Colonising The Galaxy

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Abstract

The Fermi Paradox is the apparent contradiction between the high probability of existence of technologically advanced civilisations given the vast amount of stars within our galaxy and the lack of evidence for extra-terrestrial (ET) contact. One of the solution to the paradox is that the colonisation of the galaxy is actually taking place, we just have not been reached yet. A computational model for interstellar colonisation was built, the time scales for such colonisation mission under different assumptions were then evaluated. The colonisation time for a laser-pushed lightsail embryo ship is 0.5 million years, much shorter than the age of the galaxy. This suggests that the solution is not probable.

The strength of the cluster of colonised planet with different safe distances were analysed, the behaviour of the system is similar to a Bethe lattice. The cluster exhibits geometrical phase transition, majority of the habitable planets are colonised with safe distance above a threshold value. Interesting behaviours of the colonised planet cluster such as the phase transitions being sharper for a larger system, and the safe distance threshold being smaller for a larger system were investigated and explained.

1 Introduction

"Is it reasonable to suppose that in a large field, that only one shaft of wheat should grow, and in an infinite Universe, to have only one living world?" Roman philosopher Metrodorus asked. Fossil evidence for life on Earth going back 3.8 billion years, practically immediately after the conclusion of the early solar system's massive meteorite bombardments. This suggested that life arises as soon as suitable conditions are achieved.[1] According to Nobel Prize winning biochemist Christian de Duve, "Life is almost bound to arise wherever physical conditions are similar to those that prevailed on our planet some four billion years ago.[2] From the history of life on Earth, it is obvious that once life starts, it has a continual tendency toward development of greater complexity and intelligence. In our galaxy there are 350 billion stars, with an age of 10 billion years, as the development of intelligent life is such a common event, many technologically advanced civilisations must have already arisen and spread across our galaxy.[3]

This conclusion contradicts with the lack of evidence of such extraterrestrial civilisations visiting Earth. This contradiction led the great physicist Enrico Fermi to pose the question, Where are they? This is the Fermi Paradox or the Great Silence problem.

The following are a few popular possible solutions[2] to the paradox:

1. Interstellar spaceflight is infeasible

2. All ET civilisations choose not to interfere with the human civilisation
3. All ET civilisations are destroyed for various reasons
4. Human civilisation is the only or the most advanced life-forms in the galaxy
5. ET civilisations are actually exploring and colonising the galaxy, and they have not reached us yet.

The first solution is unlikely as there is no know law of physics or engineering preventing interstellar space flight. Various possible propulsion technologies and life-support technologies are discussed in the following sections. The second, third and fourth explanations are statistically unlikely considering the long age of the Universe and large number of habitable planets in our galaxy. The plausibility of the last solution was investigated in this project by computationally modelling the colonisation of the galaxy and evaluating the time scale of this colonisation.
As the human civilisation is the only civilisation known to the author at the time of writing, most of the analyses are based on considerations for the human civilisation and human beings.

2 Galactic Habitable zone

Circumstellar habitable zone (CHZ) is the region within a stellar system where water is in liquid form on the surface of a terrestrial or Earth like planet for at least a few billion years. The inner boundary is the smallest orbital that a planet could have without losing its ocean from evaporation, while the outer boundary is the largest orbit before liquid water on the planet is frozen. Extend this concept to the whole galaxy, the galactic habitable zone (GHZ) is the region where habitable planet are much more likely to exists. Its boundaries are determined by mainly two requirements, the availability of planet building material and adequate protection from cosmic threats.[42] [43]

2.1 Metallicity

Only hydrogen and helium, with a few other light element are synthesised in the Big Bang nucleosynthesis. Heavier elements are produced in fusion within stars and supernovae. Metallicity is the ratio of the number metal atoms to the hydrogen atoms, it measures the availability of materials to build a habitable planet. Regions with higher metallicity have larger planets, which has higher ability to retain an atmosphere and sustain geological activities that are essential for a planet to be habitable. However, a planet is also inhabitable if the metallicity is too high, because the planet would be too large and completely covered with water. A mix of land and sea like the

Earth is important for atmospheric temperature control and other processes. The metallicity falls off exponentially with respect to the distance from the galactic centre as shown in the graph. As metal atoms are being produced in fusion and supernovae, the GHZ moves outward over time.[42]

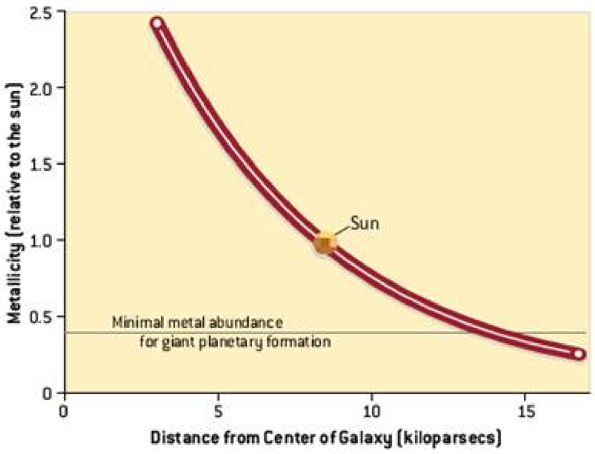

Figure 1: Metallicity decreases exponentially with respect to the distance from the galactic centre. [42]

2.2 Cosmic Threats

There are two main categories of cosmic threats: impacts by comets, and blasts of radiation. For the solar system, comets resides in the Kuiper belt and the Oort cloud. Both metallicity and number density of stars increases near the galactic centre, resulting in larger number of comets near the galactic centre. As a result, planetary systems in the inner galaxy should suffer higher comet influxes.[42]

Most of the particle radiation and electromagnetic radiation screened by the magnetic field and ozone layer of the planet. however sufficiently energetic radiation could generate secondary particles upon hitting the atmosphere. Galactic nucleus outburst are emitted when a star or cluster is pulled into the supermassive black hole at the centre of the galaxy. Supernovae and gamma-ray bursts are also more threatening in the inner galaxy.[42]

Therefore planets in the inner region of the galaxy would suffer from various cosmic threats, while planets in the outer region might not have have enough metallicity to form larger terrestrial planets for development of complex life-forms, which results in the GHZ as shown in the green shaded region in figure2.

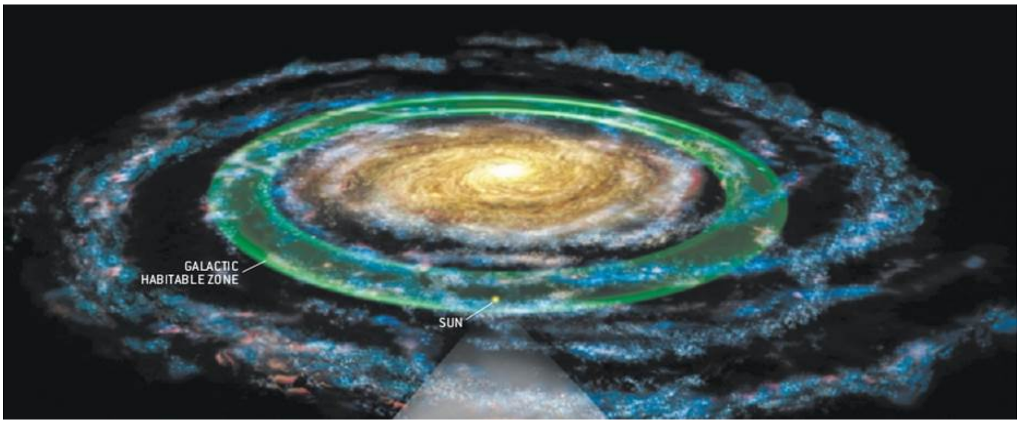

Figure 2: The green shaded region indicates the Galactic Habitable Zone where habitable planets are much more likely to exists. [42]

2.3 Habitable Planet Density

Stephen H. Dole has developed the classical Dole equation[4] in 1964, taking into account of various astrobiological requirements to estimate the habitable planet density in the galaxy. The total number of habitable planets N_{HP} is:

$$N_{HP} = N_s P_p P_i P_D P_M P_e P_B P_R P_A P_L \tag{1}$$

- $N_s = 6.448 \times 10^8$, number of stars in the suitable mass range 0.35 to 1.43 solar masses
- $P_p = 1.0$, probability that a given star has planets in orbit around it
- $P_i = 0.81$, probability that the inclination of the planets equator is correct for its orbital distance
- $P_D = 0.63$, probability that at least one planet orbits within an ecosphere
- $P_M = 0.19$, probability that the planet has a suitable mass, 0.4 to 2.35 Earth masses
- $P_e = 0.94$, probability that the planets orbital eccentricity is sufficiently low
- $P_B = 0.95$, probability that the presence of a 2^{nd} star has not rendered the planet uninhabitable
- $P_R = 0.9$, probability that the planets rate of rotation is neither too fast nor too slow
- $P_A = 0.7$, probability that the planet is of the proper age
- $P_L = 1$, probability that, all astronomical conditions being proper, life has developed on the planet

This equation was further developed into the Statistical Equation for the Habitables (SEH).[5] Each of independent variables above were changed into a non-negative random variables with standard deviations. Central Limit theorem was then applied to the logarithmic form of the equation and as a result, the random variable N_{HP} was found to be lognormally distributed. Assuming a 10% standard deviation for each of the ten variables, $\langle N_{HP} \rangle = 1.012 \times 10^8 \approx$ 100 million with a standard deviation of $\rho_{N_{HB}} = 200$ million.
The habitable planet density ρ_{HB} is

$$\rho_{HB} = \frac{\langle N_{HB} \rangle}{V_{GHZ}} = 9.44 \times 10^{-5} \text{ planets per ly}^3 \tag{2}$$

2.4 Civilisation Development and Establishment

Civilisations are classified into types according to their level of development in the Kardashevs scale[6] [7] .

