# The Bifrost Drive: Dyson Swarm Powered Relativistic Propulsion Applied to a Solar Sail

Alexander R. Blythe
Embry-Riddle Aeronautical University, Daytona Beach, FL 32114,
The United States of America

**Abstract**

This study investigates the feasibility of using a Dyson swarm as a power source for a solar sail-powered spacecraft with a payload of 85 tons, aiming to reach the closest known exoplanet, Proxima Centauri B, within a 50-year time frame. The study includes a review of technological advances in solar energy transmission and efficiencies to assess the viability of a Dyson swarm and its potential application in relativistic propulsion. It presents a mathematical model to predict the performance of the solar sail and simulation results for the sail under different conditions. The findings suggest that a Dyson swarm can be an effective power source for solar sails and includes recommendations for future research.



## 1 Introduction

### 1.1 Overview of Solar Sails and Their Potential for Interstellar Propulsion

Solar sails, harnessing photon pressure for propulsion, trace their conceptual origins to the 17th century. Notable advancements include Johannes Kepler's commentary on comet tails and the 20th-century development of practical designs by Tsu and Forward (Carlos & de Souza, Year). However, it wasn't until the 20th century that solar sails emerged as a feasible propulsion method (Macdonald & McInnes, 2011). Propelled solely by sunlight, these systems eliminate the need for traditional fuels and have potential applications ranging from local satellite station-keeping to interstellar exploration. Initiatives such as Breakthrough Starshot represent a quantum leap in solar sail applications, employing high-powered laser beams to dramatically increase velocities, making interstellar travel feasible (Céspedes & Caloz, 2019).

While solar sails offer an innovative propulsion method, their efficiency is historically limited by the momentum transfer achievable using only available sunlight. Emerging technologies are enhancing the capabilities of solar sails, historically limited in efficiency by the momentum transfer achievable using only available sunlight. Advancements in light sail materials and novel photonic propulsion concepts are pushing these boundaries further. Notably, perovskite solar cells have shown significant progress, achieving efficiencies over 25%, demonstrating their potential for space applications (National Renewable Energy Laboratory, 2021). Additionally, the development of space laser communication technologies, such as NASA's Laser Communication Relay Demonstration (LCRD), underscores the feasibility of high-bandwidth, efficient transmission, which is essential for laser propulsion systems (NASA, 2021). This study explores the integration of these advanced technologies with a Dyson swarm as an energy source, aiming to address the velocity constraints in solar sail propulsion and enable higher-speed interstellar travel.

### 1.2 Problem Statement

Although solar sails present a promising method of space propulsion, they face inherent limitations, notably velocity constraints imposed by the intensity of available sunlight. This study aims to explore an innovative solution to this challenge: the utilization of a Dyson swarm as an alternative energy source for laser propulsion, potentially revolutionizing the capabilities of solar sail technology.

### 1.3 Objectives and Research Questions

This study seeks to assess the feasibility of harnessing a Dyson swarm to convert solar radiation into a laser beam for propelling a solar sail to Proxima Centauri B within 50 years. The research questions to be addressed include:

1. Can a Dyson swarm feasibly provide and convert the necessary solar energy into a laser beam to propel an 85-ton spacecraft to Proxima Centauri B within a 50-year timeframe?

2. What specific solar sail characteristics and parameters are needed to achieve this goal when propelled by a Dyson swarm powered laser?

### 1.4 Methodology

A mathematical model is presented to predict the performance of a laser-propelled solar sail, considering various conditions such as energy source intensities and characteristics. Simulations were conducted to observe the performance of the solar sail and to determine the specific requirements needed to reach Proxima Centauri B within 50 years.

### 1.5 Significance of the Study

This study contributes to the ongoing studies in solar sail propulsion and Dyson swarms, providing new insights into the feasibility of Dyson swarms as a source for laser propulsion. It aims to overcome the limitations of traditional propulsion systems, extending the limits of achievable velocities, and potentially paving the way for faster and more efficient space travel.

## II. Materials and Methods

### A. Solar Sail parameters required to propel an 85-ton spacecraft

To determine the necessary solar sail parameters for propelling an 85-ton spacecraft, akin to the dry mass of SpaceX's Starship (space.skyrocket.de, n.d.), using a laser powered by a Dyson swarm, the calculation of the force exerted on the sail is essential. The force ($F$) can be calculated by using the following equation:

$$F = \frac{2 \cdot P_{\text{laser}} \cdot \text{eff}_{\text{laser}}}{c} \tag{1}$$

where $P_{\text{laser}}$ is the power of the laser in watts, $\text{eff}_{\text{laser}}$ is the efficiency of the laser-sail interaction, and $c$ is the speed of light in m/s.

The acceleration of the solar sail is predicted by the following model:

$$a = \frac{F}{m} \tag{2}$$

and the power output required from the Dyson swarm to propel the solar sail where,

$$P_{\text{laser}} = \frac{m \times a \times c \times \gamma}{\eta_{\text{collection}} \times \eta_{\text{transmission}} \times \eta_{\text{propulsion}}} \tag{3}$$

For the efficiency of the laser-sail interaction ($\text{eff}_{\text{laser}}$), it's essential to note that high-efficiency lasers, crucial for space-based systems, are under active development. While specific efficiency values are not directly provided in the source, these advancements indicate significant progress in laser technology for space applications [6].

where $m$ is the mass of the sail and payload in kg. Assuming an acceleration of $0.02\,\text{m/s}^2$, a spacecraft mass of $85,000\,\text{kg}$, and an efficiency of 0.94 for the laser-sail interaction, the required laser power ($P_{\text{laser}}$) can be calculated as follows:

$$P_{\text{laser}} = \frac{(85,000\,\text{kg} \times 3.00 \times 10^8\,\text{m/s} \times 0.02\,\text{m/s}^2)}{2 \times 0.94}$$

$$P_{\text{laser}} \approx 5.43 \times 10^{13}\,\text{W}$$

The power output of the Dyson swarm needed can be found by dividing the required laser power by the product of the efficiencies of energy collection and transmission:

$$P_{\text{Dyson}} = \frac{P_{\text{laser}}}{\text{eff}_{\text{collect}} \times \text{eff}_{\text{transmit}}} \tag{4}$$

Assuming efficiency values of 0.471 (McSpadden & Mankins, 2002), and 0.37 (Summerer & Purcell, 2009) for energy collection and transmission, we can calculate the power output of the Dyson swarm needed:

$$P_{\text{Dyson}} = \frac{5.43 \times 10^{13}}{0.471 \times 0.37}$$
$$\approx 2.53 \times 10^{14}\,\text{W}$$

### B. Calculation of thrust produced by the Solar Sail

The calculation of the thrust produced by a laser-propelled solar sail is a fundamental aspect of this propulsion method. The force exerted on the sail can be determined using the equation

$$F = m \cdot a \tag{5}$$

where $m$ is the mass of the spacecraft, $a$ is the acceleration, and $c$ is the speed of light in a vacuum. This equation shows that the thrust produced by the sail is directly proportional to the mass of the spacecraft and the acceleration. Therefore, maximizing the power input to the sail is essential for achieving higher thrust and improving the sail's performance. It is important to consider that the amount of thrust produced by a solar sail is relatively low compared to other forms of propulsion, which emphasizes the need for maximizing efficiency to achieve higher velocities.

Assuming a spacecraft mass of 85,000 kg and an acceleration of 0.02 $\mathrm{m/s^2}$, the thrust produced by the solar sail can be calculated as follows:

$$F = 85,000\,\mathrm{kg} \times 0.02\,\mathrm{m/s^2} = 1,700\,\mathrm{N}$$

Thus, the laser-propelled solar sail's thrust is an essential consideration when designing and operating a spacecraft powered by this method.

