10^{-28} particles per cubic centimetre that would be dangerous to a probe traveling at $99\%c$. Plugging these numbers into equation (2), we get $R = 30.7$. We'll round this up, and assume that 40 probes are launched for each galaxy in order to guarantee that one arrives.

This is certainly an overestimate, since a lot of the probes will not be traveling out to those distances, and because due to the expansion of the universe, the probes will find their speed slowly dropping down from $99\%c$ (relative to the dust around them).

For the slower probes ($80\%c$ and $50\%c$ respectively), the needed redundancy R is below 2, so we will simply assume a pair of probes launched towards each galaxy. We will arbitrarily assume the same redundancy for the probes with a 500 ton payload – the cross section will certainly be larger (though certainly smaller in proportion to mass), but the probe will have more methods of shielding available.

Of course, the density of *interstellar* space is much higher than that of *intergalactic* space – matter is much more common inside the galaxies. So much so that it may be unfeasible to launch a universe-colonisation directly from our own sun. But even adding a few staging points a few kiloParsecs away from our galaxy would not add much time on a cosmic scale.

4. The launch phase

We will need a large source of energy to power the multitude of launches needed. Barring some exotic way of directly transforming matter into energy, the most likely source of energy is the sun itself, in all its $3.8 \times 10^{26} W$ glory. The concept of the Dyson sphere [32] is a staple in science fiction: a collection of solar captors partially or completely surrounding the sun to capture a large proportion of its radiated energy. How would we actually go about building such a mega structure? And what would we do with it when we had it?

4.1. Design of the Dyson sphere

The most realistic design for a Dyson sphere is that of a Dyson swarm ([32, 33]): a collection of independent solar captors in orbit around the sun. The design has some drawbacks, requiring careful coordination to keep the captors from colliding with each other, issues with captors occluding each other, and having difficulties capturing all the solar energy at any given time. But these are not major difficulties: there already exists reasonable orbit designs (e.g. [34]), and the captors will have large energy reserves to power any minor course corrections. The lack of perfect efficiency isn't an issue either, with $3.8 \times 10^{26} W$ available. And the advantages of Dyson swarms are important: they don't require strong construction, as they will not be subject to major internal forces, and can thus be made with little and conventional material.

The lightest design would be to have very large lightweight mirrors concentrating solar radiation down on focal points, where it would be transformed into useful work (and possibly beamed across space for use elsewhere). The focal point would most likely some sort of heat engine, possibly combined with solar cells (to extract work from the low entropy solar radiation).

The planets provide the largest source of material for the construction of such a Dyson swarm. The easiest design would be to use Mercury as the source of material, and to construct the Dyson swarm at approximately the same distance from the sun. A sphere around the sun of radius equal to the semi-major axis of Mercury's orbit (5.79×10^{10} m) would have an area of about $4.21 \times 10^{22}\,\mathrm{m}^2$.

Mercury itself is mainly composed of 30% silicate and 70% metal [35], mainly iron or iron oxides [36], so these would be the most used material for the swarm. The mass of Mercury is 3.3022×10^{23} kg; assuming 50% of this mass could be transformed into reflective surfaces (with the remaining material made into heat engines/solar cells or simply discarded), and that these would be placed in orbit at around the semi-major axis of Mercury's orbit, the reflective pieces would have a mass of

$$\frac{0.5 \times 3.3022 \times 10^{23}}{4.21 \times 10^{22}} = 3.92\,\mathrm{kg/m}^2.$$

Iron has a density of $7874\,\mathrm{kg/m}^3$, so this would correspond to a thickness of 0.5 mm, which is ample. The most likely structure is a very thin film (of order 0.001 mm) supported by a network of more rigid struts.

4.2. Disassembling Mercury

In order to construct the Dyson swarm, we would have to take Mercury completely apart (this section is inspired by Robert Bradbury's unpublished analysis of planetary disassembly). Disassembling a whole planet would be a slow process, requiring vast amounts of energy (the gravitational binding energy of Mercury is 1.80×10^{30} J). However, the material removed will be made into solar captors which will generate energy, allowing a more efficient removal of matter, thus generating a feedback loop.

Making a few conservative assumptions, we can see that the disassembly can proceed at a very fast pace. The assumptions are:

1. The overall efficiency of the solar captors is 1/3, by the time the solar energy is concentrated, transformed and beamed back to Mercury.
2. The initial energy generating source will be a $1\,\mathrm{km}^2$ array of solar panels, constructed on Mercury itself.
3. Of the energy available, 1/10 will be used to propel material into space (using mass-drivers for instance [37]), the rest going to breaking chemical bonds, reprocessing material, or just lost to inefficiency. Lifting a kilo of matter to escape velocity on Mercury requires about nine mega-joules, while chemical bonds have energy less that one mega-joule per mol. These numbers are comparable, considering that reprocessing the material will be more efficient than simply breaking all the bonds and discarding the energy.
4. It takes five years to process the material into solar captors and place them in the correct orbit – much larger than the circa 88 day orbital period of Mercury.
5. Half of the planet's material will be suitable to construct solar captors.

These assumptions are approximations over the course of the disassembly: for instance, initially, it would be trivial to place the solar captors in a good solar orbit, a process that would be more complicated once there are a lot of other captors already in place. Towards the end of the disassembly, there would be little gravitational potential to overcome, so the breaking and reforming of chemical bonds would require more energy relative to moving the material. The core is more iron-rich than the surface, so there would be more wasted material initially (possibly requiring the initial solar captors to be less iron-based), and there are worries as to how the core could be cooled during disassembly – though conversely, the core heat might be harvested to power the project.

Note that these assumptions are perfectly compatible with our models of exploratory engineering – it seems perfectly plausible, today, that a major government could set up a small mining operation on Mercury that propelled material into orbit where a factory reprocessed it into solar captors. It would cost a lot and would be unlikely to be attempted, but there are no fundamental technological barriers to doing so. What we are looking at here, is a fully automated version of this process.