- Type I
  - $\approx 4 \times 10^{12} W$ power consumption (original Kardashevs definition)
  - Adopting Lemarchands definition $\approx 10^{16}$-$10^{17} W$ power consumption in order to fit into the Kardashev rating scheme
  - Achieved full mastery of all planetary resources
- Type II
  - $\approx 4 \times 10^{26} W$ power consumption
  - Capable of harnessing the energy from its stellar system
- Type III
  - $\approx 4 \times 10^{37} W$ power consumption
  - Has access to the full potential of its galaxy

The intermediate values of the Kardashev scale is obtained by interpolating and extrapolating the power consumptions of different types of civilisations to give the Kardashev rating[8]

$$K = \frac{log_{10} MW}{10} \tag{3}$$

Based on the world energy consumption from 1965 to 2012, the human civilisation would reach type I in 2262 as shown in figure3. Note that this estimation is highly uncertain as it is based on data from a relatively short period of time. It is assumed that a type I civilisation is capable to undertake colonisation missions. Upon arrival at the planet, the area for establishing the initial settlement is carefully screened, with the potential risks regarding weather, incompatibilities with existing vegetation, creatures, microbes identified and the

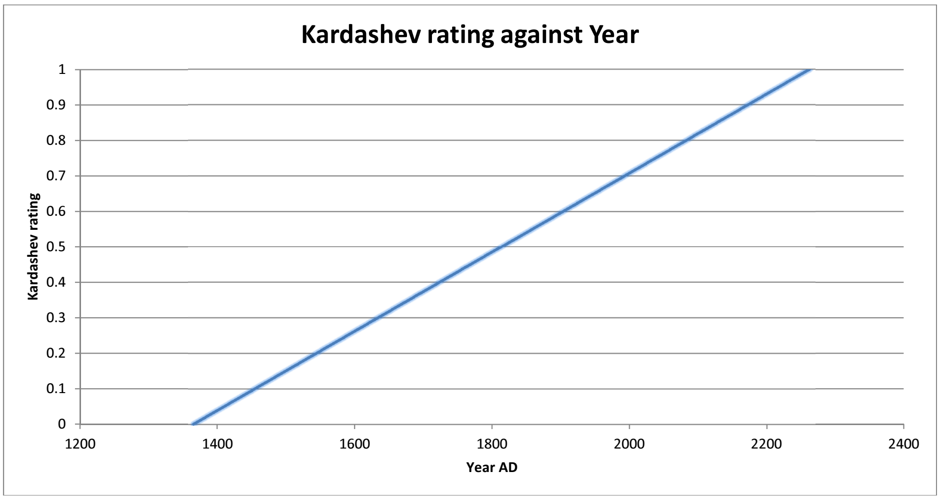

Figure 3: Based on the world energy consumption from 1965 to 2012, it is estimated that the human civilisation would reach type I in 2262.

impact of the settlement on the ecosystem assessed.[22] After the assessment, the colonist starts to build a society and increase its population. Once the society is matured and is sufficiently advanced in technology, new spacecraft will be sent out to colonise other nearby habitable planets. The duration for civilisation establishment is assumed to be 900 years which is the time for a civilisation to develop from type 0 to type I.

3 Interstellar travel technologies

Most of the technologies discussed in the following sections are beyond the current technological capabilities of our civilisation. Mechanisms and the possible designs of these systems are also discussed.

3.1 Propulsion and Braking

3.1.1 Rocket Equation

Rockets are totally self-contained propulsion systems, they work exclusively on the principle of conservation of momentum.
The ultimate velocity attained by the spacecraft is described by the rocket equation.

$$M = M_i e^{-\frac{\Delta V}{w}} \tag{4}$$

or alternatively:

$$ln\frac{M}{M_i} = -\frac{\Delta V}{w} \tag{5}$$

For spacecraft with velocity close to the speed of light c, the relativistic effect is taken into account in the relativistic rocket equation[18]

$$M = M_i \left[\frac{1 + \Delta V/c}{1 - \Delta V/c} \right]^{\frac{c}{2w}} \tag{6}$$

or alternatively

$$ln \frac{M}{M_i} = -\frac{c}{2w} ln \left[\frac{1 + \Delta V/c}{1 - \Delta V/c} \right] \tag{7}$$

where ΔV is the change in velocity, M and M_i are the mass and initial mass of the spacecraft respectively, and w is the exhaust velocity of the spacecraft, which is dependent on the propulsion technology used.

3.1.2 Specific Impulse

The efficiency of rocket propulsion system is expressed as specific impulse I_{sp}. It is the change in momentum of the rocket per unit mass of rocket fuel. The effective exhaust velocity w is related to I_{sp}

$$I_{sp} = \frac{w}{g} \tag{8}$$

where g is the gravitational constant.[15]
The specific impulse is used to compare the efficiency of different propulsion systems.
The above equations are used to analyse the duration for interstellar mission using nuclear fusion and antimatter propulsion system. Note that they are not applied for the analysis of laser-pushed lightsail system because the system carries no propellant and therefore is not a rocket.

3.1.3 Chemical Propulsion

The fastest spacecraft to date is the Voyager launched in 1977. The thrust is generated by chemical reactions and it has a final velocity of 17km/s (equivalent to 0.000057c) leaving the solar system.
The maximum enthalpy, energy per unit mass, of chemical fuels are limited by the laws of chemistry to $\approx 13 MJ/kg$. As a result, chemical propulsion system's exhaust velocity is limited to w_{max} = 5 km/s.[1] Using a chemical propulsion system would take hundred thousands to millions of years to reach a nearby habitable planet. It is clear that galaxy colonisation requires more advanced interstellar propulsion methods.

3.1.4 Nuclear Fusion Propulsion

The 13 MJ/kg enthalpy of chemical fuels have limited the exhaust velocity to 10km/s. Nuclear fusion reactions like D-T fusion, D-D fusion and D-He^3 on the other hand, has hundreds of millions MJ/kg enthalpy available to produce

much larger exhaust velocity.[1]
Ignition is a condition which energy is produced in a rate that no external heating power would be required. Most of the current nuclear reactor research efforts are on the D-T fusion. This is because the reaction has the lowest requirement, indicated in the Lawson parameter, 4×10^{21} keV-particle-seconds/m^3, for ignition. Therefore most of the current nuclear reactor research efforts are on D-T fusion.[1]

$$D + T \rightarrow He^4 + n + 17.6\text{MeV} \tag{9}$$

where D is deuterium and T is tritium. 80% of the energy yield is in the uncharged neutrons and there is no effective way to convert this energy into thrust.[19] Apart from that, hazardous radioactive materials would be generated in the reactor metal structure as a result of neutron absorption.[1] Therefore the D-T fusion reaction is not considered as the method for interstellar travel.
The D-D reaction produces fusion energy by the nuclear interaction of two D nuclei, and it is more difficult to initiate than the D-He^3 reaction. The reaction has two branches with approximately equal likelihood of occurring

$$D + D \rightarrow He^3 + n + 3.27\text{MeV} \tag{10}$$

$$D + D \rightarrow T + p + 4.03\text{MeV} \tag{11}$$

where He^3 is helium-3, n and p are neutron and proton respectively.[9]
A deuterium nucleus fuses with a helium-3 nucleus in the D-He^3 reaction[9]

$$D + He^3 \rightarrow \alpha + p + 18.3\text{MeV} \tag{12}$$

In the magnetic confinement fusion design, a large volume of reacting thermonuclear fusion plasma is contained within a large magnetic confinement chamber. Most of the fusion products are allowed to escape from one end of the nuclear reactor and directed away by a magnetic nozzle to produce thrust. While the rest would be used to heat the plasma to sustain the fusion reaction.[10][1] However the need for heavy confinement magnets and the large volume of fusion plasma makes it less suitable than the pulsed propulsion design described below for interstellar mission.[19]
The pulsed nuclear propulsion design was studied in the Daedalus project. A series of pellets of fusion fuel are ejected rapidly into the apt region of the spacecraft. Ignited and detonated by focusing high-intensity laser light, relativistic electron beams or small quantities of antimatter at the target zone, ultra-hot plasma are produced and directed away from the ship by a magnetic nozzle to produce thrust.[10][11][12][19]
In the Daedalus project, a giant two-stage probe, with a mass of 450 tonnes would be propelled by the pulsed nuclear system described above. The spacecraft has initial mass of 54000 tonnes, 50000 tones of which was the propellant. The first stage would have an acceleration of about 1.5% of 1g, produced by 250 small nuclear explosions per second, lasting for 750 days. Then the second