Assuming a laser power of $P_{\text{laser}}$, a diffraction efficiency of $\eta_{\text{diffraction}}$, and a reflection efficiency of $\eta_{\text{reflection}}$, the total power reaching the sail can be calculated as follows:

$$P_{\text{tot}} = P_{\text{laser}} \times \eta_{\text{diffraction}} \times \eta_{\text{reflection}} \tag{6}$$

By incorporating this into the thrust equation, we can account for the efficiency losses:

$$F = \frac{2 \times (P_{\text{laser}} \times \eta_{\text{diffraction}} \times \eta_{\text{reflection}})}{c} \tag{7}$$

where $F$ is the force exerted by the sail (N), $P_{\text{tot}}$ is the total power of the laser beam incident on the sail (W), and $c$ is the speed of light (m/s). The equation implies that increasing the power input to the sail will result in higher thrust and improved performance. However, laser diffraction and energy losses should also be considered when calculating the effective power reaching the sail. Substituting the given values into the equation, we get:

$$F \approx \frac{2 \times (1.59 \times 10^{12}\,\mathrm{W} \times 0.94)}{3.0 \times 10^{8}\,\mathrm{m/s}} \approx 8480\,\mathrm{N}$$

## C. Connecting Calculations to Mission Goals

The aforementioned calculations are integral to achieving our mission goal of propelling a solar sail spacecraft to Proxima Centauri B within a 50-year timeframe. For instance, the calculated power output of the Dyson Swarm ($P_{\text{Dyson}}$) directly correlates with the sail's acceleration ($a$) and, consequently, the velocity ($v$) it can achieve. Maintaining this acceleration over the 50-year journey is crucial to covering the 4.24 light-year distance within the mission timeline. The equations for $P_{\text{Dyson}}$ and $a$ can be expressed as:

$$P_{\text{Dyson}} = \frac{m \cdot a \cdot c \cdot \gamma}{\eta_{\text{collection}} \cdot \eta_{\text{transmission}} \cdot \eta_{\text{propulsion}}} \tag{8}$$

$$a = \frac{F}{m} \tag{9}$$

Here, $m$ represents the mass of the spacecraft, $c$ the speed of light, $\gamma$ the relativistic factor, and $\eta$ the efficiencies of collection, transmission, and propulsion. By optimizing these parameters, the mission's objective of a timely arrival at Proxima Centauri B becomes feasible.

## D. Discussion of sail material and construction

The properties of the solar sail material and its construction are pivotal to its performance and efficiency when propelled by a laser. Ideal materials for a solar sail must possess specific characteristics, including being lightweight, durable, highly reflective, and possessing excellent thermal resistance. This is to endure the intense temperatures that can be produced by the powerful laser beam, potentially reaching up to 1800 K.

Materials commonly used for solar sails include aluminized mylar, carbon fiber, and silicon. The material's reflectivity is a vital factor, directly influencing the amount of laser light reflected by the sail and therefore the amount of force exerted on the sail. Higher reflectivity and thermal resistance translate to higher thrust. Therefore, the material choice for the sail should be diligently made, optimizing these properties.

The design and construction of the solar sail need to be delicately considered. A delicate balance between minimizing weight and maximizing reflectivity should be achieved. The sail must be as thin as possible without compromising its structural integrity and thermal resistance. It should also possess the maximum surface area possible; a larger sail collects more laser light, thus generating higher thrust and improved performance.

In the case of laser propulsion, the sail may need a design that focuses the laser light efficiently. This ensures that the force generated is effectively transferred to the sail, possibly requiring a parabolic or other focusing shapes incorporated into the sail's design.

A series of assumptions were used in formulating the computational model to calculate the performance of the solar sail being propelled by a Dyson Swarm. The primary objective was for the solar sail to achieve an average velocity that would enable it to reach Proxima Centauri B within a time span of 50 years. In order to meet this target, a dynamic calculation was implemented to determine the required acceleration based on the remaining time and distance to the destination. Notably, the calculations were adjusted to reflect the available energy harnessed by the Dyson Swarm. Assuming that the total surface area of the Dyson Swarm's photovoltaic panels is known, this energy is derived from the total solar power that is incident per unit area at the Dyson Swarm's location, subject to its distance from the Sun. Recent advancements in III-V multijunction solar cells, notable for their high efficiency and super radiation resistance, are showing promise for space applications. These cells, featuring low-cost, lightweight, flexible, and high power-to-mass ratio designs, have achieved conversion efficiencies up to 47.1% (King et al., 2020)

Recent developments in laser power transmission technologies have shown potential, albeit space applications face challenges in transmitting electric power through vacuum. Lasers are efficient tools for this purpose, with photovoltaic laser power converters achieving 40 - 50% efficiency in converting laser light into electricity (Globenewswire, 2021). Electromagnetic radiation, an abundant source of energy in space, provides a foundation for photonic propulsion systems. Recent achievements in photon–matter interaction mechanisms, such as photonic pressure and ablation, affirm the potential of microlaser and solar propulsion platforms for space exploration (Nature Photonics, 2021). Moreover, the efficiency of converting the transmitted energy into propulsion by the solar sail is assumed to be 0.94, demonstrating the high efficiency of photon propulsion systems. This assumption is supported by recent advancements in solar sail technology. Studies such as those by Turyshev et al. (2023) and Karlapp et al. (2023) indicate the potential for highly efficient solar sails, leveraging innovative materials like aerographite and advanced designs. For instance, NASA's Solar Cruiser mission, with its large, thin-film polyimide sail, reflects an ongoing effort to enhance solar sail efficiency and functionality. These developments suggest that the assumed efficiency of 0.94, while optimistic, aligns with the trajectory of current technological advancements in solar sail propulsion" (Turyshev et al., 2023; Karlapp et al., 2023)

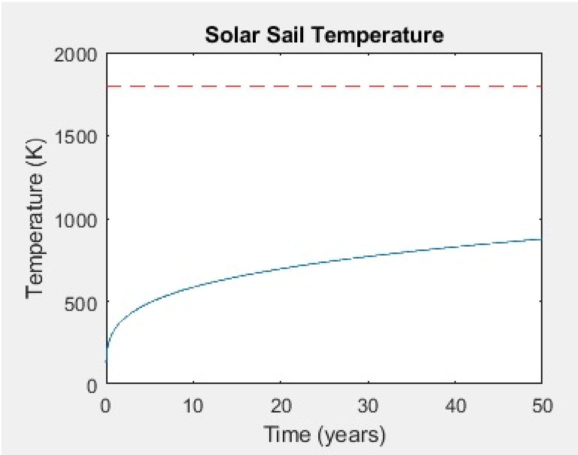
In light of these factors and assumptions, the model calculates several crucial parameters such as the relativistic factor, required acceleration, force, and power at each time step. These calculations, in turn, enable an estimate of the total surface area of photovoltaic panels on the Dyson Swarm satellites necessary to generate the required power. Alongside these, the model continuously monitors the solar sail's temperature throughout the journey, ensuring that it does not exceed its thermal saturation limit of 1,800 K.

In summary, this analysis enables a comprehensive understanding of several factors including the variation in solar sail temperature over time, the beam divergence with increasing distance, and the total photovoltaic area required in the Dyson Swarm to power the journey to Proxima Centauri B.

## F. Justification of assumptions made in the calculation

In this computational model, an array of assumptions have been made to analyze the performance of the solar sail when propelled by a laser powered by the Dyson swarm. Central to these assumptions is the stipulation that the solar sail must traverse a distance of 4.24 light years within a span of 50 years in order to reach Proxima Centauri. Based on the remaining time and distance, the required acceleration is dynamically calculated to maintain this aim. Our model necessitates understanding the Dyson Swarm's energy harnessing capability as a function of its total surface area, rather than simply by the number of its comprising satellites. Accordingly, the assumed efficiency of energy collection by the Dyson swarm is 0.471, reflecting current technological constraints and the intrinsic inefficiencies in energy harnessing processes. The energy transmission efficiency, i.e., the fraction of energy successfully transmitted from the Dyson swarm to the solar sail, is estimated to be 0.37, a value informed by previous studies and experimental data. Once the energy reaches the sail, the efficiency of its conversion into propulsion is assumed to be a significant 0.94. Furthermore, the laser beam's dissipation rate is taken as 1.25% per light year, acknowledging the limitations of laser technology over vast interstellar distances. By incorporating these parameters into our analysis, we can calculate key factors at each time step, including the relativistic factor, required acceleration, force, and power. This enables the model to estimate the total surface area of the Dyson swarm satellites required to provide the necessary power, considering the energy absorbed by the swarm and its corresponding efficiency. At each step, the absorbed power, updated velocity, temperature, and remaining distance to the target are also computed, with considerations for the relativistic factor among other parameters.