Then if these assumptions are taken to be reasonable, the disassembly of Mercury proceeds at a brisk pace, reaching exponential speeds through the feedback loop. As can be seen in the graph in Figure 2, the power available increases initially in five-year cycles, which gradually smooth out to become linear on the log scale. Mercury itself will be completely disassembled in 31 years and 85 days, with most of the mass loss happening in the last 4 years, as shown in the graph in Figure 3.

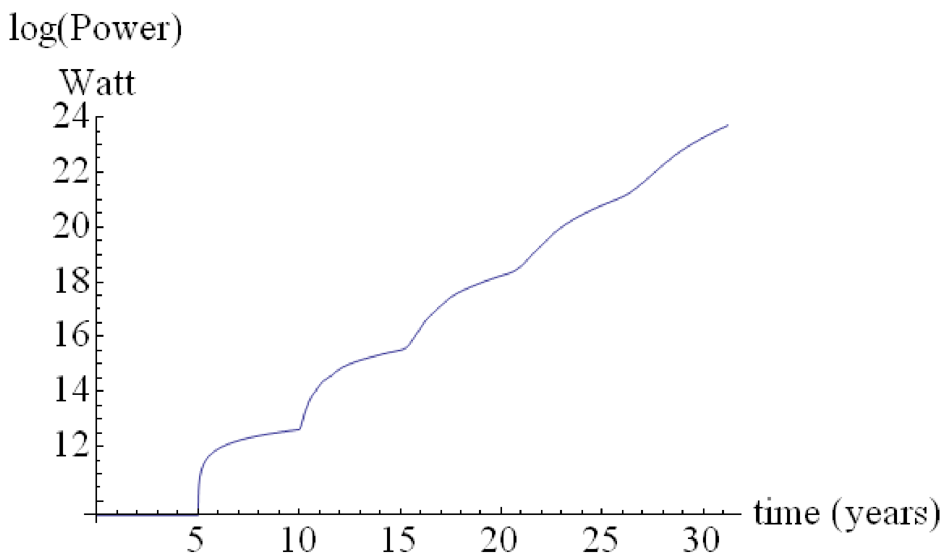

Figure 2: Power available during the disassembly of Mercury.

The details turn out to be not all that important: as long as the feedback loop is possible, exponential growth will generally ensure that the Dyson sphere is constructed in a small number of iterations of the cycle of mining, processing, and placing the solar panels in orbit.

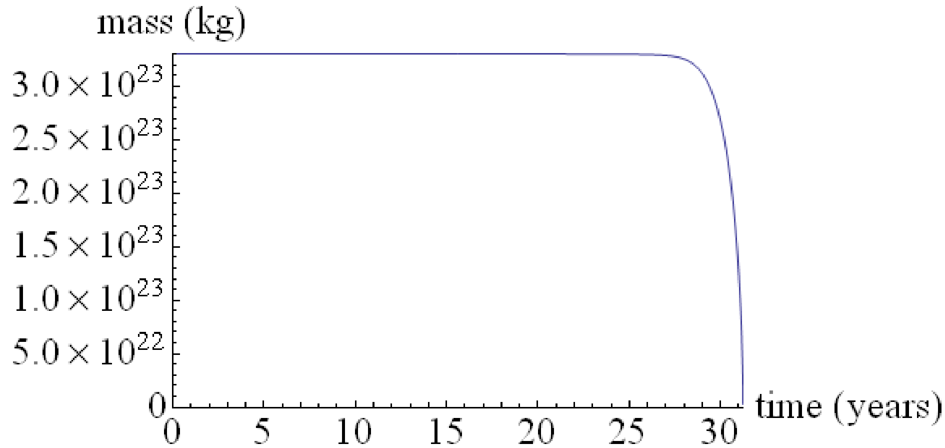

Figure 3: Mass remaining during the disassembly of Mercury.

4.3. The launch system

We will need some method for launching all these probes at their distant targets. Using rockets is highly inefficient, instead some form of fixed launch system, such as coilguns, should be used. The theoretical efficiency of coilguns, given superconductors, seems to be close to 1 [38]. Other designs such as quenchguns could be used. Again, these seem to have theoretical efficiency of 1 [39, 40]. Finally, one could use laser propulsion [41] or particle beam propulsion [42] to get the probes up to the needed velocity without needing to build the long barrels of coilguns or quenchguns.

Because practical efficiency never reaches the theoretical limit, we'll content ourselves with assuming that the launch system has an efficiency of at least 50%.

4.4. Launch targets

Traditionally, space exploration has been conceived similarly to exploration on Earth: short hops to close targets, after which resources are gathered for the next step. This is the model implicitly used in for instance [43], which envisages a 'colonisation front' moving out through the galaxy, using up resources and thus denying pursuers the opportunity to catch up with them. But apart from risks of collision (see section 3.3), getting to the furthest galaxies is as easy as getting to the closest: the only difference is a longer wait between the acceleration and deceleration phases. A zig-zag course between stars and galaxies would take more time than going straight to the destination, an important consideration when the expansion of our universe will put more and more galaxies out of reach. And, as we shall see, the resources needed to shoot off at high speed are relatively small: there is no need to leap-frog from star to star, gathering energy at each step. Two or three stages would be enough to colonise every reachable star.

It is this 'high fanout' approach that distinguishes our model from previous ones, and is critical in making expansion so easy. There are some extra considerations needed to hit galaxies that are on the other side of the Milky Way, but we'll neglect this: one or two waypoints are enough to get around the problem.

4.4.1. The Friedmann metric and its geodesics

In geometric units, set $c = 1$. Our universe is expanding at an accelerating rate, that will become approximately de Sitter [44] in the far future. In a de Sitter universe, the universe is expanding at an exponential rate, implying that distant parts of the universe will never be able to reach each other by signal or rocket, because they are moving apart faster than light.