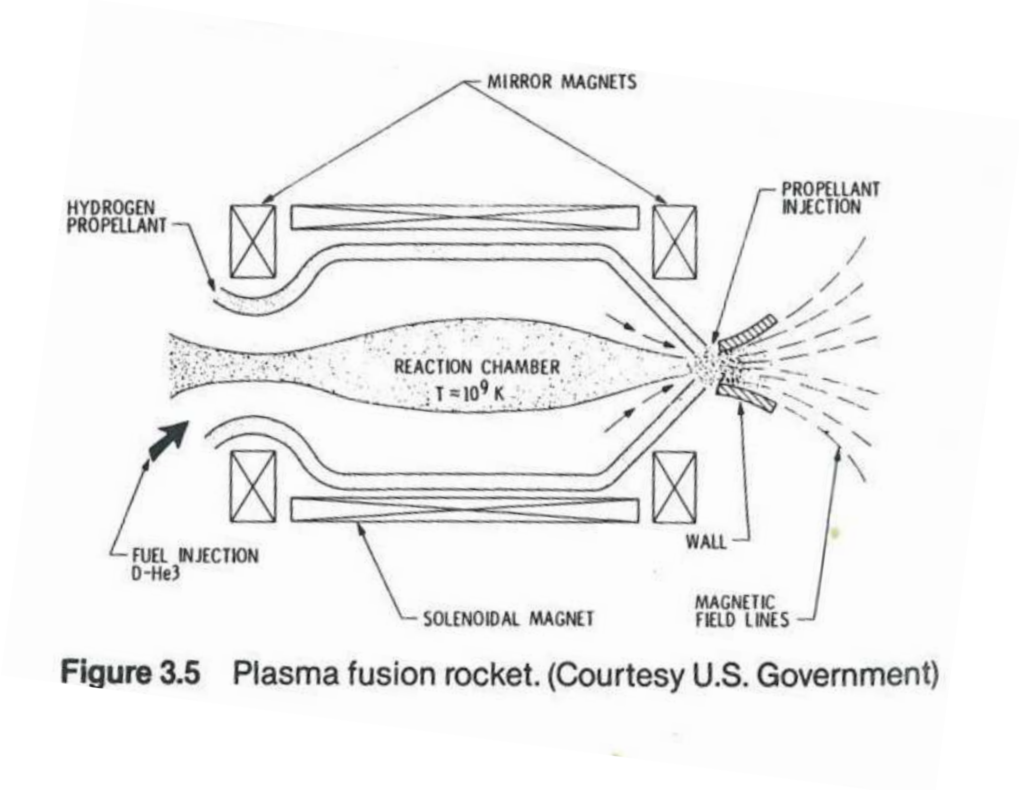

Figure 4: Magnetic Confinement fusion design.[13]

stage would be fired for another 640 days. The cruise speed of 0.12c would be reached. This study was for a one-way journey to Barnard's star from Earth (5.9ly) which would last for around 50 years.[11] The magnetic nozzles used by the fusion propulsion have about 60% of efficiency. Therefore the exhaust velocity of a D-He^3 propulsion system is around 0.057c.[19]
Both D-d and D-He^3 interstellar fusion propulsion systems are compared in table1.

Table 1: Comparing chemical system, D-D and D-He^3 fusion system for interstellar propulsion

	Chemical	D-D fusion	$D-He^3$ fusion
Useful Enthalpy (MJ/kg)	13	208×10^6	347×10^6
Theoretical Exhaust velocity	5000 m/s	0.068c	0.088c
Exhaust velocity	4500 m/s	0.04c	0.057c
Specific Impulse (s)	460	1.2×10^6	1.7×10^6

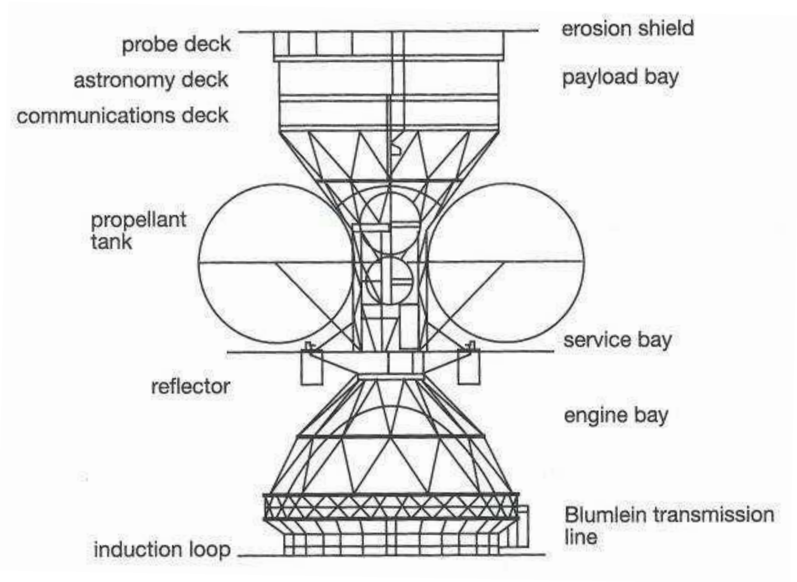

Figure 5: Pulsed nuclear fusion propulsion design in project Daedalus. A giant two-stage probe, with a mass of 450 tonnes would be propelled by directed hot plasma produced from detonated pellets of fusion fuel. [13]

3.1.5 Antimatter Annihilation Propulsion

Antimatter annihilation is ideal for interstellar propulsion. Antimatter has an enthalpy of 90 billion MJ/kg, the highest possible enthalpy of any known substance.[14]

The idea of using matter/antimatter annihilation for interstellar propulsion were first proposed by Eugene Sänger in the 1950s. Electron and positron annihilate to give high-energy gamma radiation to produce thrust. The problem with the original design, the "Sänger Photon Rocket", is that the gamma radiations come out in random directions and could not be directed to generate thrust.[10] The problem is circumvented by using the energy of annihilation to heat the surface of a solid of high-temperature material such as graphite or tungsten to incandescence. The resulting photons radiated by the incandescent object is then directed rearward with mirrors to produce thrust. This design is known as a photon rocket shown in figure6. The photon rocket would have effective exhaust velocity of 0.5c. Therefore it will have $I_{sp} \approx 1.5 \times 10^7$s [1]

Another design for solving the random directions problem is to use proton/antiproton annihilation to produce pions.(figure7) An average of 1.5 positively charged pions, 1.5 negatively charged pions and 2 neutral pions are produced per annihilation. The neutral pions decay immediately to gamma rays, while the charged pions have longer lifetime and decay into gamma rays and neutrinos. Before the charged pions decays, they are directed rearward using a magnetic nozzle to produce thrust. It is suggested that 30% to 50% of annihilation energy is useful for generating thrust in this design.[10][11]

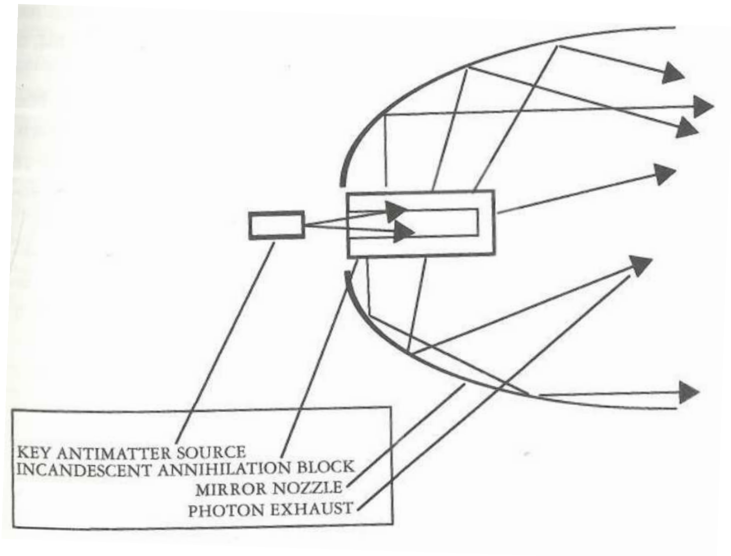

Figure 6: Photon rocket design. Energy from annihilation heats the surface of a solid of high-temperature material such as graphite or tungsten to incandescence. The photons radiated by the incandescent object is then directed rearward with mirrors to produce thrust.[1]

There are two main obstacles in using antimatter for interstellar propulsion.