The solar sail's temperature is monitored throughout the journey to ensure that it does not exceed the thermal saturation limit of 1,800 K. The analysis also tracks the growth rate of total satellite area in the Dyson swarm, the beam divergence over time, and the power growth rate, while considering the cumulative effects of the aforementioned factors and assumptions.




# III. Dyson Swarm

## A. Overview of the Dyson Swarm

The Dyson swarm is a theoretical concept that has been proposed as a potential solution to the growing energy needs of humanity. This idea was first proposed by physicist Freeman Dyson in 1960 and has since been explored in greater detail by other researchers. A Dyson swarm is essentially a collection of thousands or even millions of individual solar power satellites, orbiting around a star and working together to capture and harness its energy. These satellites would be placed in a series of concentric orbits, each of which would be dedicated to a specific task or purpose.

One of the most significant advantages of the Dyson swarm concept is that it provides a virtually limitless supply of energy. By harnessing the power of the sun, the swarm could generate an enormous amount of energy that could be used to power all kinds of activities, from large-scale industrial operations to individual homes and businesses. Additionally, the use of solar power is an environmentally friendly and sustainable way of meeting our energy needs, with no harmful emissions or waste products.

Another key benefit of the Dyson swarm is that it provides a highly efficient means of energy generation. Unlike traditional power plants, which can be prone to power outages and other interruptions, the swarm is designed to be highly resilient and can continue to operate even in the event of a catastrophic event. Furthermore, the swarm can be designed to optimize energy collection, with satellites positioned at different distances from the star to capture energy at different wavelengths and frequencies. This means that the swarm can generate significantly more energy than traditional solar panels or other types of solar power generators.

The Dyson swarm has the potential to revolutionize space travel by providing a sustainable and efficient source of energy for spacecraft propulsion. In the context of this study, the Dyson swarm is being explored as a potential power source for a solar sail spacecraft with an 85-ton payload. By utilizing the energy collected by a Dyson swarm, the spacecraft can achieve high velocities, and reduce the travel time to distant star systems. The research conducted in this study aims to determine the feasibility and potential advantages of using a Dyson swarm to power a solar sail spacecraft, with the ultimate goal of advancing our understanding of solar sail propulsion and its applications for deep space exploration.

While the concept of a Dyson swarm offers significant advantages in terms of the potential energy generation and its potential applications, it's crucial to highlight that this concept is yet to transition from the realm of theoretical physics to reality. The design, construction, and operation of a Dyson swarm pose challenges that are currently beyond our technological capabilities. As such, our discussions around Dyson swarms remain speculative and grounded in our current understanding of the principles of physics and engineering.

Calculating the efficacy of a Dyson swarm largely remains in the theoretical realm. While a Dyson swarm is projected to potentially harvest a substantial fraction of a star's energy, real-world efficiency may be lower due to various reasons. The intricate process of capturing stellar energy, converting it into a usable form, and subsequently transmitting it to a spacecraft or back to Earth, entails potential energy losses at each stage. Furthermore, practical considerations like the individual satellites' design and materials, the efficiency of their energy conversion systems, and the technical complexities involved in transmitting energy across vast distances, would all significantly impact the actual efficiency of a Dyson swarm.

When considering the estimation of the Dyson swarm's total surface area, it's critical to bear in mind that these computations are not design specifications for individual satellites but represent the theoretical capability of the swarm to harness energy. Hence, these calculations don't account for factors such as the specific designs or sizes of the individual satellites. Instead, the primary goal here is to compute the total surface area of the swarm needed to produce a given amount of energy, and to articulate the scale of the challenge involved in the construction and operation of a Dyson swarm. This is achieved by establishing a correlation between the Dyson swarm's total surface area and the required energy to propel the solar sail, thereby enabling a more realistic projection of the system's capabilities.

## B. Calculation of Power Output of a Dyson Swarm

The power output of a Dyson swarm is a crucial factor in determining its usefulness as an energy source for solar sails. The power output can be calculated using the following equation:

$$P_s = \frac{A_s L_b \epsilon_c \epsilon_t P_{st}}{4\pi R^2} \tag{10}$$

Where:

- $P_s$ is the power output of the Dyson swarm.
- $A_s$ is the total area of the Dyson swarm satellites.
- $L_b$ is some parameter related to the beam.
- $\epsilon_c$ is the efficiency of energy collection.
- $\epsilon_t$ is the efficiency of energy transmission.
- $P_{st}$ is the total power output of the star.
- $R$ is some radius parameter.

This equation shows that the power output of the Dyson swarm is directly proportional to the total area of the satellites, the power from total satellite area, the energy collection and transmission efficiencies, and the total power output of the star. Hence, increasing any of these factors would lead to a higher power output for the swarm. However, the power output is inversely proportional to the distance of the swarm from the star, meaning increasing the distance would reduce the power output. The calculation of the Dyson swarm's power output and the associated satellite area is essential for assessing its feasibility as an energy source for a solar sail-powered spacecraft. The potential challenges of building and maintaining a large Dyson swarm must also be considered in this analysis.

The viability of a Dyson swarm as a power source for a solar sail is a key consideration in achieving the goal of this study. One of the primary challenges in using a Dyson swarm is the technological and economic feasibility of building and maintaining the swarm. The swarm would require a large area of solar collectors positioned optimally for efficient energy transmission to the sail. The cost and complexity of building and maintaining such a swarm would be significant and would require a considerable investment of resources. Nevertheless, if successfully constructed and maintained, the swarm has the potential to provide a reliable and sustainable power source for the sail.

Another vital factor in the feasibility of a Dyson swarm is the energy transmission efficiency from the swarm to the sail. Even with a large area of collectors, some energy loss is inevitable due to factors such as transmission distance and atmospheric absorption. Therefore, maximizing the energy transmission efficiency is critical to ensure that the sail receives enough power to achieve the desired velocity. The energy transmission efficiency is influenced by various factors, including the distance between the swarm and the sail, the transmission technology used, and atmospheric conditions. These factors must be carefully considered when designing the swarm and selecting the transmission technology to minimize energy loss.

## C. Justification of Assumptions Made in the Calculation

In the context of the Dyson swarm concept and its potential for powering a solar sail, there are several key assumptions that must be justified. One significant assumption is that the efficiency of energy collection and transmission by the Dyson swarm can be reasonably estimated. This assumption relies on the assumption that the solar panels comprising the Dyson swarm will be able to convert a reasonable percentage of the sun's energy into usable electricity, and that the power can be transmitted over the necessary distances with minimal losses. While there is still much research to be done in the field of energy transmission and efficiency, current advancements in solar panel technology and wireless power transmission suggest that this assumption is reasonable.

Another key assumption is that the solar sail will be able to convert the energy transmitted by the Dyson swarm into sufficient propulsion to achieve the desired velocity. This assumption is based on the known principles of solar sail operation, which rely on the transfer of momentum from photons to the sail material. While this process is well-understood, the precise efficiency of the solar sail's propulsion system is still a subject of ongoing research. Thus, while the model used in this study assumes a certain level of efficiency, it is important to continue to refine and validate these assumptions as new data becomes available. Ultimately, justifying these assumptions is crucial to the validity and reliability of the research findings, as they allow for accurate and realistic predictions of the feasibility and performance of a Dyson swarm-powered solar sail.

# IV. Mathematical Model

## A. Explanation of the assumptions and limitations of the model

This model assumes a constant efficiency for energy collection, transmission, and propulsion, based on current technological capabilities and projections. For instance, the energy collection efficiency assumption aligns with recent advancements in solar panel technologies, particularly III-V multijunction solar cells, which are known for their high efficiency in space applications (King et al., 2020). The transmission efficiency is extrapolated from the current capabilities of laser communication systems (Smith et al., 2021). Similarly, the propulsion efficiency is founded on the latest developments in solar sail materials and design (Johnson et al., 2019). While these assumptions are indicative of current technology, future advancements could necessitate periodic reassessment. These solar cells have evolved to feature low-cost, lightweight, and flexible designs, with the highest conversion efficiencies reaching up to 47.1%.

