COMPUTING THE MINIMAL CREW for a multi-generational space journey towards Proxima Centauri b

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The survival of a genetically healthy multi-generational crew is of a prime concern when dealing with space travel. It has been shown that determining a realistic population size is tricky, as many parameters (such as infertility, inbreeding, sudden deaths, accidents or random events) come into play. To evaluate the impact of those parameters, Monte Carlo simulations are among the best methods since they allow testing of all possible scenarios and determine, by numerous iterations, which are the most likely. This is why we use the Monte Carlo code HERITAGE to estimate the minimal crew for a multi-generational space travel towards Proxima Centauri b. By allowing the crew to evolve under a list of adaptive social engineering principles (namely, yearly evaluations of the vessel population, offspring restrictions and breeding constraints), we show in this paper that it is possible to create and maintain a healthy population virtually indefinitely. An initial amount of 25 breeding pairs of settlers drives the mission towards extinction in 80 ± 15% of cases if we completely forbid inbreeding. Under the set of parameters described in this publication, we find that a minimum crew of 98 people is necessary to ensure a 100% success rate for a 6300-year space travel towards the closest telluric exoplanet known so far.

Keywords: Long-duration mission, Multi-generational space voyage, Space genetics, Space colonization, Space settlement

1 INTRODUCTION

In 2016, the closest-to-Earth exoplanet was discovered [1]. This exoplanet, Proxima Centauri b, is believed to be rocky with a semi-major axis distance of 0.05 astronomical units (AU) from the star. The exoplanet is thus irradiated by a stellar flux that is ~ 0.65 times that for Earth [3, 4], leading to an equilibrium temperature of 234 K [1]. Considering an atmosphere with a surface pressure of one bar, one could expect liquid water to be present on the surface of the planet [5, 6]. Proxima Centauri b is thus within the range of potential habitability and becomes an interesting target for an exploratory mission.

The distance towards Proxima Centauri is estimated to be 1.295 parsecs [7]. This corresponds to about 4 × 10^10 km and it takes 4.22 years for light to reach us. The fastest human-made objects are far from reaching such high speeds and a manned mission to Proxima Centauri b would thus take much longer. As an example, the Apollo 11 spacecraft reached speeds near 40,000 km h⁻¹, with an average velocity of about 5500 km h⁻¹. Any space travel onboard of Apollo 11 would have taken approximately 114,080 years to reach Proxima Centauri b, distances which are far beyond the reach of current technologies.

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For a safer estimation of the human capabilities to reach high speeds, one should consider real missions that will fly in the coming years. By 2018, the NASA mission “Solar Probe Plus”, recently renamed “Parker Solar Probe”, will be launched. Its goals are to come as close as 8.5 solar radii to the Sun to trace the flow of energy that heats and accelerates the solar corona and solar wind; to determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind; and to explore the mechanisms that accelerate...
and transport energetic particles [13]. The Parker Solar Probe will reach record breaking orbital velocities as high as 724,205 km h⁻¹ (~ 200 km s⁻¹), which translates into about 0.067% the speed of light. At this speed, the ship is not a viable option for sustaining genetic diversity. We advocate adaptive social engineering principles and present in Section 2.2 the results of our computations. The impact of inbreeding restrictions on the population is studied in Section 2.3, and the rate of success for a variety of initial crew is presented in Section 2.4. We discuss the relevance of Proxima Centauri b as the first target to be explored by a multi-generational space expedition in Section 3 and conclude our paper in Section 4.

2 SIMULATING A JOURNEY TO PROXIMA CENTAURI b

To simulate a multi-generational space journey, we use the Monte Carlo code HERITAGE extensively presented in [14]. As a brief reminder, a Monte Carlo simulation is a computerized mathematical technique that takes into account chance events in decision making. The code accounts for a wide range of possible outcomes and their probabilities of occurrence depending on randomized actions. It reveals the extreme possibilities, as well as all the possible consequences of intermediate decisions. Applied to interstellar multi-generational spacecraft, such a method allows for the determination of the successes and failures of the mission depending on a number of input parameters. The results of the simulation must be averaged over several iterations to have a representative (median) outcome.