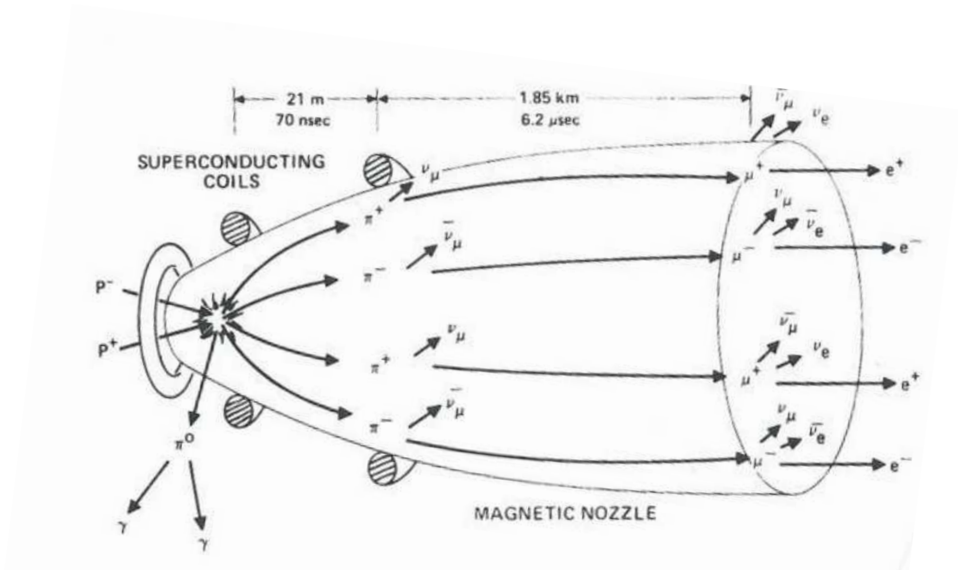

Figure 3.7 Antimatter rocket. (Courtesy Robert L. Forward)

Figure 7: Pions produced in proton/antiproton annihilation are directed rearward to produce thrust.[10]

The high economical cost of antimatter production and the difficulty in storage

of large quantity of antimatter particles.
Most of the antimatter produced globally are made either at CERN or Fermilab. The global production rate of antiparticles is currently in the nanograms range annually, at an estimated cost of about $100 trillion per gram. However, it is important to note that U-235 and liquid hydrogen were both extremely expensive when they were first used, and their production cost dropped dramatically once the production infrastructure was built. CERN and Fermilab are not dedicated facilities for antimatter production, therefore the production rate could be increased and economical cost lowered dramatically once the production infrastructure is in place.[14]
HiPat is currently the most advanced antiproton portable trap. It has the capacity to hold roughly 1picogram of antiproton for several days.[14] More advanced technology for antimatter storage has to be developed for the propulsion method to be practical.

3.1.6 Laser-Pushed Lightsail Propulsion

From the rocket equation, the spacecraft could achieve higher ultimate velocity with more fuel. However, having more fuel also implies more mass to be accelerated, which in turn requires more fuel and time in the early accelerating stage of the flight. What if the main "engine" and "propellants" of the spacecraft could be left in the home planet and still propel the spacecraft to the destination?
The idea of using laser for interstellar travel is suggested by Robert Forward shortly after the invention of laser in 1960. Lasers are coherent and parallel electromagnetic radiations, collimated by a huge lens, such that it can be beamed over interstellar distances. The fact that photons exerts radiation pressure on objects was proved by physicist Peter Lebedev. In his experiment, mirrors suspended on thin fibres in vacuum jars were turned by shining light upon them.[1] These factors makes laser-pushed lightsails a possible propulsion mechanism for interstellar travel.
Energy from starlight is converted into coherent laser beams using a large arrays of solar-pumped lasers orbiting around the star . The beams are collimated and transmitted over interstellar distances using large lightweight optical system. Giant lightweight reflective sails attached to the spacecraft are then pushed by the radiation pressure from the laser photons.[17]
Apart from the advantage of reducing the mass to be accelerated, the loss in case of mission failed is also largely reduced. If mission failed for a rocket, all the fuel and engines are lost. For the laser-pushed lightsail system, although the spacecraft is lost, the solar-pumped laser could still be used for future missions. Therefore the cost of failing mission is minimised.
The acceleration of the laser-pushed lightsail spacecraft could be found by considering the momentum transferred from the photons to the lightsail.

Total momentum of the light beam of power P_b is given by the equation,

$$\Delta p_i = \frac{P_b}{c} \tag{13}$$

Assume 100% reflectivity of the advanced lightsail, total momentum change of the spacecraft per second is:

$$\Delta p_s = \frac{2P_b}{c} \tag{14}$$

Therefore the acceleration of the spacecraft is:

$$a_s = \frac{2P_b}{M_s c} \tag{15}$$

Where M_s is the mass of the spacecraft.
A type I civilisation consumes power of order $10^{16}W$-$10^{17}W$, assume 2.5% of the total consumption (10^{17}) of a type I civilisation is used to power the laser, a spaceship of mass $6 \times 10^6 kg$ (estimated mass of an embryo ship) would be accelerated with $a_s = 2.85ms^{-2}$ to cruise speed of $0.3c$ in one year.
It should be noted that the slightest lateral deviation of the laser beam would cause it to miss the lightsail. It is impossible to correct the deviation using a control loop as a result of the delay of information transfer due to the vast interstellar distance and the universal speed upper limit.
It should also be noted that scattering of the laser light by interstellar dust might make this method impractical.[11]

3.1.7 Magnetic sail decelerator

Bussard ramjet was proposed by physicist Robert Bussard in 1960. It is a theoretical fusion ramjet that would gather interstellar hydrogen in flight and produce thrust through proton-proton fusion reaction. The advantage of the ramjet is that the spacecraft could accelerate continuously to asymptotically approach the speed of light. To gather interstellar hydrogen, due to the diffuse nature of the interstellar medium, a huge scoop based on magnetic or electrostatic fields is required. Unfortunately, this scoop would generate more drag than the thrust produced by the ion engines in the Bussard ramjet. As a result, the system is impractical.[1]
It was later suggested that the idea of the magnetic scoop could be modified and use instead as a magnetic sail for deceleration of the spacecraft.
A loop of cable hundreds of kilometres in diameter would be deployed when the spacecraft approaches its destination. Current will then be initiated in the cable, which is made up of high-temperature superconducting materials such as $YBa_2Cu_3O_7$. High-temperature superconductors are required despite the ambient temperature of 2.7K in interstellar space because the magsail would be operating mainly in interplanetary space, where ambient temperatures are above the critical temperatures of low-temperature superconductors. Once the current flows, it will be maintained indefinitely without further

power.Deflected charged particles from plasma wind would impart momentum to the magsail.[19][1] This momentum could be used to decelerate a spacecraft moving in high velocity relative to the interstellar medium.
The loop could be positioned with its dipole axis at any angle with respect to the plasma wind, there are two extreme cases of configurations for the magsail are discussed below. In the axial configuration, charged particles coming in parallel to the loop axis of the sail are reflected. The equation of motion of the spacecraft would be in the form of

$$\frac{dV}{dt} = -\frac{V}{\tau} \tag{16}$$

which gives solution of

$$V = V_0 e^{-t/\tau} \tag{17}$$

where τ, the exponential velocity decay time is a function of the superconductor current to mass ratio and the ratio of magsail mass to payload mass.[19]
The normal configuration has charged particles approaching the magsail perpendicularly to the loop axis. The total effective reflection area for the normal configuration would be 5.5 times that of the axial configuration. Based on the predictions made by the YBCO researchers for their technological several decades into the future, a magsail with a payload ratio of around 0.8 and radius of 100km could reduce the speed of a spacecraft from 0.95c to 0.04c in around 320 days, 0.01c in 620days.[20],
The ship can then be decelerated with small amount of fuel and eventually land on the target planet.

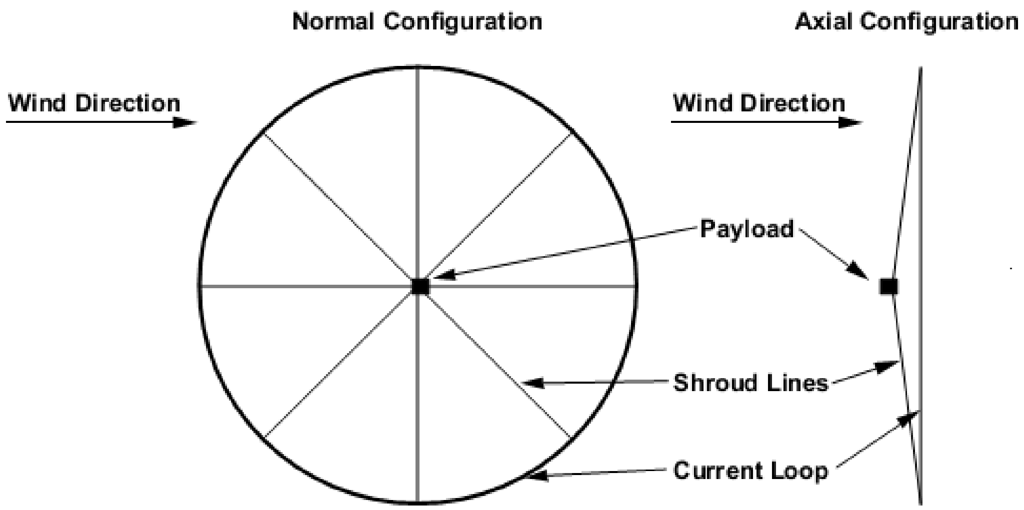

Figure 8: The normal and axial configuration of the magnetic sail decelerator.