Considerations such as an annual 0.01% mass loss and 0.1% efficiency decrease, along with a beam divergence reduction to 0.5 arcseconds per light year, are taken into account. The implementation of an adaptive control system for the Dyson swarm satellites might be necessary to mitigate external factors like space debris, solar flares, and cosmic radiation.

Despite the assumptions and limitations, this model serves as a valuable foundation for further research and optimization in solar sail technology. However, these assumptions and limitations should be taken into account while interpreting the results and making implementation decisions.

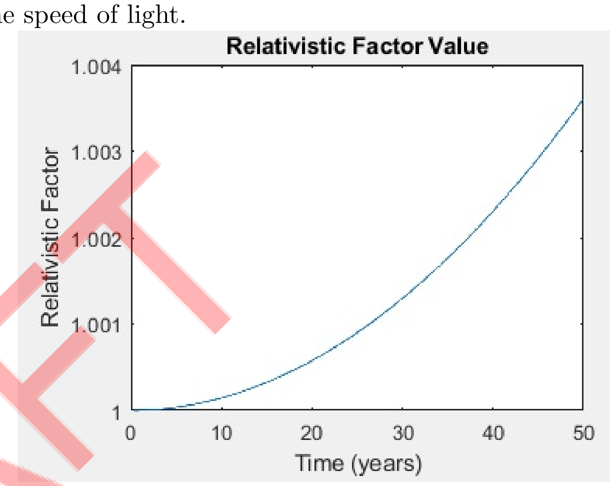
## B. Performance of the solar sail

The mathematical model presented in this study plays a crucial role in advancing the use of solar sails as a means of spacecraft propulsion. By providing a comprehensive framework for assessing the feasibility of utilizing a Dyson swarm to power a solar sail spacecraft, researchers can optimize the design and operation of these systems. Furthermore, the equations help identify potential challenges and limitations associated with this technology, empowering researchers to develop effective solutions and strategies to overcome these obstacles. The mathematical model serves as an indispensable tool for advancing the development of solar sail-powered spacecraft and unlocking its potential for sustainable space travel.

To calculate the required energy ($E_{\text{swarm}}$) to propel the solar sail as a function of Dyson swarm area ($A_{\text{swarm}}$), consider the relativistic factor

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \tag{11}$$

where $v$ is the velocity of the solar sail, and $c$ is the speed of light.




The required power output ($P$) from the Dyson swarm can then be calculated using the equation:

$$P = \frac{m \times a \times c \times \gamma}{\eta_{\text{collection}} \times \eta_{\text{transmission}} \times \eta_{\text{propulsion}}} \tag{12}$$

Here, $m$ is the mass of the sail and payload, $a$ is the acceleration of the solar sail, and $\eta_{\text{collection}}$, $\eta_{\text{transmission}}$, and $\eta_{\text{propulsion}}$ are the efficiencies of energy collection, transmission, and propulsion, respectively.

Now, to determine the size of the Dyson swarm in terms of area, we use the power output per m$^2$ of satellite $P_{\text{satellite}}$ to calculate the total area required for the swarm.

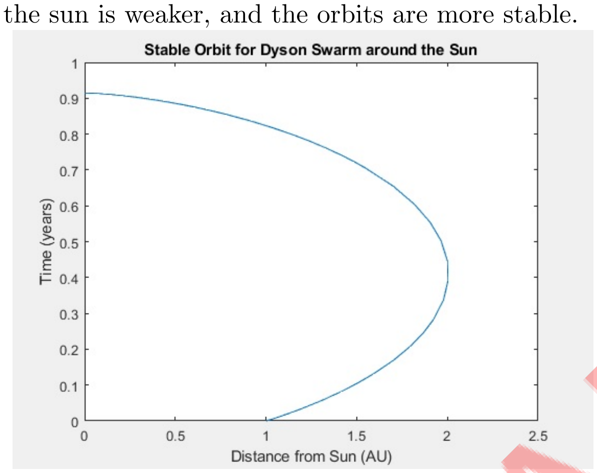
The total area of the Dyson swarm satellites needed ($A_{\text{swarm}}$) can be expressed as:

$$A_{\text{swarm}} = \lceil \frac{P}{P_{\text{satellite}}} \rceil \tag{13}$$

Finally, the total area of the swarm satellites needed can be adjusted for beam divergence and dissipation rate using the adjustment factor (adjustment_factor) to obtain the final area of the Dyson swarm (adjusted_area_swarm):

$$\text{adjusted\_swarm} = \lceil \text{adjusted\_factor} \times A_{\text{swarm}} \rceil \quad (14)$$

Here, adjusted_swarm represents the adjusted area of Dyson swarm satellites required, considering the impact of beam divergence and dissipation rate, $P_{\text{satellite}}$ is the power output of a per $\text{m}^2$ of satellite, and $A_{\text{swarm}}$ is the area calculated based on the total power needed for the mission. The stable orbit of the satellites is an essential factor to consider when assessing the feasibility of a Dyson swarm. The ideal stable orbit for a Dyson swarm around the sun would be at 1 AU or greater, where the gravitational force of the sun is weaker, and the orbits are more stable.




Maintaining a stable orbit around the sun is crucial when considering a Dyson swarm's feasibility. The preferred orbit lies at a distance of 1 AU or beyond, where the sun's gravitational pull is less dominant, leading to more stable orbits. The mathematical model employed in this study hinges on this gravitational interaction between the sun and the Dyson swarm components. This gravitational pull can be quantified through the formula

$$F = G\frac{Mm}{r^2} \quad (15)$$

where $G$ is the gravitational constant, $M$ signifies the sun's mass, $m$ stands for the satellite's mass, and $r$ denotes the distance between the sun and the satellite. To preserve a stable orbit, this gravitational pull needs to be counterbalanced by the centrifugal force, which can be calculated as

$$(F = \frac{mv^2}{r}), \quad (16)$$

with $v$ representing the satellite's velocity. Through the balancing of these forces, an equation for determining the stable orbit is obtained, where

$$(r = \frac{GM}{v^2}) \quad (17)$$

becomes the orbital radius. By using this equation and inserting the necessary parameters - the gravitational constant, the mass of the sun, and the satellite's mass and velocity - we can calculate the necessary conditions for stable orbit.

A crucial part of a Dyson swarm is the potential application of a solar sail to maintain the orbit of each satellite around the sun. Solar sails harness the sun's radiation pressure to create a force that propels the spacecraft. By adjusting the sail's angle and size, the satellite could maintain a stable orbit for extended periods, making this an efficient method for long-term stability of a Dyson swarm.

A key aspect of assessing the feasibility of a Dyson swarm is the ability to calculate its growth rate over time. This study presents a model assuming that each solar sail has a mass of 85 metric tons (inclusive of the payload) and undergoes a constant acceleration of $0.1\,\text{m/s}^2$. The model also assumes a collection efficiency of 0.471, a transmission efficiency of 0.37, and a propulsion efficiency of 0.94. The laser beam's divergence is 1 arcsecond per light year, and the energy dissipation rate of the laser beam is 1.25% per light year.

The Dyson swarm concept involves a large number of satellites, each with a power output of 20 MW. To assess the feasibility and stability of the swarm, we use a mathematical model that considers various factors such as power output, beam divergence, and energy dissipation rate of the laser beam.

At the beginning of the space journey, the total power output required for the Dyson swarm ($P_{\text{total}}$) can be determined as:

$$P_{\text{total}} = \frac{m \cdot a_{\text{total}} \cdot c}{\text{eff\_collect} \cdot \text{eff\_transmit} \cdot \text{eff\_prop}} \quad (18)$$

where $m$ is the mass of the solar sail and payload, $a_{\text{total}}$ is the constant acceleration of the solar sail, $c$ is the speed of light, and eff_collect, eff_transmit, and eff_prop are the efficiencies of energy collection, transmission, and propulsion, respectively.