This is also a concern in our universe: not every galaxy we can see is one we can reach. The Friedmann metrics are the metrics of homogeneous, isotropic, expanding (or contracting) universes, which approximate our own universe on the large scale. Taking the approach of paper [45], for our universe this metric is

$$g = dt^2 - a(t)^2 d\Sigma^2,$$

where $d\Sigma^2$ is a flat metric, and galaxies in the expanding universe stay immobile in these flat coordinate – these are the so-called comoving coordinates. The expansion parameter $a(t)$ follows the first Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3} + \frac{8\pi(\rho_m + \rho_r)}{3},$$

where Λ is the cosmological constant, $\rho_m \propto a^{-3}$ is the average matter density in the universe, and $\rho_r \propto a^{-4}$ is the average radiation density. Let $H = \frac{\dot{a}}{a}$ be the Hubble parameter, whose current value is H_0; then the first equation is often re-written as

$$\frac{H^2}{H_0^2} = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_\Lambda,$$

where $\Omega_\Lambda = \frac{\Lambda}{3H_0^2}$, $\Omega_r = \frac{8\pi\rho_r}{3H_0^2}$, $\Omega_m = \frac{8\pi\rho_m}{3H_0^2}$.

According to [45, 46], the current values for these variables can be calculated as

$$\begin{aligned} H_0 &= 71\frac{\mathrm{km}}{\mathrm{sMpc}} = 2.3 \times 10^{-18}/\,\mathrm{s}, \\ \Omega_\Lambda &= 0.73, \\ \Omega_r &= 8.35 \times 10^{-5}, \\ \Omega_m &= 0.27 - \Omega_r. \end{aligned}$$

If χ is a flat coordinate field in the comoving coordinate frame, we can compute the various Christoffel symbols for g, taking into account the fact that g is constant in the co-moving directions:

$$\begin{aligned} a'(t)a(t) &= \Gamma^t_{\chi\chi} \\ \frac{a'(t)}{a(t)} &= \Gamma^\chi_{\chi t} = \Gamma^\chi_{t\chi} \\ 0 &= \Gamma^\chi_{\chi\chi} = \Gamma^t_{tt} = \Gamma^t_{\chi t} = \Gamma^t_{t\chi}. \end{aligned}$$

Then any geodesic $\psi(x) = (\tau(x), \sigma(x))$ must must obey the geodesic equations

$$\tau''(x) + a'a\,(\sigma'(x))^2 = 0 \tag{3}$$

$$\sigma''(x) + 2\frac{a'}{a}\sigma'(x)\tau'(x) = 0. \tag{4}$$

The tangent field of geodesic of g is auto-parallel under the Levi-Civita connection of g, and hence must be of constant g norm-squared:

$$a^2\,(\sigma'(x))^2 - (\tau'(x))^2 = C. \tag{5}$$

Substituting this into equation (3) gives an equation with only τ terms:

$$\tau''(x) + \frac{a'}{a}\left(C + (\tau'(x))^2\right) = 0.$$

This, along with equation (5), is enough to fully define the geodesic; though equation (5) is first order, rather than second, this is compensated by the extra parameter C. So, putting in all the implicit dependencies, we need to solve the following system of equations:

$$\begin{aligned}
\frac{a'(t)^2}{a(t)^2} &= H_0^2\left(\Omega_r a^{-4}(t) + \Omega_m a^{-3}(t) + \Omega_\Lambda\right) \\
0 &= \tau''(x) + \frac{a'(\tau(x))}{a(\tau(x))}\left(C + (\tau'(x))^2\right) \\
\sigma'(x) &= \frac{1}{a(\tau(x))}\sqrt{(\tau'(x))^2 + C}.
\end{aligned}$$

This is a system ODE's, with each equation being independent of the ones beneath it.

4.4.2. Reaching into the universe

If we want to see the trajectories of probes emitted from our sun, we take our present moment as the origin of these geodesics. We will take $a(t) = 1$ at the present day, so that all distances reached by geodesics are in current Parsecs. Seeing our galaxy as approximately immobile in the comoving coordinates, the parameter C gives the velocity with which we sent out the probes: a probe moving away at relative velocity pc, for $p \leq 1$, will have $C = p^2 - 1$.

The equations can then be solved numerically by Mathematica [47] for different values of p (and hence C). The results are plotted in the graph of Figure 4 for initial speeds of 50%c, 80%c, 99%c, and, for comparison purposes, c. These show how far these probes can reach in Parsecs in current comoving coordinates.

In order to estimate how many galaxies are within reach, we need to know the density of galaxies in the reachable universe. The observable universe is of approximate volume 1.3×10^{31} cubic Parsecs [48], and has about 1.7×10^{11} 'bright' galaxies [45]. This gives the figures in Table 4 on the (approximated) number of galaxies reachable at the various speeds – hence the minimum number of probes that need to be sent out, to colonise all galaxies reachable at that speed.