4 Life Support System

The impact of the Life Support System (LSS) on space flight missions is outline in the flowchart9. It is obvious that a suitable LSS is vital to the success of

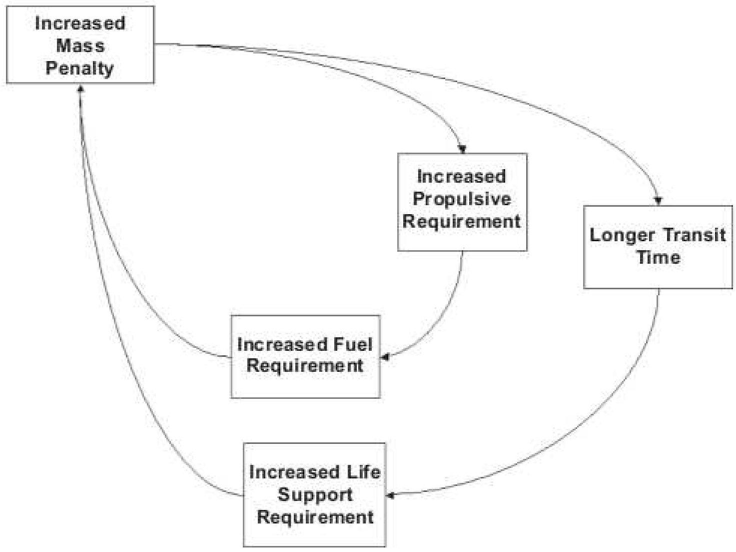

Figure 9: Impact of the LSS on space flight missions

an interstellar colonisation mission, various LSSs are discussed in the following sections.

4.1 World Ship

A generation ship is a manned interstellar spacecraft where crew and colonists lives on-board for at least several decades. A world ship is a generation ship that has population size larger than 100,000 and have cruise velocity smaller than 0.01c.[23] A large population size reduces the founder effect, which is the loss of genetic variation that occurs when a new population is established by a very small group of individuals from a larger population[24], as well as to reduce the inevitable effect of inbreeding on the ship. A broad genetic diversity of the gene pool leads to a much greater chance of survival, for example, the diversity would reduce the probability of the whole population being wipe out by a single sweep of disease.[25]
Apart from the benefit of a broader genetic diversity, larger populations are able to develop more complex technologies and succeed in knowledge transfer which is vitally important for a interstellar colonisation mission. First, larger population are able to transfer knowledge in a more robust way as random losses of knowledge have less impact. Second, knowledge transfer in larger populations is more robust against transfer errors, which degrade knowledge and technologies.[25] Therefore a large population size is necessary for the interstellar colonisation mission.

There are numerous possible problems associated with the idea of a generation ship, they include:

- High vulnerability to infectious disease due to the small, dense population on board[25]
- Interference in vertebrate embryo development due to low atmospheric pressure and elevated oxygen levels increases infant mortality and miscarriages[27]
- Health conditions such as muscle atrophy, bone loss, significant loss of calcium from weight-bearing portions of the skeleton resulting in increased risk of renal stone formation, cardiac dysrhythmia (abnormal electrical activity in the heart)[27]
- New cultural and physiological traits being developed and sabotage the mission[25]

Apart from the problems described above, there are also other stressors listed in table10.

Physiological/Physical	Psychological	Psychosocial	Human Factors	Habitability
Radiation	Isolation & confinement	High team coordination demands	High & low levels of workload	Limited hygiene
Absence of natural time parameters	Limited possibility for abort/rescue	Interpersonal tension between crew/ground	Limited exchange of info/comms with external environment	Chronic exposure to vibration and noise
Altered circadian rhythms	High-risk conditions & potential for loss of life	Family life disruption	Limited equipment, facilities and supplies	Limited sleep facilities
Decrease in exposure to sunlight	System & mission complexity	Enforced interpersonal contact	Mission danger & risk associated with: equipment failure, malfunction, or damage	Lighting & illumination
Adaptation to micro-gravity	Hostile external environment	Crew factors (i.e., gender, size, personality, etc.)	Adaptation to the artificially engineered environment	Lack of privacy
Sensory/perceptual deprivation of varied natural sources	Alterations in sensory stimuli	Mulitcultural issues	Food restrictions/ limitations	Isolation from support systems

Figure 10: List of possible stressors on space colonists.[28]

In particular, interpersonal and psychosocial issues would become especially salient due to the differences in nationality, religion, social values, and political beliefs.[28] An international shuttle crew debrief was conducted for nine US astronauts who flew on the International Space Station. Forty-two incidents related to multicultural factors were reported, five of the in-flight incidents were rated as having a high mission impact.[29] Note that the colonist onboard the world ship are ordinary citizens instead of well-trained astronauts, the situation will be even worse. Even if most of the initial colonists could survive, there is no guarantee that their offspring would be as capable.

It is obviously improbable for a world ship to accomplish a long duration mission, the longest acceptable duration of the mission is around three 25-year generations.

4.2 Sleeper Ship

The sleeper ship is a spacecraft transporting colonists that are artificially hibernated with reduced metabolic rate possibly by lowering their body temperature. Although human does not hibernate naturally, it is not unreasonable to assume that a "hibernation-like" reduction in metabolic rate could be induced in human.[36]
Most of potential problems that is limiting the safe duration of a world ship arise from human factors. Applying hypometabolic stasis (HS) to the colonists would not only provide solution to these problems, but the lifespans of the colonists might also be lengthened.[35]
The living space and life-support systems required by hibernated colonists would be much less comparing with awake colonists. The effect of it on the requirements placed on the main areas of life support is summarised in table11.

Life Support Area	Purpose	Effect of HS
Atmosphere Management	Atmosphere composition control, temperature and humidity control, pressure control, atmosphere regeneration, contamination control, ventilation	Reduced heating requirement, reduced regeneration requirement
Water Management	Provision of potable and hygienic water, recovery and processing of waste water	Reduced drastically
Food Production and Storage	Provision and, potentially, production of food	Reduced Drastically
Waste Management	Collection, storage, and processing of human waste and refuse	Reduced Drastically
Crew Safety	Fire detection and suppression, radiation shielding	Augmented?
Crew Psychology	Maintenance of crew mental health	Reduced Drastically

Figure 11: Effect of applying Hypometabolic stasis to the colonists on the life-support system.[35]

Even though the ageing problem and various psychological and psychosocial problems could be circumvented through application of HS, radiation damage to the hibernated colonists would still place a limit on the acceptable duration of the mission.[30] Prolonged exposure to radiation would cause bone, blood, and other cells to malfunction and die. Mutations could occur due to altered genetic code by radiation exposure, which might results in infertility or stillbirth.[34] The radiation problem is devastating and would limit the acceptable duration of the mission.

4.3 Embryo ship

Frozen human embryos instead of fully grown human are transported on an embryo ship. The embryo would be developed into fully-grown human beings at the destination. Frozen embryo kept in liquid nitrogen is currently the only proven biostasis available for human beings.[30] The advantage of embryo ship is that the limit on the safe duration due to cosmic radiation for the aforementioned means of interstellar travel could be circumvented. Plasma shielding is used to shield the frozen embryos from the galactic cosmic rays (GCR). This plasma shield could not be employed for the sleeper ship and the world ship because a very strong magnetic field would be required to shield such a large volume[39]. Such a strong field might have adverse effect on the colonists on board, the field might also affect normal functioning of the equipment on the spacecraft. Another advantage of embryo ship is that frozen embryos are able to withstand much higher inertial force during the acceleration and deceleration.[30]

It was suggested that androids with artificial intelligence could be used to nurture, raise and educate the children grown from the frozen embryo at the destination. However, the possibility of creating a machine that is genuinely intelligent in human terms is still subject to considerable debate.[33] A better approach might be to use whole brain emulation technology to digitalise real human beings, simulate the original brain in androids, then let the androids with emulated human brains to parent the children.

4.3.1 Plasma shield

The dangerous components in GCR consist of positively charged particles, since the neutral radiation has a negligible effect and negatively charged particles can be shielded easily. The positively charged particles are extremely penetrating, and require massive passive shield. A small amount of passive shielding would even have negative effect since considerably more intense secondary radiation would be produce upon impact of the GCR on a light shield.[39]

The plasma shield, was proposed by Levy and Janes[40][41] as a solution to the radiation problem. The shield is positively charged to repel the positively charged radiation, a magnetic field then is then applied to direct away electrons, thereby preventing them from discharging the shield.[39] On the embryo ship, the container for the embryos would be protected from damaging radiation using this plasma shield, until the destination is reached and there is atmosphere to protect the embryos from radiations.

4.3.2 Whole Brain Emulation

Whole Brain emulation is a one-to-one modelling of the function of the human brain. The basic idea of the technology is to scan a particular human brain structure in detail, and construct a software model of it such that the emulation would behave in essentially the same way as the original brain when the model is run on appropriate hardware.[37] This currently theoretical technology would enable digital immortality, which could be used as the method to digitalise the interstellar mission crew, simulate them in androids and let them parent the children born from the frozen embryos.

5 Computational Model

5.1 Parameters

Using the rocket equations for fusion and antimatter annihilation propulsion, a balance is found between the amount of fuel and the final speed of the spacecraft based on the estimated masses of different type of spacecrafts. The safe distances are then by simply multiplying the final speed with the safe duration, the time for deceleration is not taken into account because it is negligible compare with the duration of the flight assume that the magsail decelerator is used. The estimated parameters are outlined in table2: In the computational

Table 2: Parameters different types of spacecraft

	World ship	Sleeper ship	Embryo ship
Mass of the spaceship /kg	1.68×10^{14} [26]	2×10^{11}	6×10^{6}
Cruise velocity (Fusion) /c	0.005[21]	0.03	0.1
Cruise velocity (Antimatter) /c	0.05	0.3	0.9
Cruise velocity (Lightsail) /c	NA	NA	0.3
Safe duration /years	75	200	1000

model, the Milky Way galaxy is modelled as a collection of N_{HB} habitable planets distributed evenly in the ring-shaped galactic habitable zone with inner boundary and outer boundary at 0.46r and 0.59r respectively.
Each colonised habitable planets has an upper limit (z-1) on the total number of spaceship that could be sent out, due to the limited resource available for colonisation missions on each planet.