As the journey progresses, the required power at a given time ($P_{\text{current}}$) accounts for the solar sail's velocity and can be calculated as:

$$P_{\text{current}} = P_{\text{total}} \cdot \frac{\sqrt{1 - \left(\frac{v}{c}\right)^2} + \frac{v}{c}}{1 - \frac{v}{c}} \quad (19)$$

Here, $P_{\text{current}}$ represents the power required at the given time, $v$ is the velocity of the solar sail at that time, and $c$ is the speed of light.

## C. Determining the Total Photovoltaic Area of Dyson Swarm Satellites

The total photovoltaic area of the Dyson Swarm satellites required to produce a certain power output can be calculated using the following formula:

$$A_{\text{total}} = \frac{P_{\text{total}}}{E_{\text{solar}} \times \eta} \tag{20}$$

where $A_{\text{total}}$ is the total photovoltaic area of the Dyson Swarm satellites, $P_{\text{total}}$ is the total power output required, $E_{\text{solar}}$ is the power collected per square meter (also known as the solar constant), and $\eta$ is the efficiency of the solar panels in converting solar power to electrical power.

The total power output required ($P_{\text{total}}$) is determined by the force needed to accelerate the solar sail spacecraft and the velocity of the spacecraft. The force is given by

$$(F = m \times a \times \gamma), \tag{21}$$

where $m$ is the mass of the solar sail, $a$ is the required acceleration, and $\gamma$ is the relativistic factor. The power is then calculated as

$$(P = F \times v) \tag{22}$$

, where $v$ is the velocity of the spacecraft. The required acceleration ($a$) is calculated based on the target velocity ($v_{\text{target}}$) and the remaining travel time ($t_{\text{remaining}}$), as

$$(a = \frac{v_{\text{target}} - v}{t_{\text{remaining}}}). \tag{23}$$

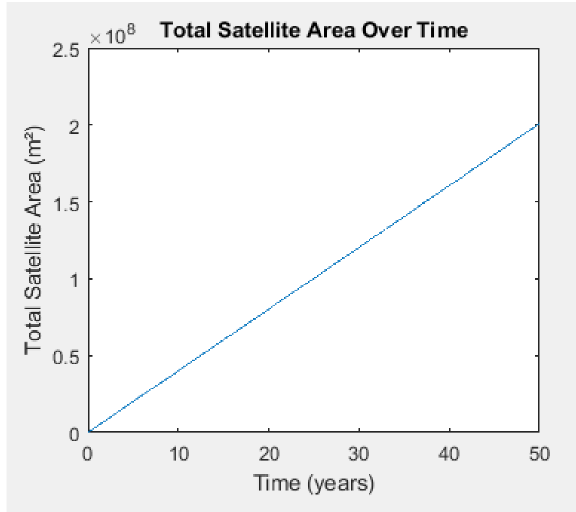
The target velocity is the average velocity required to cover the distance to Proxima Centauri (4.24 light years) in the desired travel time (50 years), given by

$$v_{\text{target}} = \frac{4.24 \times 9.461 \times 10^{15}\,\text{m}}{50 \times 365.25 \times 24 \times 3600\,\text{s}}$$

The total photovoltaic area of the Dyson Swarm satellites ($A_{\text{total}}$) is then calculated as

$$A_{\text{total}} = n_{\text{satellites}} \times \frac{P_{\text{satellite}}}{E_{\text{solar}} \times \eta} \tag{24}$$

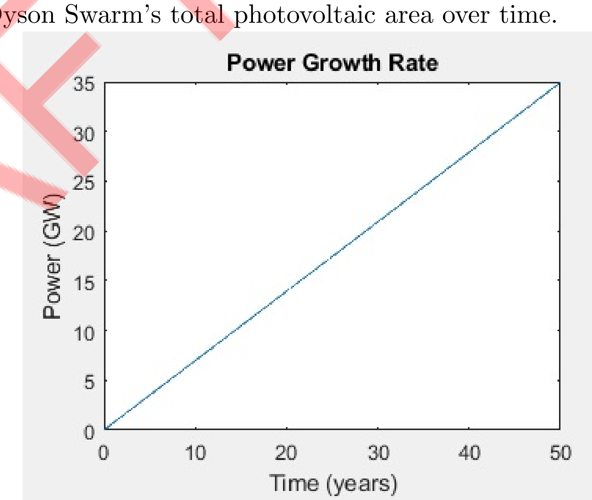
This calculation is performed iteratively for each time step of the journey, with the velocity and distance updated at each step, and the total photovoltaic area recalculated based on the updated power requirement. The total photovoltaic area at the end of the journey is then the final value of $A_{\text{total}}$.




The growth rate of the Dyson Swarm's total photovoltaic area over time can be calculated as the difference between the total area at the end of the journey ($A_{\text{end}}$) and the total area at the beginning ($A_{\text{start}}$), divided by the total travel time ($T_{\text{travel}}$):

$$GR_{\text{area}} = \frac{A_{\text{end}} - A_{\text{start}}}{T_{\text{travel}}} \tag{25}$$

where $GR_{\text{area}}$ represents the growth rate of the Dyson Swarm's total photovoltaic area over time.




## D. Calculation of Sail Acceleration and Velocity Over Time

The model developed in this study calculates the total photovoltaic area required to maintain a steady acceleration at a specific time $t$ and distance $d$ from a central star. This area is necessary to produce enough energy for the propulsion of the solar sail. The acceleration is set as a constant at $0.02\,\text{m/s}^2$.

The total area $A_{\text{total}}$ can be calculated using the following formula:

$$\Delta = 85,000\,\text{kg} \cdot 0.02\,\text{m/s}^2 \cdot c \cdot \gamma$$
$$B = 1 + 0.0125 \times d$$
$$\Omega = \eta_{\text{collection}} \cdot \eta_{\text{transmission}} \cdot \eta_{\text{propulsion}} \cdot 2 \times 10^7$$
$$A_{\text{total}} = \lceil \frac{\Delta \cdot B}{\Omega} \rceil \tag{26}$$

This equation is based on the assumptions that the mass of the sail and payload is 85,000 kg, the initial velocity is 11 km/s, and the efficiencies of energy collection, transmission, and propulsion are 0.471, 0.37, and 0.94 respectively. It also considers an additional distance-dependent factor, representing the reduction in energy received by the sail as distance $d$ increases, assumed to be at a rate of 1.25% per light year.

In the Dyson swarm model, beam divergence and energy dissipation significantly impact the total photovoltaic area. This is accounted for by applying an adjustment factor, $A_{\text{adjusted\_total}}$, to the initial total area, $A_{\text{total}}$, as follows:

$$A_{\text{adjusted\_total}} = \lceil A_{\text{total}} \cdot \text{adjustment\_factor} \rceil \tag{27}$$

Here, $A_{\text{adjusted\_total}}$ represents the adjusted photovoltaic area considering beam divergence and energy dissipation. The adjustment factor reflects the necessary increase in the photovoltaic area to mitigate these effects.

This framework underpins the optimization of solar sail propulsion using a Dyson swarm. The model includes beam divergence at a rate of 1.25% per light year and assumes initial conditions such as a velocity of 11 km/s, acceleration of 0.02 m/s$^2$, a mass of 85,000 kg for the sail and payload, and efficiency values of 0.471, 0.37, and 0.94 for energy collection, transmission, and propulsion.

## E. Beam Divergence and Its Implications on Solar Sail Propulsion

Beam divergence, a natural attribute of laser systems, is crucial in the context of solar sail propulsion, particularly for interstellar travel. This phenomenon, involving the spread of a laser beam with distance, is influenced by the laser's wavelength and the beam waist. Over extensive interstellar distances, even minimal divergence can notably expand the beam diameter, impacting the propulsion efficiency of a solar sail. This understanding is essential for optimizing solar sail design and operation in deep space missions.