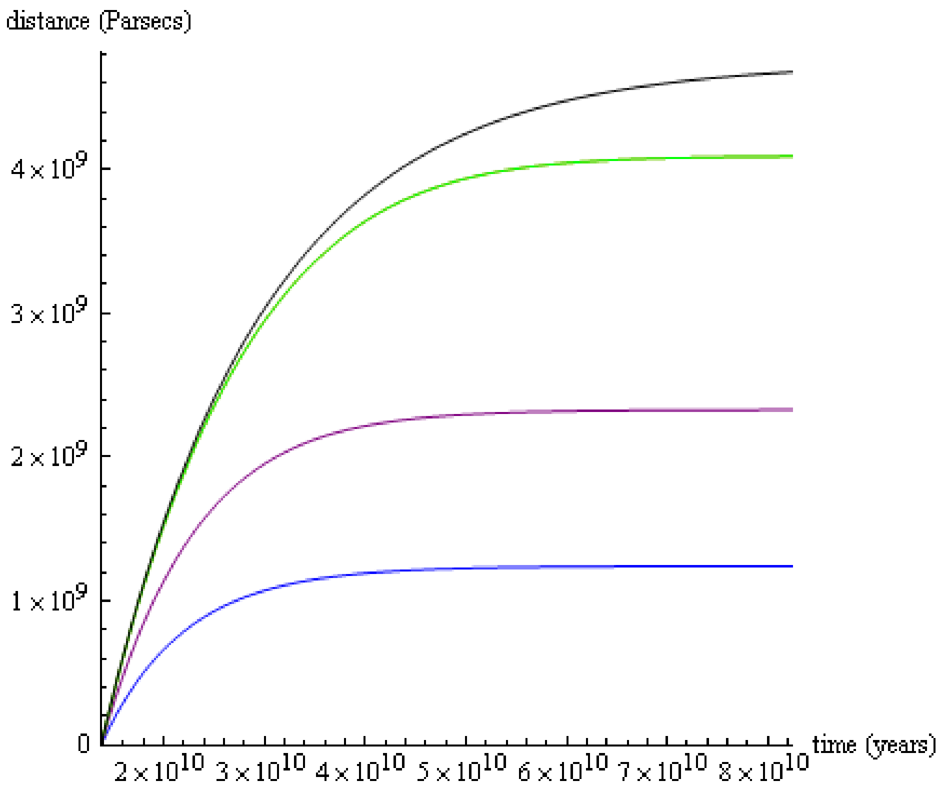

Figure 4: Distance reached by probes with speeds of 50%c, 80%c, 99%c and c, in comoving coordinates.

Speed	50%c	80%c	99%c
Maximum distance	1.24×10^9	2.33×10^9	4.09×10^9
Galaxies reached	1.16×10^8	7.62×10^8	4.13×10^9

Table 4: Table of maximal reachable distance (in Parsecs) and approximate maximal number of galaxies reachable, at various launch speeds.

Note that despite the vast number of destinations and the extra redundancy, the total mass of probes is insignificant compared to the mass used to build the Dyson swarm.

5. Total energy and time requirements

So for each of the modes of deceleration – no deceleration, matter-antimatter, fusion, fission – we have a mass for the probe, a speed to be accelerated to, and hence a number of galaxies to be aimed for. For the matter-antimatter powered probes, we will also need to manufacture the antimatter to put on board (the energy costs of furnishing the other probes with hydrogen or uranium 235 are negligible in comparison with other costs).

We recall the assumptions: the probes will be carrying either fission rockets, fusion rockets, matter-antimatter rockets, or no rockets at all. They will have masses of 35 t, 15 t, 5 kg and 1 kg respectively. The first two will be launched at speeds of 50%c (aimed at 1.16×10^8 galaxies) and 80%c (aimed at 7.62×10^8), with a redundancy of two. The last two will be launched at 99%c (aimed at 4.13×10^9 galaxies), with a redundancy of 40. The Dyson sphere is assumed to have an efficiency of one third (solar power output is 3.8×10^{26} W), while the launch system has an efficiency of a half.

Putting all this together, the full energy costs of blasting these probes to every reachable galaxy is given in Table 5. The table also gives the time required for powering this mass launch if all the Dyson sphere's energy were diverted towards it, and then gives the same result for the upper-bound 500 t replicator. Other, more efficient colonisation paths may be possible: for instance aiming for clusters or superclusters instead of galaxies, and spreading out from there (which could cut energy demands by a further factor of a hundred or a thousand).

Rocket type:	**Fission**	**Fusion**	**Antimatter**	**No rocket**
Probe mass	35000 kg	15000 kg	5 kg	1 kg
Velocity	50%c	80%c	99%c	99%c
Kinetic energy	4.87×10^{20}	8.99×10^{20}	2.74×10^{18}	5.47×10^{18}
Fuel energy	≈ 0	≈ 0	4.49×10^{17}	0
Number of probes	2.31×10^8	1.52×10^9	1.65×10^{11}	1.65×10^{11}
Total energy	1.13×10^{29}	1.37×10^{30}	5.27×10^{29}	9.05×10^{28}
Time required, 30g replicator	**1780 seconds**	**21600 seconds**	**8310 seconds**	**1430 seconds**
Time required, 500t replicator	**938 years**	**11400 years**	**4390 years**	**754 years**

Table 5: Time and energy requirements for universal colonisation.

These are all very low numbers; the times required for the 30 gram replicators are insignificant on a human scale (a maximum of 6 hours in the worse – fusion – case), and the times required for the 500 ton replicators are insignificant on a cosmic scale. It is not our contention that a universal colonisation is likely to happen in this exact way, nor that the whole energy of a star will be diverted towards a this single goal (amusing as it is to picture a future 'President of the Solar System' proclaiming: "Everyone turn off their virtual reality sets for six hours, we're colonising the universe!"). Rather this reveals that if humanity were to survive for, say, a million years – still a comically insignificant interval – and we were to spread over a few star systems, and spend nearly all available energy for our own amusement, we could still power these launches, many times over, from small amounts of extra energy. Hence on a cosmic scale, the cost, time and energy needed to commence a colonisation of the entire reachable universe are entirely trivial for an advanced human-like civilisation.

5.1. After the universe, the galaxy

Once universal colonisation is en route, a second wave to colonise the galaxy could be launched on similar time scales. There are more stars in a galaxy than galaxies in the universe, but the speeds required are much less. Similarly, the intergalactic replicators, upon arrival, will be launching their own galactic colonisation on roughly the same time scales, plus the time taken to construct a Dyson sphere: the colonisation won't proceed in a series of steps, but by sending out probes to every star almost simultaneously. This assumes the incoming replicator can reliably target a star that has planets to disassemble, a not unreasonable requirement seeing the prevalence of planets we have discovered [49]. Thus the 'time to colonisation' is mainly the travel time, and nearly every star can be grabbed in two or three generations of replicators.

6. Sharpening the Fermi paradox

6.1. Reaching us

The main purpose of the forgoing was to show that, given certain assumptions, it was possible for humans to launch the colonisation of the entire universe on scales of time and energy that are cosmically insignificant – only requiring about two replication stages to reach every star we could ever reach, with a rapid launch phase. If human civilisation could achieve this, then it is highly likely that any star-spanning alien civilisation would be capable of doing so as well. We can run the equations of section 4.4.1 backwards in time, to see how many galaxies could reach us at various speeds (the dotted lines representing exact billion years into our past). These results are presented in Figure 5 and Table 6.