5.2 Algorithm

The main flow of the colonisation of a computational modelled galaxy, the process of generating the virtual galaxy and the process of colonisation of the nearest habitable planet from the current planet are described in flowchart12. flowchart14 and flowchart13 respectively. The C++ source code is in the Appendix section for reference.

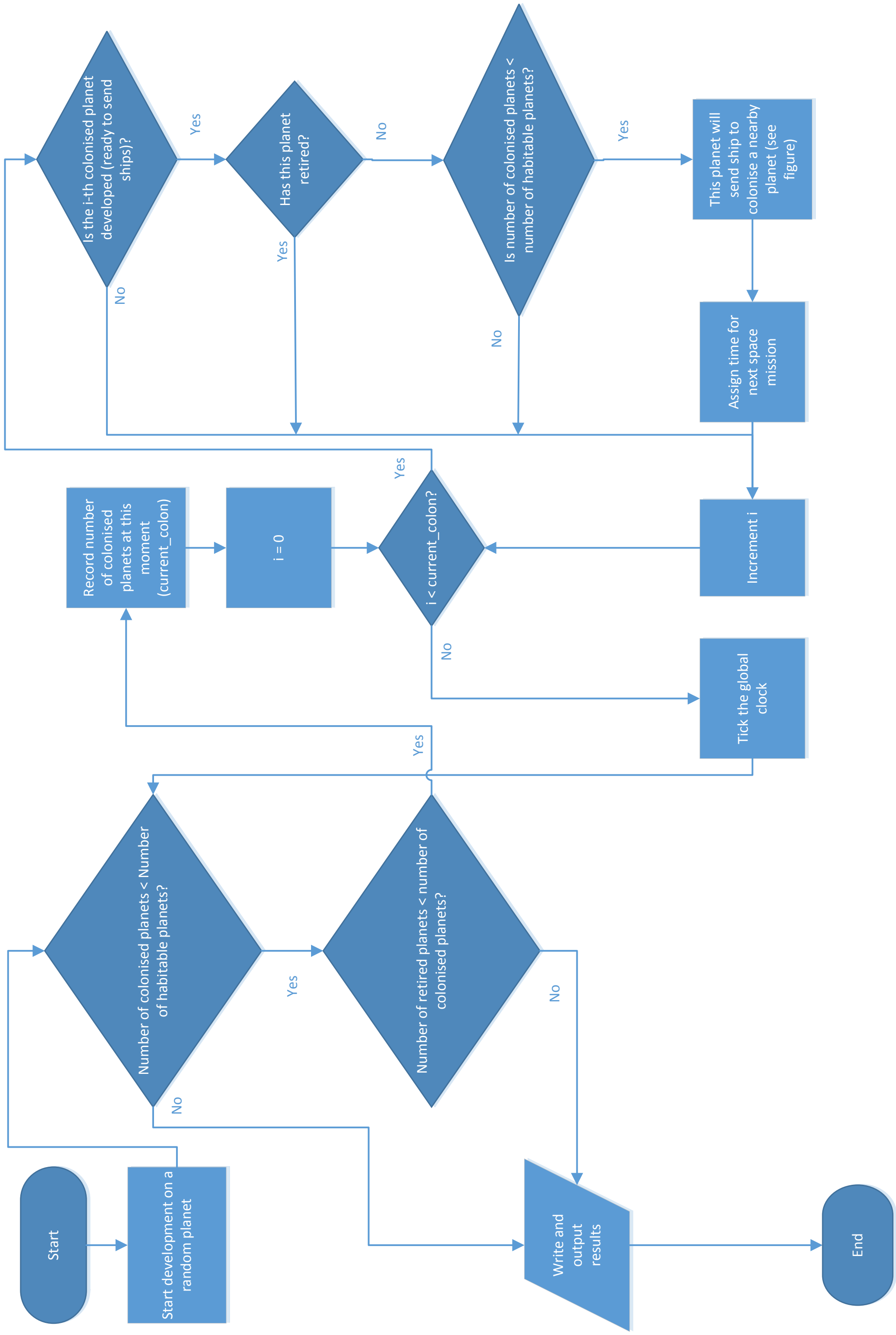

Figure 12: Flowchart describing the main flow of the colonisation of a computational modelled galaxy with a collection of habitable planets.

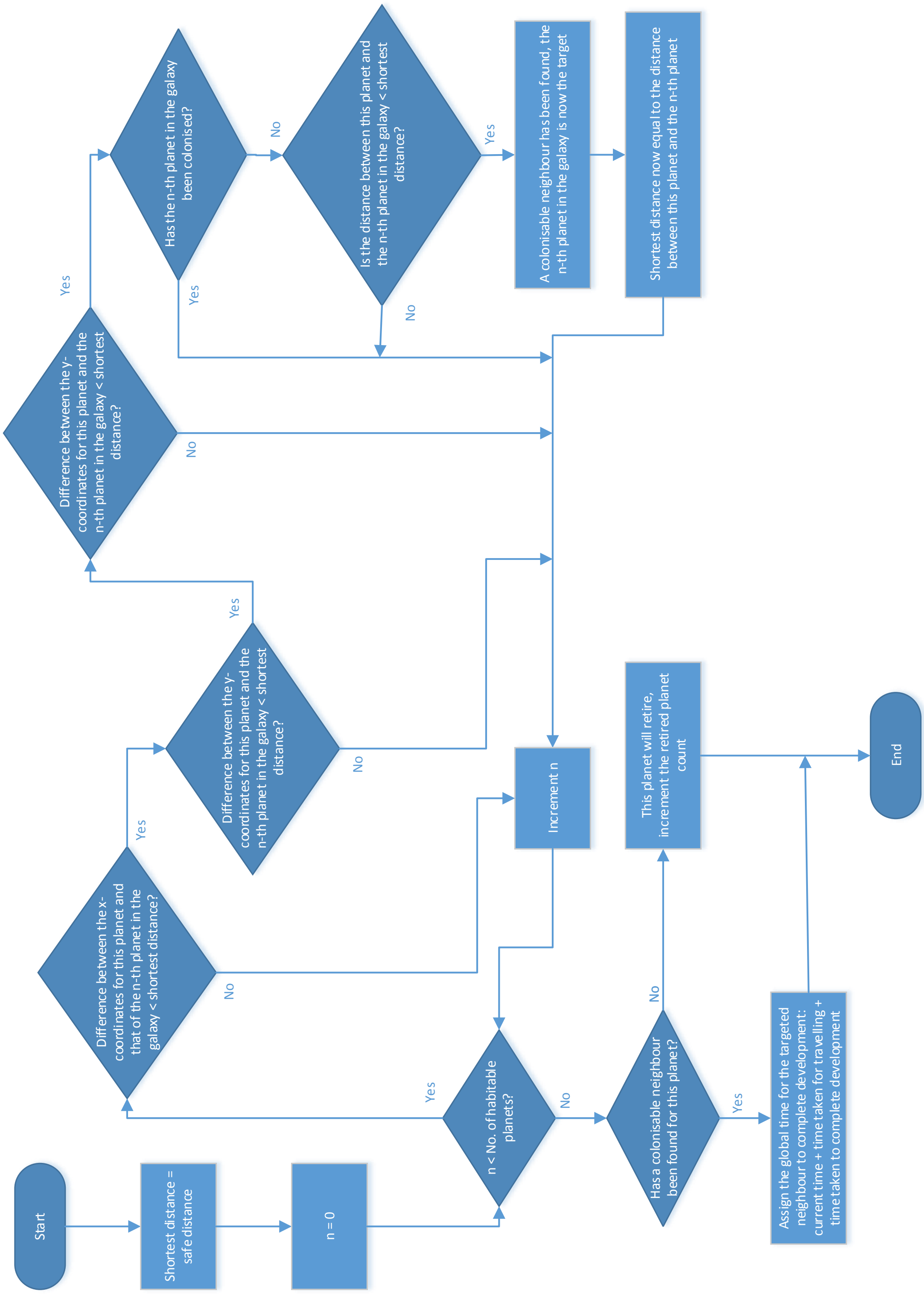

Figure 13: Flowchart describing the process of colonisation of the nearest habitable planet from the current planet.

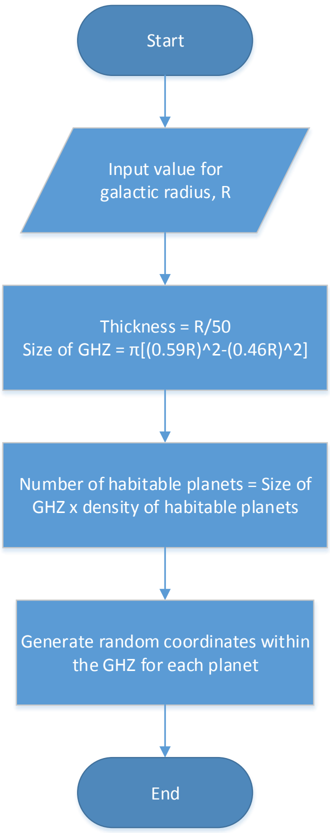

Figure 14: Flowchart describing the process of generating the virtual galaxy.