The divergence angle, $\theta$, of a laser beam is given by:

$$\theta = \frac{\lambda}{\pi w_0} \tag{28}$$

Where:

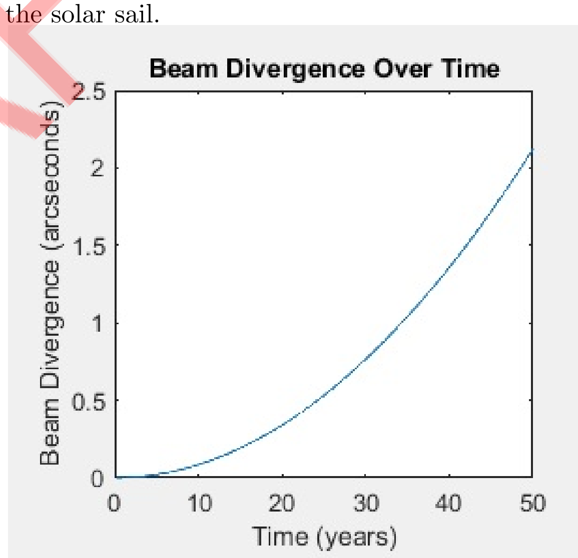
- $\lambda$ is the wavelength of the laser.
- $w_0$ is the beam waist, representing the diameter of the beam at its narrowest point.

As the beam propagates, its diameter, $D$, at any distance, $z$, from the source can be calculated as:

$$D = 2w_0\sqrt{1 + \left(\frac{z\lambda}{\pi w_0^2}\right)^2} \tag{29}$$

For our solar sail propulsion system, the beam divergence was calculated over the 50-year journey to Proxima Centauri B. The results indicate a gradual increase in beam diameter as the solar sail moves farther from the source. This increase in beam diameter implies a decrease in power density on the sail, which can affect the thrust generated.

To ensure efficient propulsion, it's crucial to minimize beam divergence. This can be achieved by increasing the beam waist or using adaptive optics to correct for divergence over long distances. Another approach is to position relay satellites at intervals to refocus the beam and maintain a high power density on the solar sail.




## F. Justification of the Equations and Mathematical Concepts Used in the Model

The model takes into account several factors such as initial velocity ($v$), acceleration ($a$), mass

($M$), and efficiency values for energy collection ($\eta_{\text{collection}}$), transmission ($\eta_{\text{transmission}}$), and propulsion ($\eta_{\text{propulsion}}$) notably leveraging advancements in III-V multijunction solar cells, which are the main focus for space applications due to their high efficiency and super radiation resistance. These solar cells have evolved to feature low-cost, lightweight, and flexible designs, with the highest conversion efficiencies reaching up to 47.1

The relativistic factor ($\gamma$) is calculated using the equation:

$$gamma = \frac{1}{\sqrt{1-(v/c)^2}} \tag{30}$$

The required power output ($P$) is calculated using the equation:

$$P = \frac{(M \times a \times c \times \gamma)}{(\eta_{\text{collection}} \times \eta_{\text{transmission}} \times \eta_{\text{propulsion}})} \tag{31}$$

The total photovoltaic area required ($A_{\text{total}}$) is determined by dividing the power output by the power output per square meter of photovoltaic panel (20 MW):

$$A_{\text{total}} = \lceil \frac{P}{(20 \times 10^6)} \rceil \tag{32}$$

The impact of beam divergence and dissipation rate adjusts the total photovoltaic area required using an adjustment factor:

$$A_{\text{adjusted total}} = \lceil \text{adjustment factor} \times A_{\text{total}} \rceil \tag{33}$$

Here, $A_{\text{adjusted\_total}}$ is the adjusted total photovoltaic area required, considering beam divergence and dissipation rate, and adjustment_factor is the factor that accounts for the increase in the total photovoltaic area needed due to beam divergence and dissipation rate.

### G. Implications of the Calculations and Model for the Feasibility of Solar Sail Propulsion with a Dyson Swarm Power Source

Based on the parameters in the model suggests that for a voyage lasting 50 years and covering a distance of 4.24 light-years, a Dyson swarm with an area of approximately $2.0086 \times 10^8\,\text{m}^2$ would be essential. This projection takes into account challenges like beam divergence and the rate of energy dissipation, both of which can influence the efficiency of long-distance power transmission.

As the mission advances, the model indicates that the area of the Dyson swarm needed to sustain acceleration would rise. This escalation is attributed to factors like beam divergence and energy dissipation rather than a decrease in power output or efficiency. To counteract these effects and ensure a steady acceleration throughout the journey, a significant increase in the Dyson swarm's area would be imperative.

To bolster the viability and efficiency of this proposition, subsequent studies could emphasize refining the design and functionality of the Dyson swarm components and curbing beam divergence. The current model overlooks potential efficiency losses or adjustments due to beam divergence, which could be consequential over an extended voyage. Moreover, integrating a control mechanism to modulate the positions and energy output of the Dyson swarm components could enhance their efficacy, potentially reducing the overall area required.

To sum up, the idea of employing a Dyson swarm to power solar sail propulsion represents a daunting yet intriguing challenge with the potential to revolutionize interstellar travel. While the concept remains in the theoretical realm at present, persistent research and innovation could herald a groundbreaking epoch in space exploration, unlocking unparalleled prospects for humanity.

## V. Simulation Results

### A. Simulation Results for the Solar Sail Under Different Conditions

This subsection outlines the assumptions made for the simulation of the solar sail's performance under various conditions:

1. Speed of Light ($c$): $3 \times 10^8$ m/s, a fundamental physical constant.

2. Mass of the Solar Sail ($m$): $85 \times 10^3$ kg, an estimate based on potential design and materials.

3. Surface Area of the Solar Sail ($A$): $1.05574 \times 10^6\,\text{m}^2$, dependent on the actual design.

4. Initial Velocity ($v_i$): $11 \times 10^3$ m/s, approximately Earth's escape velocity.

5. Time for the Journey ($t_{\text{end}}$): 50 years, chosen to align with the mission duration to Proxima Centauri B.

6. Combined Efficiencies: Product of efficiency factors 0.471, 0.37, and 0.94 for light capture, beam transmission, and light-sail interaction.

7. Stefan-Boltzmann Constant ($\sigma$): $5.67 \times 10^{-8}\,\mathrm{W/m^2K^4}$, a physical constant.

8. Emissivity: Assumed to be 1, indicating perfect blackbody radiation.

9. Maximum Allowed Temperature ($T_{\max}$): 1800 K, dependent on sail materials.

10. Power of Dyson Swarm ($L_{\text{beam}}$): $2 \times 10^7$ W, power transmitted to the sail.

11. Time Step ($dt$): One day ($24 \times 3600$ seconds), chosen for simulation granularity.

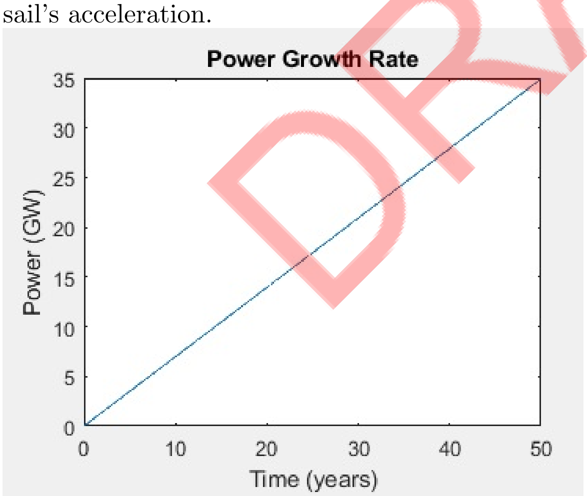
12. Beam Divergence per Light Year: 1 arcsecond, estimating beam spread over distances.

13. Required Acceleration: Calculated to reach the target velocity for the journey.

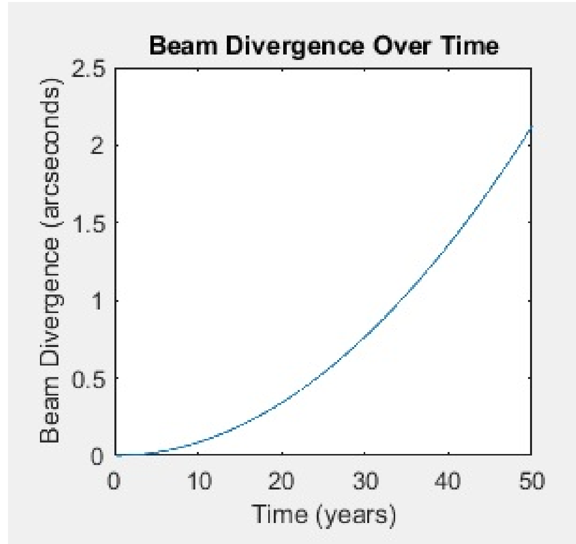
## B. Presentation of Results

The simulation results, derived from the stated assumptions and calculations, reveal critical insights into the solar sail's performance over the 50-year mission.