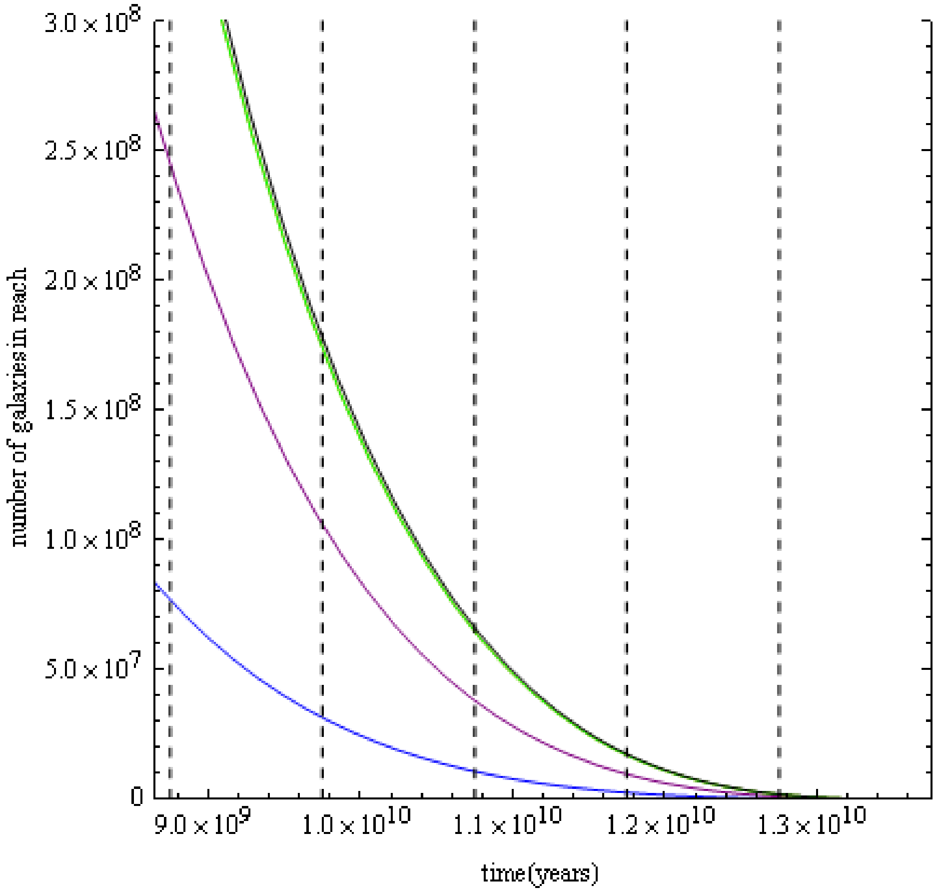

Figure 5: Number of galaxies that can reach us with speeds of 50%c, 80%c, 99%c and c, from different starting moments.

We plotted them going back up to five billion years, since the Earth is certainly not among the earliest terrestrial planets. Indeed it has been estimated that of the stars that could have planets with complex life on them in the Milky Way, 75% of them are older than our sun [3]. Thus it certainly seems plausible that life could have evolved a few billion years earlier than ourselves. And by the arguments presented above, the window of time

	50%c	80%c	99%c
1 billion years	2.63×10^5	1.03×10^6	1.89×10^6
2 billion years	2.57×10^6	9.63×10^6	1.67×10^7
3 billion years	1.07×10^7	3.80×10^7	6.46×10^7
4 billion years	3.14×10^7	1.06×10^8	1.74×10^8
5 billion years	7.69×10^7	2.45×10^8	3.88×10^8

Table 6: Number of galaxies that could have reached us, at various starting points and various speeds.

between 'technological civilisation' and 'mass expansion' are incredibly brief. As can be seen, even at half of light-speed (fission rockets), and going back two billion years, we have over two and half million galaxies within reach for a civilisation capable of this kind of expansion. At the faster speeds, and going further back, many more galaxies need to be added to the Fermi paradox, up to 388 million in the worst case (99%c, five billion years ago).

6.2. Why would they want to expand?

The above is a demonstration of possibility: given the assumptions, alien technological civilisations in these galaxies could reach us. But in order to sharpen the Fermi paradox, we would need to show that they are likely to want to do so. There are in fact some very general arguments, applying to most putative alien civilisations and to future human civilisations, why such an expansion is likely to be attempted.

The argument is often given that advanced aliens would not wish to colonise or explore the galaxy, for a variety of more or less plausible reasons. The problem with this argument is that it assumes a uniformity of motive: that all aliens would share the same desires to avoid expansion – or at least that all those capable of expanding, and capable of preventing others from expanding, share the same desires. This is certainly not a trait that evolution would have selected for; and looking at the variety in the human population, we can already see several groups who would be inclined to start the exploration on their own, if they could. For instance, total utilitarians desirous of spreading value across the universe, space-fans like the British Interplanetary Society, who explicitly desire to start a colonisation project, not to mention certain religious groups. As the quantity of energy available to the whole civilisation expands, these groups will get closer and closer to the ability to start the mass colonisation project on their own – especially if, as seems likely, these groups are also those most willing to take over nearby stars and other sources of energy.

Not all groups will be motivated by such explicitly exploratory aims; some, whether criminal or oppressed, will simply seek to escape from a dominant group. Because of the expansion of the universe, it is possible for some groups to escape at speeds that will *never* be caught: aiming for the edge of the universe at such a high fraction of c that by the time the dominant culture realises in which direction they have left, it will be too late to catch them (this scenario is more plausible for a civilisation spread over several star-systems). With only a few probes needed, escaping at these kinds of speed becomes feasible, especially if non-rocket means are available to slow the probe upon arrival. Another escape tactic would simply be a mass exodus, counting on the fact that the dominant civilisation will not be able to catch up every escaping probe in every direction.

Escaped probes may not be likely to paint a large fraction of the universe in alien colours; however, trying to prevent such escape might do so. If the dominant group wishes to prevent escape, the best way is simply to get there first: send out their probes en mass to be able to prevent any internal exodus. They would need to cover the majority of the universe with 'police probes' in order to prevent any subgroup from escaping. Even if they had no desire to use the universe for anything, such 'police probes' could remain unobtrusively present to prevent unauthorized changes. In fact, with the right backup strategy they could remain in place indefinitely [50].