6 Results and Discussions

6.1 Colonisation Time Scale

The results for the colonisation of some scaled down galaxies are extrapolated to obtain the results for a full scale galaxy colonisation. This extrapolation is reasonable as long as their length scales are larger than the distance between habitable planets such that other physics does not intervene. The plot of colonisation time against radii of the galaxies for embryo ships are shown in plot15 The colonisation time for the full scale galaxy with radius of 50000ly is outline in table3, note that all types of world ships, nuclear fusion propelled sleeper ship and laser-pushed lightsail sleeper ship does not have large enough safe distance to achieve complete colonisation of the galaxy. The age of the oldest star in the Milky Way galaxy, HE 1523-0901,is 1.32×10^{10} years.[44] The time scale involved for colonisation of the galaxy is significantly smaller than the age of the Milky Way galaxy in all cases. This suggests that the galaxy should have been colonised if intelligent extra-terrestrial civilisations exists.

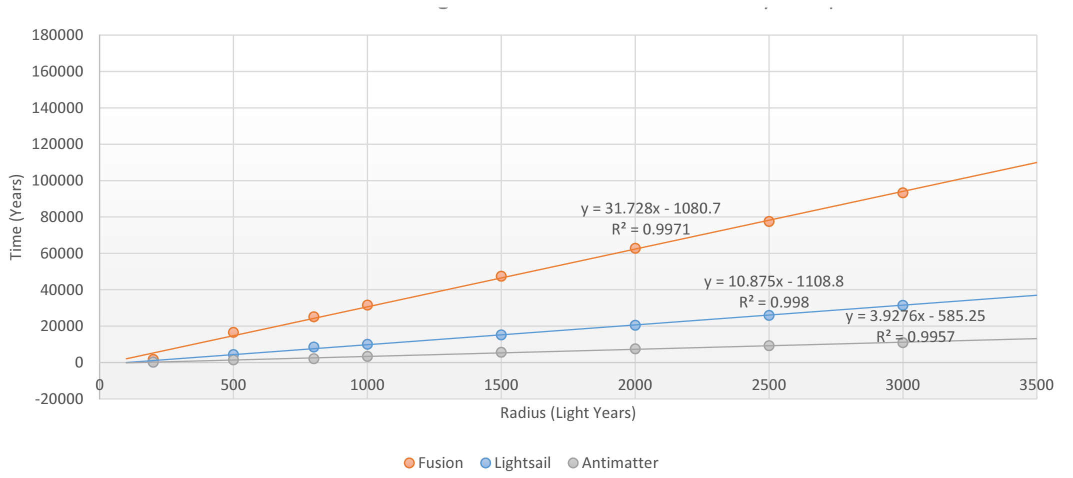

Figure 15: Plot of Colonisation time (years) against galactic radius (light years) for Embryo ship with different types of spaceship.
Orange - Nuclear fusion rocket, Blue - Laser-pushed lightsail, Grey - Antimatter annihilation rocket

Table 3: Colonisation time with different types of spaceships

Spaceship type	Colonisation time (years)
Antimatter Sleeper ship	1.6 million
Fusion Embryo ship	1.6 million
Lightsail Embryo ship	0.5 million
Antimatter Embryo ship	0.2 million

6.2 Bethe lattice

A Bethe lattice, also known as the Cayley tree is a system where each sites site has a fixed number of neighbours z and there no loops between any two sites, i.e. there is a unique path. A system with higher dimension are less likely to return to a previous point, therefore a Bethe lattice has infinite dimensions as no loop is allowed.
The galaxy in the computational model could be modelled by a Bethe lattice. Each colonised planet is able to send out z-1 spaceships, therefore it has z neighbours including the previous colonised planet. The lattice site is said to be occupied if it is colonised. The paths are unique because a colonised planet would not be "re-colonised". In the Bethe lattice, a percolating cluster exists if the occupation probability p of each neighbour is above the percolation threshold p_c.
Because there is no loop in the lattice, in order to have a percolating cluster, there must be at least one neighbour that is occupied for each site.[45]

$$p(z-1) \geq 1 \tag{18}$$

For the percolation threshold p_c

$$p_c = \frac{1}{z-1} \tag{19}$$

By considering contributions from each brances, the average cluster size $\chi(p)$ is given by:

$$\chi(p) = \frac{p_c(1+p)}{p_c - p} \text{ for } 0<p<p_c \tag{20}$$

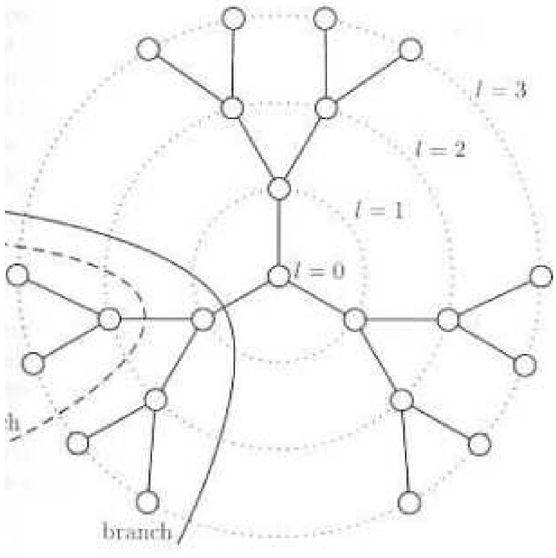

Figure 16: Example of a Bethe lattice with z=3 and four generations l=0,1,2,3, where the parent in the centre is the 0th generation.[45]

6.3 Safe Distance Threshold

The occupation probability of each site in the Bethe lattice is the probability that a habitable planet is colonised, which increases with the safe distance of the spaceship. All z neighbours are colonised if the safe distance is larger than all the distances between the parent planet and the smallest z-1 neighbours. However, if there are less than z-1 neighbouring planets with distance below the safe distance, there will be uncolonised neighbours.
Consider the cluster of colonised planets, with the safe distance for interstellar travel (l) as the parameter, the cluster exhibits geometrical phase transition, i.e. the fraction of the system being colonised has a significant change for a small change in the safe distance near the threshold. Above the threshold, the majority of the habitable planets within the scaled galaxy are colonised, there is a giant percolating cluster of colonised planets as shown in figure17 and figure18. Below the threshold, only a small isolated cluster of planets are

colonised as shown in figure19 and figure20. This phase transition is expected as a Bethe lattice's expected cluster size diverges at percolation threshold $p = p_c$.

The finite-size effect affects the result when the boundaries of the GHZ are seen by the cluster. This effect is smaller for a larger system because the ring-shaped GHZ is larger. As seen in plot21, the phase transition for a larger system is sharper.[46]

Apart from that, the safe distance threshold is smaller for larger scaled galaxies. Planets near the boundary is harder to reach than those in the inner region because there is no path for spaceships to reach the planet from outside the boundary. This is similar to the site percolation problem where clusters that do not seem to connected inside the window could turn out to be connected to the percolating cluster. As the size of the scaled galaxy increases, the surface area to volume ratio decreases. As a result, the fraction of habitable planets that are close to the boundary is smaller in a larger system. Therefore spaceships with a smaller safe distance could colonise the majority habitable planets in a larger system.

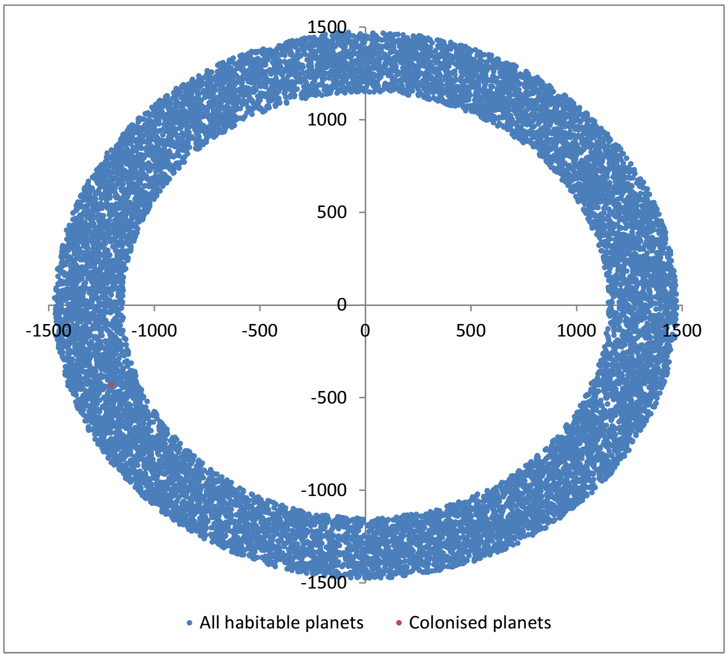

Figure 17: XY plot for fraction of colonised planets.
Galactic radius r=2500ly, safe distance=10.0ly. 0% colonisation.
blue - habitable planets, red - Colonised planets