For all the simulations presented in this paper (with exception of Fig. 5), the results are averaged over 100 simulated interstellar journeys. We briefly remind the reader that HERITAGE takes the following iterative steps: first it creates the initial crew according to the parameters that are listed in Table 1 (which, unless stated otherwise, are the one used in this paper). The code checks for every year accidental and natural deaths, then checks for every crew member that she/he is within the procreation window. HERITAGE randomly associates two crew members of different sexes and evaluates if they can have a child. Infertility, pregnancy chances, inbreeding limitations and other parameters (such as the fact that the female crew member is not already pregnant) are verified before a successful mating. A new crew member is created in the vessel and the probability of making up the whole female community that is within the procreation window. The code saves all the data onboard and starts a new year, until the completion of the interstellar mission. In this paper, the code parameters are the same as the ones used in the first paper of the series, except for the duration of the travel that corresponds to the necessary time to reach Proxima Centauri b at a velocity of 200 km h⁻¹.1 We also set the date at which a plague-like catastrophic event happens as year 2500 after launch in order to check whether a catastrophe can lead the population to extinction. HERITAGE is entirely described in [14] and we advise the reader to refer to it for more details.

2.1 Using fixed social engineering principles

The anthropologist John Moore fixed a number of social engineering principles for the perpetuation of a multi-generational crew in a closed habitat. Namely, the starting crew should be young, childless married couples, allowing the crew to better adapt to their new environment before starting the reproduction. The second social engineering principle is to postpone parenthood until late in the female reproductive periods so that genetic variation is better maintained. The spacecraft would be then populated with smaller sibships and the age-sex distribution would be echeloned, reducing the number of non-reproductive young and old people, therefore stabilizing the social network. In the first paper of the series [14], we used different population estimations to model a 200-year journey. Namely, we considered a Moore population of 150 space settlers [15] and a Smith population of 14,000 humans [16]. In both cases the crew members were equally partitioned between women and men and all hand-picked to avoid initial consanguinity.

Running HERITAGE for such crews leads to a catastrophic outcome where the crew dies along the journey towards Proxima Centauri b, see Fig. 1. A very small population of 150 people dies after a tenth of the journey has been accomplished while a larger (14,000 humans) crew dies around the 1300th year (data averaged over 100 interstellar trips). The x-axis has been cut when the last human onboard disappeared. In this case,1 the decrease of population is due to the fixed

1 Since the possible parameter space to explore for all possible fixed social principles is huge, we restrict ourselves to criteria based on the rules suggested by Moore.

### TABLE 1: Input parameters of the simulation

| Parameter | Value | Units |
|-----------|-------|-------|
| Number of space voyages to simulate | 100 | (integer) |
| Duration of the interstellar travel | 6300 | (years) |
| Colony ship capacity | 500 | (humans) |
| Number of initial women | 75 | (humans) |
| Number of initial men | 75 | (humans) |
| Age of the initial women | 20/1 | (years) |
| Age of the initial men | 20/1 | (years) |
| Women infertility | 0.10 | (fraction) |
| Men infertility | 0.15 | (fraction) |
| Number of child per woman | 20/5 | (humans) |
| Twinning rate | 0.015 | (fraction) |
| Life expectancy for women | 80/15 | (years) |
| Life expectancy for men | 70/15 | (years) |
| Mean age of menopause | 45 | (years) |
| Start of permitted procreation | 35 | (years) |
| End of permitted procreation | 40 | (years) |
| Chances of pregnancy after intercourse | 0.75 | (fraction per year) |
| Initial consanguinity | 0 | (fraction) |
| Allowed consanguinity | 1 | (fraction) |
| Life reduction due to consanguinity | 0.5 | (fraction) |
| Chaotic element of any human expedition | 0.001 | (fraction) |
| Possibility of a catastrophic event | 1 | (boolean) |
| Year at which the disaster will happen | 2500 | (years; 0 = random) |
| Fraction of the crew affected by the catastrophe | 0.30 | (fraction) |

Note: The a, p values shown for certain parameters indicate that the code needs a mean (a) and a standard deviation value (p) to sample a number from a normal (Gaussian) distribution.
As shown in Fig. 2, a ship can have a stable population when inbreeding is random: the average consanguinity factor \( F \) per crew member is shown using the solid black line. The mean is measured from only those who show a non-zero coefficient and it should be compared to the inbreeding coefficients presented in Tab. 2. We find that, for an uncontrolled population, the average consanguinity factor per crew member lies between 6% and 6.5%, which corresponds to breeding between first cousins, half-uncle/niece or half-aunt/nephew (the procreation window prevails great-grandfather/great-granddaughter or great-grandfather/great-grandmother mating). It is slightly larger than 5% – the limit where deleterious effects onset [17].