Civilisations based around small amounts of stars remain vulnerable to large scale disasters, such as nearby supernovas or gamma-ray bursts. It would therefore be rational to take the decision to spread out across across the galaxy to prevent such accidental disasters. Civilisations based around a single galaxy, on the other hand, remain vulnerable to internal conflicts and war: spreading across the universe (especially in high speed dashes at distant galaxies that will soon slip over the cosmic event horizon) reduces this risk. Thus rational survival reasoning may cause civilisations to want to colonise large tracts of the universe in this way.

If the alien civilisation is capable of solving their species coordination problem, and take control of all their subgroups without resorting to a preemptive colonisation, they may still be tempted to take over the universe to prevent others from doing so. The game theoretic reasoning could proceed with each alien civilisation perfectly willing to see the universe uncolonised, but unwilling to run the risk of other civilisations grabbing resources and galaxies that might be used against them for undesirable ends. Since they expect that other putative civilisations will be running the same reasoning, they are aware of the risk of getting preempted. Since they will presumably all be aware that a 'reasonable defensive measure' for one side will be an aggressive attack for the other, there is no justifiable reason to hang back: any risk is always minimised by grabbing the universe first (which can be done at very low cost). It is better have unused and unobtrusive police systems in place than to get a nasty surprise.

These reasons can be summarised as:

- Subgroups desiring colonisation.
- Subgroups desiring escape.
- Main groups wishing to prevent colonisation or escape.
- Civilisations wishing to reduce the risk of catastrophic collapse.
- Civilisations taking over the universe to prevent others from doing so.

Thus there seems to be strong reasons to expect any technological civilisation with the resources of one or several stars to launch such an expansionary colonisation project, and the Fermi paradox is indeed sharpened.

6.3. Robustness of the result

The efficiency of solar capture does not change the results much: planetary disassembly and launch time scales linearly with the available energy. This also suggests that the same procedure can be implemented at dimmer stars.

The amount of material needed for a Dyson swarm of this kind is modest on a solar system scale (less than 0.1% of the total planetary mass). It might turn out that certain elements necessary in bulk for the mining propulsion, probe launch system or the probes themselves are not available in Mercury, necessitating mining elsewhere. However, even with a uranium fraction on the order of 10^{-8} Mercury has $\approx 3 \cdot 10^{15}$ kg (assuming typical abundance), around 20 tons per probe even in the most numerous probe case. The same is likely to hold true in most main sequence solar systems.

While we have not gone into significant technical detail of the launching system there are numerous different proposals and methods in the literature:

it would be highly surprising if none could be implemented given the assumed resources and the use of fairly small probes.

In the estimation of the authors, the assumptions on intergalactic dust and on the energy efficiency of the rockets represent the most vulnerable part of the whole design; small changes to these assumptions result in huge increases in energy and material required (though not to a scale unfeasible on cosmic timelines). If large particle dust density were an order of magnitude larger, reaching outside the local group would become problematic.

7. Discussion: what does this imply?

We have showed that, given certain technological assumptions, intergalactic colonisation appears to be possible given known natural laws and the resources within a solar system. This process could be initiated on a surprisingly short timescale (decades) – well within timescales we know some human societies have planned and executed large projects. A star-spanning civilisation would find the energy and resources required so low, they could do this project as an aside to their usual projects. Thus if interstellar expansion can be attempted, then intergalactic expansion should also feasible. Indeed, there is likely no inherent limitation on the scales of activities of technological civilisations beyond those imposed by the laws of nature and available resources [51].

This result implies that the absence of aliens is more puzzling than would it would be if we simply considered our own galaxy. This makes the Fermi paradox more puzzling and more relevant to the future fate of humanity, increasing the value of SETI and of various attempts to explain the paradox [52].

But what kind of civilisations should we be looking for? Robin Hanson has argued that a spreading interstellar species will tend to (culturally) evolve towards a tendency for rapid expansion with no concern for leaving useful resources for future use [43]. However, his model (a staple of science fiction, based strongly on human modes of exploration on Earth) presupposes short jumps between colonies, leading to many generations of colonies and hence making them more susceptible to drift towards this attractor state. In a high-fanout colonisation scenario there are few generations and far less opportunity for this form of evolutionary convergence: at one extreme there will be at most two colonisation steps between the original culture and all its descendant colonies. This means that there is no tendency to waste resources, and hence that the entire colonisation endeavor will be both easier to control centrally and harder to detect.

Indeed, if the alien civilisations wished to remain undetectable, it would be relatively easy for them to do so. We are unlikely to notice a single Dyson sphere in a distant galaxy. The probes would have a very low mass, and though they would likely have a characteristic deceleration radiation pattern, this wouldn't last long and we would be lucky to notice it in the tiny expanse of time we could have done so. Once inside the Milky Way, it would suffice to either Dyson a single star, or to construct smaller and undetectable solar captors on a series of planets (maybe in a dozen star systems). With this energy, the alien probes could then discreetly rush every star in the galaxy – the lower velocities needed mean that we would be even less likely to notice the deceleration, which could presumably be deliberately concealed if need be. Indeed, discreetly grabbing the cosmos would only be slightly harder than blatantly doing so.

How does all this leave the various traditional explanations for the Fermi paradox? One proposed way out of the paradox is various convergence hypotheses: alien civilizations will over time converge on particular behaviors that resolve the silent sky (e.g. [53]). This must not only act on all individual members of a civilization, no matter what values they have (or later come up with) and their degree of dispersion, but also for all individual civilizations, no matter what kind of beings they are, their initial and later values, and lack of causal contact. Our result implies that the convergence has to be even more profound than typically assumed, perhaps stretching credulity. However, the high fanout does make it more reasonable to suppose that a single civilizations will be able to keep motivational homogeneity across all its 'colonies'.

One explanation that is not strongly affected by our conclusion is the "already here" explanation, where an early civilization seeded the local volume with probes. If the programming of the probes includes preventing other probes from being built and there is a sufficiently strong incumbent advantage to prevent latecomer species from rebelling, such a hegemony could enforce "quiet" policies such as the Zoo or Interdict hypothesis [54, 8]. Since the programming of the probes could have been set by a single decision-maker and could remain unchangeable, this possibility does not need to assume strong cultural convergence.