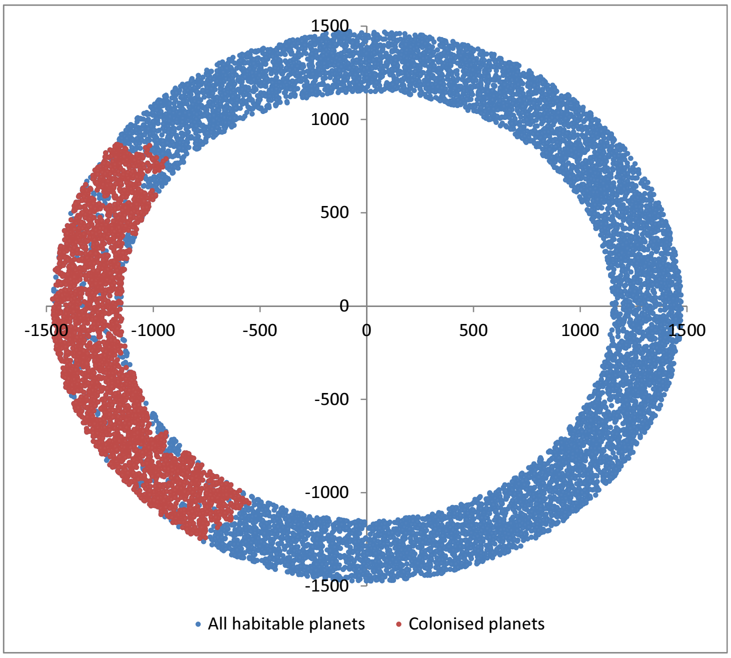

Figure 18: XY plot for fraction of colonised planets.
Galactic radius r=2500ly, safe distance=24.3ly. 31.0% colonisation.
blue - habitable planets, red - Colonised planets

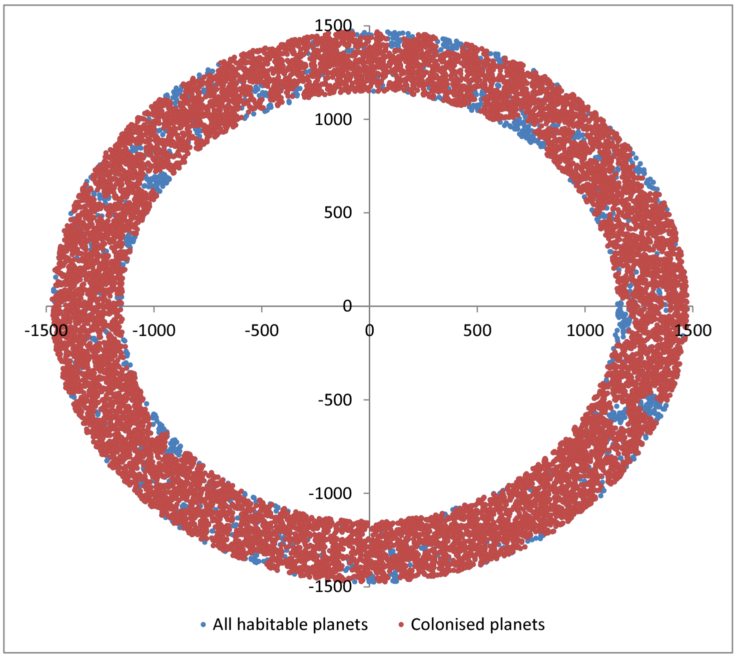

Figure 19: XY plot for fraction of colonised planets.
Galactic radius r=2500ly, safe distance=24.4ly. 92.5% colonisation.
blue - habitable planets, red - Colonised planets

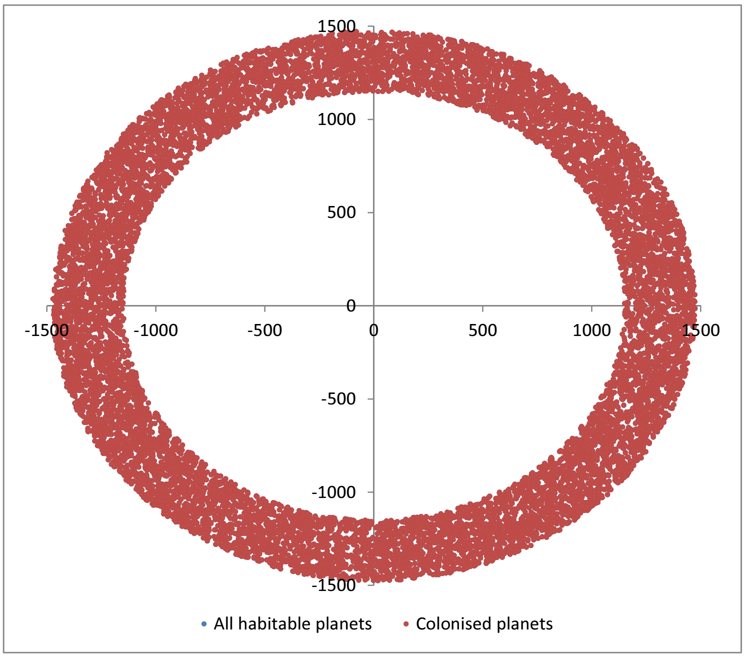

Figure 20: XY plot for fraction of colonised planets.
Galactic radius r=2500ly, safe distance=40.0ly. 100.0% colonisation.
blue - habitable planets, red - Colonised planets

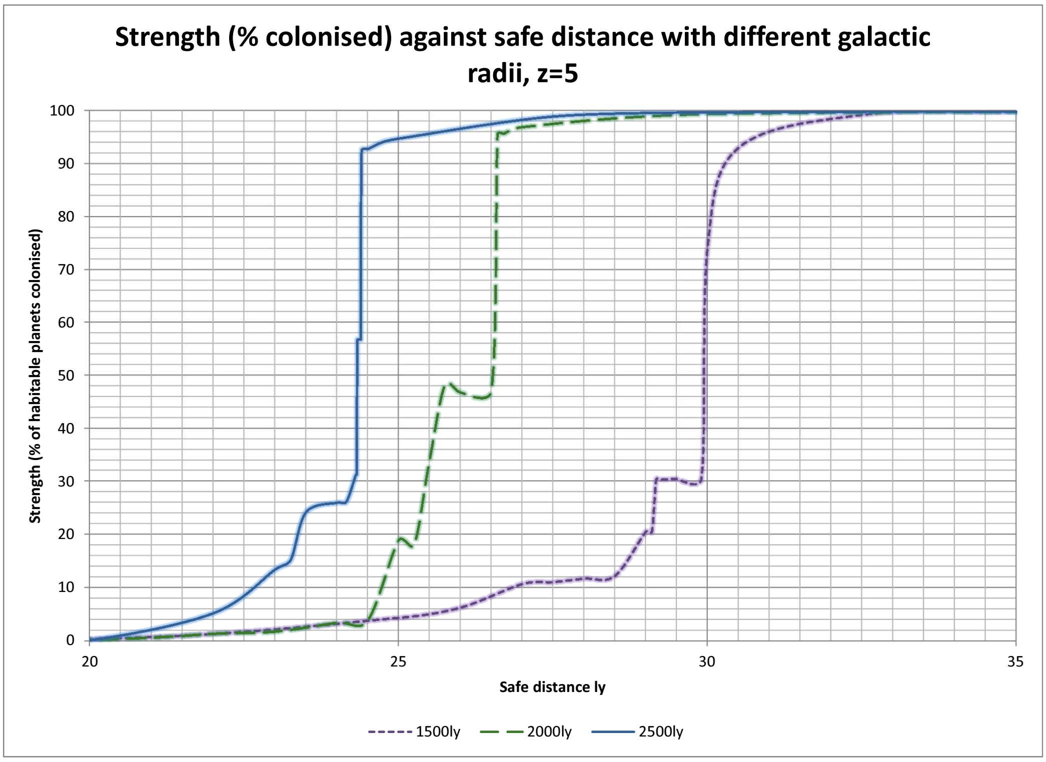

Figure 21: Strength (percentage colonised) of the cluster of colonised habitable planet against safe distance with different galactic radii.
threshold at 30ly for r=1500ly,26.5ly for r=2000ly and 24.3ly for r=2500ly
purple - 1500ly, green - 2000ly, blue - 2500ly

7 Conclusion

The estimated time required for colonisation of the galaxy is considerably shorter than the age of the galaxy. The limit of safe distance for complete colonisation of the galaxy suggests that even if interstellar spaceflight is feasible, it's safe duration and velocity of the spaceship might limit the fraction of the galaxy that can be colonised. This provides a possible explanation to the Fermi paradox.
From the fact that the GHZ is moving outward over time and the inner region is not likely to be habitable due to cosmic threats, it is argued that civilisations could have safely arisen only in the past five billion years.[42] For this reason, the human civilisation might actually be the most advanced life forms in the galaxy and therefore provide another possible solution to the Fermi paradox.
There are still many other possible explanations to the Fermi Paradox yet to be explored. It is possible that rise of intelligent life is extremely rare and the human civilisation might be the most advanced civilisation in the Milky Way galaxy.
The Search for Extraterrestrial Intelligence activities should be continued and seek improvements in their methodology if necessary. If no other Extraterres-

trial civilisations are found, the human civilisation should not be satisfied with the status quo and should consider taking up the challenge of colonising the galaxy.

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