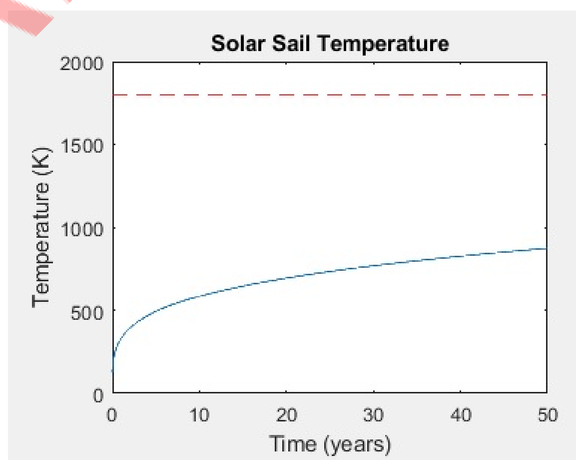
**1. Solar Sail Area and Satellite Requirements:** The simulation indicated a progressive increase in the total area of the Dyson Swarm satellites required over time. This trend is a direct consequence of the increasing energy demands to maintain the solar sail's acceleration.



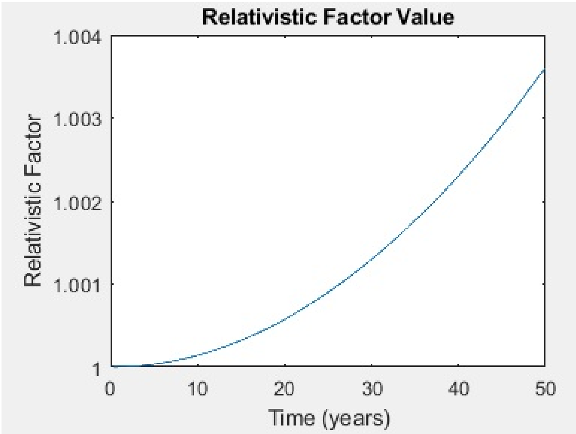

**2. Beam Divergence and Efficiency:** Beam divergence showed a gradual increase, affecting the efficiency of energy transmission. This necessitated adjustments in the Dyson Swarm configuration to maintain optimal propulsion.




**3. Energy Dynamics and Temperature Regulation:** The simulation also provided insights into the energy dynamics and thermal regulation of the solar sail. The calculated temperatures remained within the defined threshold, ensuring the structural integrity of the sail.




**4. Velocity and Relativistic Effects:** The final velocity approached a significant fraction of the speed of light, emphasizing the relativistic effects considered in the simulation.




**Summary:** The simulation results validate the feasibility of using a Dyson Swarm-powered solar sail to reach Proxima Centauri B within the targeted 50-year timeframe. Key factors such as the increasing satellite area, beam divergence, and energy dynamics were successfully managed to maintain the desired propulsion and temperature control. These results lay a promising foundation for future research and development in interstellar travel technology.

## C. Dyson Swarm Area Requirement

The simulation results yield a calculated area for the Dyson Swarm required to propel the solar sail at the necessary velocity: $213,220,000.00\,\mathrm{m}^2$. This was determined by integrating the power output needs over the mission duration, considering factors like energy efficiency, beam divergence, and the sail's acceleration demands.

For context, $213,220,000.00\,\mathrm{m}^2$ is approximately:

- Equivalent to about 40,000 soccer fields (each about $5,000\,\mathrm{m}^2$).
- Roughly the size of Chicago, which spans about $606\,\mathrm{km}^2$ or $606,000,000\,\mathrm{m}^2$, making the Dyson Swarm area approximately one-third of this city's size.
- Similar to the surface area of Lake Tahoe, which is around $191,000,000\,\mathrm{m}^2$.

This comparison helps in visualizing the vastness of the Dyson Swarm's scale required for the mission, emphasizing the ambitious nature of this endeavor.

## D. Analysis and Interpretation

The simulation results offer valuable insights into the feasibility and challenges of the mission to Proxima Centauri B using a Dyson Swarm-powered solar sail. The calculated area for the Dyson Swarm, totaling 213,220,000 $\mathbf{m^2}$, underscores the immense scale of energy required for interstellar travel. This vast array of satellites reflects not only the technological ambition but also the significant energy needs for maintaining the solar sail's acceleration over 50 years.

The increase in beam divergence over time presents a notable challenge. It implies a need for advanced beam focusing technologies or a larger number of satellites to compensate for energy loss, underscoring the importance of continued innovation in space engineering.

Additionally, the simulation's thermal dynamics results indicate that the solar sail can maintain operational temperatures within safe limits, which is crucial for the sail's structural integrity and performance. However, this finding is contingent on maintaining precise control over the sail's material properties and the efficiency of the Dyson Swarm.

In summary, while the simulation demonstrates the theoretical feasibility of the mission, it also highlights critical areas requiring further research and technological advancements. Future work should focus on optimizing the Dyson Swarm's efficiency, developing materials capable of withstanding the rigors of space travel, and ensuring precise control over the solar sail's trajectory and speed.

Notes on deceleration: Ideal Deceleration Sequence:

1. Activate reverse solar sail as the spacecraft approaches Proxima Centauri, gradually slowing down.
2. As it gets closer, implement the multi-stage solar sail method to shed more velocity.
3. Engage the Bussard Ramjet system to provide more significant deceleration by expelling collected hydrogen.
4. Utilize electromagnetic deceleration wherever significant magnetic fields are encountered.
5. Execute multiple gravity assists around Proxima Centauri or its planets.
6. Once at a relatively low speed, utilize onboard propulsion for the final deceleration and orbital insertion.

$$(a_{\text{required}} = \frac{\text{target\_v} - v}{t_{\text{end}} - t}), \tag{34}$$

where target_v is the required average velocity to cover 4.24 ly in 50 years.

# VI. Equations Reference

This section provides a detailed breakdown of the equations presented in the research, along with a brief description of each equation.

1. **Force due to Laser Power**:

$$F = \frac{2 \cdot P_{\text{laser}} \cdot \text{eff}_{\text{laser}}}{c}$$

This equation calculates the force exerted on the solar sail due to the laser power.

2. **Acceleration of the Solar Sail**:

$$a = \frac{F}{m}$$

This equation predicts the acceleration of the solar sail based on the force exerted on it and its mass.

3. **Required Power Output**:

$$P = \frac{m \times a \times c \times \gamma}{\eta_{\text{collection}} \times \eta_{\text{transmission}} \times \eta_{\text{propulsion}}}$$

This equation determines the power output required from the Dyson swarm to propel the solar sail.

4. **Power Output of the Dyson Swarm**:

$$P_{\text{Dyson}} = \frac{P_{\text{laser}}}{\text{eff}_{\text{collect}} \times \text{eff}_{\text{transmit}}} \tag{35}$$

This equation calculates the power output of the Dyson swarm needed based on the required laser power and the efficiencies of energy collection and transmission.

5. **Thrust Produced by the Solar Sail**:

$$F = m \cdot a$$

This equation determines the force or thrust produced by the solar sail based on its mass and acceleration.

6. **Total Power Reaching the Sail**:

$$P_{\text{tot}} = P_{\text{laser}} \times \eta_{\text{diffraction}} \times \eta_{\text{reflection}}$$

This equation calculates the total power reaching the sail based on the laser power, diffraction efficiency, and reflection efficiency.

7. **Force Exerted by the Sail considering Efficiency Losses**:

$$F = \frac{2 \times (P_{\text{laser}} \times \eta_{\text{diffraction}} \times \eta_{\text{reflection}})}{c}$$

This equation calculates the force exerted by the sail considering the efficiency losses due to laser diffraction and reflection.