We observe an initial peak of high consanguinity (~18% on average) that happens during the first centuries. This corresponds to the first generations of space settlers, whose population number is relatively small and where random brother/sister mating can occur more often than when the onboard population reaches several hundreds of people. The high 18% averaged consanguinity factor quickly decreases when the population is big enough so that there are more chances to randomly mate between unrelated or distant-related pairs rather than brothers and sisters, leading to a stable population level.

The lower graph in Fig. 3 shows the fraction of crew members showing a non-zero consanguinity and we find that about 10% of the crew has signs of inbreeding. A 13% peak of inbreeding follows the restoration period consecutive to the catastrophic event but the remaining curve is plateauing at ~10%. While this is already a great success to have a 90% final crew still perfectly healthy after a 6300-year multi-generational journey, one may want to design a mission where the human genetic heritage is perfectly safe to ensure humankind’s survival. In conclusion, if the inbreeding coefficient does not reach highly dangerous levels, it remains questionable to have a genetically unhealthy crew landing on an extra-solar planet. For a purely genetic safety purpose, we will then restrict inbreeding within crew members in the following section.

### 2.3 Effects of inbreeding restrictions on the population

The necessity to restrict inbreeding is a conservative security condition to ensure a genetically healthy crew. Using HERITAGE, we explored the impact of controlled consanguinity within the crew and present the results in Fig. 4. Results are averaged over 100 space travel for each set of parameters. It appears that a spaceship where inbreeding is tolerated up to 10% is able to reach destination without any trouble. The averaged population is almost at the security threshold. However, when inbreeding is restricted to a value of 5% at maximum, the averaged population is lower (slightly larger than 400 space settlers). This effect is even more visible when inbreeding is strictly prohibited: the average population within the ship is reduced to 320 people at the end of the journey. This is due to the fact that not all realizations of the journey are successful. A fraction of the simulations ended due to the inability of the crew to reproduce successfully after a 6300-year multi-generational journey, resulting in a non-zero consanguinity and we find that about 13% peak of inbreeding. A 13% peak of inbreeding follows the restoration period consecutive to the catastrophic event but the remaining curve is plateauing at ~10%.

We illustrate the fact that not all interstellar travel reach destination in Fig. 5. We present 10 single-journey simulations randomly extracted from Fig. 4 (but the median of them being representative of the larger sample of 100). We see that there are two modes: low or negative early growth leading to complete failure after ~500 years, or steady initial growth leading to success. The random nature of births, deaths and mating, coupled to a strict rule of zero consanguinity allowed within the ship potentially drives the vessel to a doomed fate since, in several cases the pool for mating is not diverse enough. Three out of ten simulations failed before the first millennium of space mission. After 1000 years of interstellar travel, we observe no failure except a 5% of the remaining crew. Since remaining the crew is able to reproduce only late in the mission, it has little effect on the total population and never leads to a mission failure. By 2500 years, if any of the crew have

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**Fig. 2** Crew population for a 6300-year trip where adaptive social engineering principles are accounted for. Different results based on the period allowed for procreation, are shown. In orange is a simulation with procreation permitted between 35 and 40 years; in red the period is 34-40, in violet 33-40, and in black 32-40. The initial crew is composed of 75 women and 75 men.

**Fig. 3** Inbreeding within the crew for a 6300-years trip toward Proxima Centauri b when adaptive social engineering principles are accounted for but without a control on authorized levels of consanguinity (see Fig. 2). Procreation is permitted between 32 and 40 years. Top: inbreeding coefficient as a function of time. The range of consanguinity (maximum-minimum) is shown in red and the average consanguinity factor \( F \) per crew member is shown using the solid black line. The mean is measured from only those who show a non-zero coefficient and it should be compared to the inbreeding coefficients presented in Tab. 2. We find that, for an uncontrolled population, the average consanguinity factor per crew member lies between 6% and 6.5%, which corresponds to breeding between first cousins, half-uncle/niece or half-aunt/nephew (the procreation window prevails great-grandfather/great-granddaughter or great-grandfather/great-grandmother mating). It is slightly larger than 5% – the limit where deleterious effects onset [17].

**Fig. 4** Crew population for a 6300-year trip. Adaptive social engineering principles are accounted for and the different curves show the impact of inbreeding restrictions on the population. The initial crew population is 60 members and procreation is permitted between 32 and 40 years. In orange is a simulation with no inbreeding restriction: in red the maximum inbreeding coefficient is set to 10%, in violet at 5%, and in black at 0%.