Our scenario gives a significant first mover advantage: elder civilizations can colonize or influence a far larger fraction than late civilizations. It does reduce the probability of the "deadly probes" scenario where replicators wipe out young civilizations, since emplacing probes everywhere is cheap and easy: overlooked civilizations would be very rare, and likely located at very remote times or peculiar locations. Since we are still around and not in any special location, this explanation is weakened.

If extinction before developing to a detectable stage is the explanation, it must strike reliably before the launch of the first probes. While it could be argued that technologies necessary for this kind of scenario are inherently risky (AI, self-replication, relativistic projectiles) it seems problematic to argue that they are always developed and misused with deadly (non-detectable) consequences before the expansion infrastructure can be built. There are potential technology paths that first lead to civilizations inhabiting a solar system (becoming far more resilient than a single-planet civilization) and then to gradual development and mastery of the risky technologies. The historical interval between gaining dangerous technologies and finishing the probe launches can clearly be made as small as a few decades. Even if such paths are rare, the vast increase of possible origin locations implied by our argument weakens the extinction explanation – which is good news for our own outlook.

Another explanation is that the technology ceiling is far lower than we have assumed. While self-replication, megascale engineering, and relativistic spacecraft are currently outside human capability there does not *seem* to be any theoretical reason why they cannot possibly be fashioned given sufficient time and effort. But it could be that there exist some fundamental limitation to what can be automated, whether macroscopic objects can be accelerated to high speed, reliably sent over long distances, or function over very long periods of time, making interstellar or intergalactic colonization impossible. However, again this requires the bound to apply to any technology invented by any species. If one were to see technology bounds as the most likely explanation of the paradox, it would suggest that investigating bounds by exploratory engineering may be a promising approach to SETI.

The "we are the first/only ones" explanation is also weakened from the expanded potential origin space: the likelihood of intelligent life must be reduced by many orders of magnitude compared to previous arguments. If this explanation is the true answer, the future is also far bigger than commonly thought: (post)humanity can expand over very vast distances and achieve very large populations in an otherwise empty and value-less universe. We may hence be obliged to safeguard the potential value of this vast future from risk to a far greater degree than is normally recognized [55].

Acknowledgments

We are very grateful for comments, support and help from Milan Ćirković, Pedro Ferreira, Eric Drexler, Nick Bostrom, Timothy Clifton, Toby Ord, Robin Hanson, Daniel Dewey and Seán Ó hÉigeartaigh.

[1] D. Brin, The 'great silence': the controversy concerning extraterrestrial intelligent life, Quarterly Journal of the Royal Astronomical Society 24 (1983) 283–309.

[2] C. H. Lineweaver, An estimate of the age distribution of terrestrial planets in the universe: Quantifying metallicity as a selection effect, Icarus 151 (2001) 307–313. arXiv:arXiv:astro-ph/0012399, doi:10.1006/icar.2001.6607.

[3] C. H. Lineweaver, Y. Fenner, B. K. Gibson, The galactic habitable zone and the age distribution of complex life in the milky way, Science 303 (5654) (2004) 59–62.

[4] W. Newman, C. Sagan, Galactic civilization: Population dynamics and interstellar diffusion, Icarus 46 (3) (1981) 293–327.

[5] R. Hanson, The great filter - are we almost past it?, http://hanson.gmu.edu/greatfilter.html (1998).

[6] N. Bostrom, Where are they? why i hope the search for extraterrestrial life finds nothing, Technology Review (2008) 72–77.

[7] R. N. Bracewell, Communications from superior galactic communities, Nature 186 (4726) (1960) 670–671.

[8] M. J. Fogg, Temporal aspects of the interaction among the first galactic civilizations: The "interdict hypothesis", Icarus 69 (1987) 370–384.

[9] R. J. Bradbury, M. M. Cirkovic, G. Dvorsky, Dysonian approach to seti: a fruitful middle ground?, JBIS 64 (2011) 156–165.

[10] J. Annis, Placing a limit on star-fed kardashev type iii civilisations, JBIS 52 (1999) 33–36.

[11] M. J. Fogg, The feasibility of intergalactic colonisation ad its relevance to seti, Journal of the British Interplanetary Society 41 (1988) 491–496.

[12] E. Drexler, Nanosystems, Wiley, 1992, Ch. Appendix A. Methodological Issues in Theoretical Applied Science.

[13] D. G. Allis, K. E. Drexler, Design and analysis of a molecular tool for carbon transfer in mechanosynthesis, J. Comput. Theor. Nanosci 2 (2005) 45–55.

[14] R. A. Freitas, W. B. Zachary, A self-replicating, growing lunar factory, in: J. Grey, L. A. Hamdan (Eds.), Proceedings of the Fifth Princeton/AIAA Conference, American Institute of Aeronautics and Astronautics, 1981.

[15] R. A. Freitas, A self-reproducing interstellar probe, J. Brit. Interplanet. Soc. (33) (1980) 251–264.

[16] M. Hilbert, P. López, The world's technological capacity to store, communicate, and compute information, Science 332 (6025) (2011) 60–65.

[17] A. Sandberg, N. Bostrom, Whole brain emulation. a roadmap., Future of Humanity Institute. Technical Report #2008-3.

[18] G. M. Church, Y. Gao, S. Kosuri, Next-generation digital information storage in dna, Science 337 (6102) (2012) 1628. arXiv:http://www.sciencemag.org/content/337/6102/1628.full.pdf, doi:10.1126/science.1226355.
URL `http://www.sciencemag.org/content/337/6102/1628.abstract`

[19] C. Walter, Kryder's law, Scientific American 293 (2005) 32–33.

[20] P. D. S. G. A. B. et al., Project daedalus – the final report on the bis starship study, JBIS Interstellar Studies, Supplement.

[21] R. A. Freitas, R. C. Merkle, Kinematic Self-Replicating Machines, Landes Bioscience, 2004.