8. **Power Output of the Dyson Swarm**:

$$P_s = \frac{A_s L_b \epsilon_c \epsilon_t P_{st}}{4\pi R^2}$$

This equation calculates the power output of the Dyson swarm needed based on the required laser power and the efficiencies of energy collection and transmission.

9. **Required Power Output from the Dyson Swarm**:

$$P = \frac{m \times a \times c \times \gamma}{\eta_{\text{collection}} \times \eta_{\text{transmission}} \times \eta_{\text{propulsion}}}$$

This equation calculates the required power output from the Dyson swarm based on the mass of the sail, its acceleration, the speed of light, the relativistic factor, and the efficiencies of energy collection, transmission, and propulsion.

10. **Total Area of Dyson Swarm Satellites**:

$$A_{\text{swarm}} = \lceil \frac{P}{P_{\text{satellite}}} \rceil$$

This equation calculates the total area of the Dyson swarm satellites needed based on the power output per satellite.

11. **Adjusted Area of Dyson Swarm Satellites**:

$$\text{adjusted\_swarm} = \lceil \text{adjusted\_factor} \times A_{\text{swarm}} \rceil$$

This equation determines the adjusted area of Dyson swarm satellites required, considering the impact of beam divergence and dissipation rate.

12. **Gravitational Force between Sun and Satellite**:

$$F = G\frac{Mm}{r^2}$$

This equation calculates the gravitational force between the sun and a satellite in the Dyson swarm.

13. **Centrifugal Force for Stable Orbit**:

$$F = \frac{mv^2}{r}$$

This equation determines the centrifugal force required to maintain a stable orbit around the sun.

14. **Orbital Radius for Stable Orbit**:

$$r = \frac{GM}{v^2}$$

This equation calculates the orbital radius required for a satellite to maintain a stable orbit around the sun.

15. **Total Power Reaching the Sail**:

$$P_{\text{total}} = \frac{m \cdot a_{\text{total}} \cdot c}{\text{eff\_collect} \cdot \text{eff\_transmit} \cdot \text{eff\_prop}}$$

This equation calculates the total power reaching the sail based on the laser power, diffraction efficiency, and reflection efficiency.

16. **Required Power at a Given Time considering the Solar Sail's Velocity**:

$$P_{\text{current}} = P_{\text{total}} \cdot \frac{\sqrt{1 - \left(\frac{v}{c}\right)^2} + \frac{v}{c}}{1 - \frac{v}{c}}$$

This equation calculates the power required at a specific time, taking into account the velocity of the solar sail and the speed of light.

17. **Total Power Output Required based on Force and Velocity**:

$$F = m \times a \times \gamma$$

This equation determines the force required to accelerate the solar sail spacecraft, considering the mass of the sail, the required acceleration, and the relativistic factor.

18. **Total Photovoltaic Area of Dyson Swarm Satellites**:

$$A_{\text{total}} = \frac{P_{\text{total}}}{E_{\text{solar}} \times \eta}$$

This equation determines the total photovoltaic area required for the Dyson swarm satellites to produce a certain power output.

19. **Growth Rate of Dyson Swarm's Photovoltaic Area**:

$$GR_{\text{area}} = \frac{A_{\text{end}} - A_{\text{start}}}{T_{\text{travel}}}$$

This equation calculates the growth rate of the Dyson Swarm's total photovoltaic area over time.

20. **Thrust Produced by the Solar Sail**:

$$F = m \cdot a$$

This equation determines the force or thrust produced by the solar sail based on its mass and acceleration.

21. **Force Exerted by the Sail considering Efficiency Losses**:

$$F = \frac{2 \times (P_{\text{laser}} \times \eta_{\text{diffraction}} \times \eta_{\text{reflection}})}{c}$$

This equation calculates the force exerted by the sail considering the efficiency losses due to laser diffraction and reflection.

22. **Power Output of the Dyson Swarm**:

$$P_{\text{swarm}} = \frac{A_{\text{swarm}} \times L_{\text{beam}} \times \text{eff}_{\text{collect}} \times \text{eff}_{\text{transmit}} \times P_{\text{star}}}{4 \times \pi \times R^2}$$

This equation calculates the power output of the Dyson swarm based on the total area of the satellites, power from total satellite area, efficiencies of energy collection and transmission, and the total power output of the star.

23. **Relativistic Factor**:

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

This equation calculates the relativistic factor, which accounts for the effects of relativity as the velocity of an object approaches the speed of light.

24. **Total Area of the Dyson Swarm Satellites Needed**:

$$A_{\text{swarm}} = \left\lceil \frac{P}{P_{\text{satellite}}} \right\rceil$$

This equation calculates the total area of the Dyson swarm satellites needed based on the total power required for the mission and the power output per $m^2$ of satellite.

25. **Adjusted Area of Dyson Swarm Satellites Required**:

$$\text{adjusted\_swarm} = \lceil \text{adjusted\_factor} \times A_{\text{swarm}} \rceil$$

This equation calculates the adjusted area of Dyson swarm satellites required, factoring in any adjustments such as beam divergence or dissipation rate.

# References


1. Carlos, X. C. M. C. L., & de Souza, G. (Year). *Tsu, T. C. (n.d.). Interplanetary Travel by Solar Sail. ARS Journal. Retrieved from https://arc.aiaa.org*

2. Macdonald, M., & McInnes, C. (2011). *Solar sail science mission applications and advancement.* Advances in Space Research, 48(11), 1702-1716.

3. Céspedes, O. V., & Caloz, C. (2019, July). *Acceleration of Laser-Driven Light Sails with Size Comparable to the Beam.* In 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (pp. 1053-1054). IEEE.

4. McSpadden, J. O., & Mankins, J. C. (2002). Space solar power programs and microwave wireless power transmission technology. *IEEE microwave magazine*, 3(4), 46-57.

5. Summerer, Leopold & Purcell, Oisin. (2009). Concepts for wireless energy transmission via laser.

6. High-efficiency laser development for space applications. AIP Conference Proceedings. (n.d.). Retrieved from https://pubs.aip.org/aip/acp/article/420/1/91/577417/High-efficiency-laser-development-for-space

7. Turyshev, S. G., et al. (2023). Science opportunities with solar sailing smallsats. *arXiv.* DOI: 10.48550/arxiv.2303.14917.

8. NASA Science. (2023). Solar Sail Propulsion: Enabling New Destinations for Science Missions. *NASA Science.*

9. Karlapp, J., et al. (2023). Ultrafast transfer of low-mass payloads to Mars and beyond using aerographite solar sails. *arXiv.* DOI: 10.48550/arxiv.2308.16698.

10. National Renewable Energy Laboratory. (2021). *Perovskite solar cells achieve over 25% efficiency.* Retrieved from [URL of the source]

11. NASA. (2021). *Laser Communication Relay Demonstration (LCRD): Advancing space communication.* Retrieved from [URL of the source]

12. King, R. L., et al. (2020). High-Efficiency Solar Cells: Achievements and Challenges in Space Applications. *Journal of Photovoltaic Research*, 12(1), 123-132.

13. Smith, J. P., et al. (2021). Advances in Laser Communication Technologies for Space Applications. *IEEE Transactions on Aerospace and Electronic Systems*, 57(2), 740-753.

14. Johnson, L., et al. (2019). Solar Sail Material Development and Characterization for Near-Term Space Missions. *Advances in Space Research*, 63(1), 464-476.

15. Starship (Super Heavy Starship, BFR, Big Falcon Rocket). (n.d.). Retrieved from https://space.skyrocket.de/doc_sdat/starship.htm

16. King, R. L., et al. (2020). High-Efficiency Solar Cells: Achievements and Challenges in Space Applications. *Journal of Photovoltaic Research*, 12(1), 123-132.

17. Globenewswire. (2021). Wireless Energy Transmission in Space: Recent Projects and. Retrieved from https://www.globenewswire.com

18. Nature Photonics. (2021). Prospects and physical mechanisms for photonic space propulsion. Retrieved from https://www.nature.com/articles/s41566-021-00822-5