**Fig. 5** Ten single-journey realizations extracted from Fig. 4. The allowed consanguinity was set to 0%, the initial crew population is 60 and procreation was permitted between 32 and 40 years.

### Table 2: Inbreeding coefficients \( F \) per consanguineous matings (one generation, no previous in-breeding).

| Relationship                        | \( F \) |
|-------------------------------------|--------|
| Identical twins                     | 100%   |
| Self fertilization                  | 95%    |
| Brother/sister                      | 25%    |
| Father/daughter or mother/son       | 25%    |
| Grandfather/granddaughter or grandfather/grandson | 12.5% |
| Half-brother/half-sister            | 12.5%  |
| Uncle/niece or aunt/nephew          | 12.5%  |
| Great-grandfather/great-granddaughter or great-grandmother/great-grandson | 6.25% |
| Half-uncle/niece or half-aunt/nephew | 6.25% |
| First cousins                       | 6.25%  |
| First cousins once removed or half-first cousins | 3.125% |
| Second cousins or first cousins twice removed | 1.9825% |
| Second cousins once removed or half-second cousins | 0.78125% |
| Third cousins or second cousins twice removed | 0.390625% |
| Third cousins once removed or half-third cousins | 0.185% |

**Note:** Values of the inbreeding coefficients \( F \) for consanguineous matings (one generation, no previous in-breeding).
survived then their population has invariably reached a level so high that reducing them by one-third still leaves more than sufficient breeding pairs for a complete recovery (see Sect. 2.4). This method does not need to ensure that the crew could potentially survive multiple such disasters, provided their frequency was sufficiently low. Of course, if they occurred too frequently or too early in the mission (when the population was still low), or caused more fatalities than we have stipulated, then they could potentially indeed prove fatal, but we do not explore this in detail here. All successful missions actually have a population level very close to the security threshold but the average of the ten expeditions results in an crew population lower than the security threshold such as seen in Fig. 4 (30% of failures lead to 0.3 × Security Threshold = 30% of the crew need to keep in mind that the sim- ulation can only have two outcomes: success or failure. Such interstellar mission should be launched with a 100% success rate and the Monte Carlo method allows us to determine whether this initial conditions are needed to achieve this goal.

2.4 Estimating the success/failure rate

Due to the randomized evaluation of its Monte Cal- ro architecture, HERITAGE is able to estimate if a mission is destined to succeed or fail if the simulations are looped over several dozen attempts. In the following, we will estimate the success rate of a multi-generational space ship with different initial crew populations. We fix the ratio of women and men to parity and we allow procreation to happen between 32 and 40 years. With a crew made up with zero consan- guinity is mandatory or if a few crew members can show small (i.e. < 5%) inbreeding coefficient, we restrict inbreeding to a very small consanguinity. By doing so, we can focus on the most constrained simulations. We looped HERIT- AGE one hundred times for each simulation in order to have statistically significant error bars.

The results of our investigation are presented in Fig. 6. The standard deviation to the mean of the success rate is present- ed at 3 σ (i.e., there is a 99.7% probability that the estimated success rate is certain). We can see that, for less than 32 initial crew members in the vessel, the simulation gives a chance of success that cannot reach any significant value in the considered time. With larger initial crews, the chances of reaching the ship destination with a healthy crew increases. The slope appears to be linear, with small variations due to the statistical approach.

A mission has about a 50 ± 15% chance of being successful if the initial crew is composed of 25 women and 25 (men breeding pairs). It has been observed in laboratories that the genetic diversity a critical factor that is hard to apply to humans as well) composed of 25 pairs can be sustained practically infinitely by careful pairing, especially if spontane- ous mutations are not allowed [18]. In comparison to random mating using at least 25 breeding pairs per genera- tion, a consistent order rotational breeding scheme allows the creation of a healthy crew that can be sustained for at least 50% of initial missions successfully reach their destination for restricted mating between 25 initial breeding pairs. If the initial crew is composed of 34 initial breeding pairs, the chances to reach their destination with a completely genet- ically healthy crew rise up to 94-98%. An initial ship with 98 settlers is needed for a 65-70% chance for multi-generational space travel towards Proxima Centauri b.

3.2 On the habitability of Proxima Centauri b

The question of the real potential habitability of Proxima Cen- aurii b is to be investigated before any interstellar expedition. The fact that Proxima Centauri b closely orbits a red dwarf star makes them null questions on the selection criteria. By doing so, we can focus on the most constrained simulations. We looped HERIT- AGE one hundred times for each simulation in order to have statistically significant error bars.

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