[22] R. M. Winglee, J. Slough, T. Ziemba, A. Goodson, Mini-magnetospheric plasma propulsion: Tapping the energy of the solar wind for spacecraft propulsion, Journal of Geophysical Research 105 (A9) (2000) 21067–21077.

[23] D. P. Whitmire, Relativistic spaceflight and the catalytic nuclear ramjet, Acta Astronautica 2 (1975) 497–509.

[24] R. L. Forward, A transparent derivation of the relativistic rocket equation, in: Proceedings of 31 st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 1995.

[25] S. Westmoreland, A note on relativistic rocketry, Acta Astronautica 67 (2010) 1248–1251, http://arxiv.org/pdf/0910.1965.pdf.

[26] G. Vulpetti, Maximum terminal velocity of relativistic rocket, Acta Astronautica 12 (2) (1985) 81–90.

[27] W. N. Association, Small nuclear power reactors, Information papers, http://www.world-nuclear.org/info/inf33.html (2012).

[28] V. Bolie, Cosmic background radiation drag effects at relativistic speeds, JBIS 34 (1981) 499–501.

[29] N. Balasanyan, V. Mkrtchian, Blackbody radiation drag on a relativistically moving mirror, Armenian Journal of Physics 2 (2009) 182–183.

[30] J. S. Mathis, K. H. Nordsieck, The size distribution of interstellar grains, Astrophysical Journal 217 (1977) 425–433.

[31] A. O. Petric, G. A. Telis, F. Paerels, D. J. Helfand, A direct upper limit on the density of cosmological dust from the absence of an x-ray scattering halo around the z=4.3 qso 1508+5714, The Astrophysical Journal 651 (2006) 41–45.

[32] F. J. Dyson, Search for artificial stellar sources of infra-red radiation, Science 131 (3414) (1960) 1667–1668.

[33] A. Sandberg, Dyson sphere faqOnline copy, retrieved 2006-09-01.
URL `http://www.nada.kth.se/ asa/dysonFAQ.html`

[34] K. G. Suffern, Some thoughts on dyson spheres, Proceedings of the Astronomical Society of Australia 3 (1977) 177.

[35] R. Strom, A. Sprague, Exploring Mercury: The Iron Planet, Springer, New York, 2003.

[36] S. C. Solomon, Mercury: the enigmatic innermost planet, Earth and Planetary Science Letters 216 (4) (2003) 441–455.

[37] H. Kolm, K. Fine, F. Williams, P. Mongeau, Overview of electromagnetic guns: electromagnetic guns, launchers and reaction engines, Tech. rep., Massachusetts Institute of Technology, Francis Bitter National Magnet Laboratory (1980).

[38] V. W. Sung, Lumped parameter modeling of the ideal railgun: Examining maximum electromechanical energy conversion efficiency, in: 2008 ASEE IL/IN Section Conference, Rose-Hulman Institute of Technology, 2008.

[39] H. Kolm, K. Fine, P. Mongeau, F. Williams, Electromagnetic propulsion alternatives, in: J. Grey, C. Krop (Eds.), Space Manufacturing Facilities III, Proc. 4th Princeton/AIAA Conf., 1979, pp. 299–306.

[40] P. Graneau, Self-energized superconducting mass driver for space launching, in: J. Bennett, T. Gora, P. Kemmey (Eds.), Proc. Conf. on Electromagnetic Guns and Launchers (Part II), 1980.

[41] G. A. Landis, Beamed energy propulsion for practical interstellar flight, JBIS 52 (1999) 420–423.

[42] G. D. Nordley, Relativistic particle beams for interstellar propulsion, JBIS 46 (1993) 145–150.

[43] R. Hanson, Burning the cosmic commons: Evolutionary strategies for interstellar colonizationPreprint at http://hanson.gmu.edu/filluniv.pdf.

[44] P. J. E. Peebles, B. Ratra, The cosmological constant and dark energy, Reviews of modern physics 75 (2003) 559–606.

[45] J. R. Gott, M. Juri, D. Schlegel, F. Hoyle, M. Vogeley, M. Tegmark, N. Bahcall, J. Brinkmann, A map of the universe, The Astrophysical Journal 624 (2) (2005) 463–484.

[46] D. N. Spergel, L. Verde, H. V. Peiris, E. Komatsu, M. R. Nolta, C. L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, L. Page, G. S. Tucker, J. L. Weiland, E. Wollack, E. L. Wright, First-year wilkinson microwave anisotropy probe (wmap) observations: Determination of cosmological parameters, The Astrophysical Journal Supplement Series 148 (1) (2003) 175–194.

[47] I. Wolfram Research, Mathematica edition: Version 8.0.

[48] I. Bars, J. Terning, Extra Dimensions in Space and Time, Springer, 2009.

[49] M. Mayor, M. Marmier, C. Lovis, S. Udry, D. Sgransan, F. Pepe, W. Benz, J.-L. Bertaux, F. Bouchy, X. Dumusque, G. L. Curto, C. Mordasini, D. Queloz, N. C. Santos, The harps search for southern extra-solar planets xxxiv. occurrence, mass distribution and orbital properties of super-earths and neptune-mass planets, Astronomy & Astrophysics 512 (2011) A48.

[50] A. Sandberg, S. Armstrong, Indefinite survival through backup copies, Tech. Rep. 2012-1, Future of Humanity Institute, Oxford University (2012).

[51] N. S. Kardashev, On the inevitability and the possible structures of supercivilizations, in: The search for extraterrestrial life: Recent developments; Proceedings of the Symposium, Boston, MA, June 18-21, 1984, no. A86-38126 17-88, D. Reidel Publishing, Dordrecht, 1985, pp. 497–504.

[52] M. M. Ćirković, The temporal aspect of the drake equation and seti, Astrobiology 4 (2) (2004) 225–231.

[53] J. M. Smart, The transcension hypothesis: Sufficiently advanced civilizations invariably leave our universe, and implications for meti and seti, Acta Astronautica 78 (2012) 55–68.

[54] J. Ball, The zoo hypothesis, Icarus 19 (1973) 347–349.

[55] N. Bostrom, Astronomical waste: The opportunity cost of delayed technological development, Utilitas 15 (3) (2003) 308–314.