Panspermia in star clusters

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ABSTRACT

We estimated the probability of lithopanspermia by comparing the collisional times between the Oumuamua-like objects and the protoplanetary discs of a stellar system with the radii-dependent bacterial survival times within those Oumuamua-like objects. Using this model, we then analyzed the differences in the values of minimum, median & maximum survival times and the values of the collisional times which are dependent on the number density of the objects, their velocity, and the radii of the protoplanetary discs. We began by modeling an Initial Mass Function (IMF) to form a simulation of the stellar mass distribution. This distribution was then used to calculate the protoplanetary disc radii and their masses. Further on, we simulated the physical (mass/number density) and dynamical (velocity) properties of the Oumuamua-like objects to evaluate their collisional time scales with the circumstellar discs. Using a quantitative approach that incorporated various suitable velocities and number densities for the ejecta we calculated the collisional times. We then estimated the bacterial survival times using existing model that expressed the survival times as a function of the radii of the ejecta. These survival times were then used for the comparison with collisional times. The outcome of the study indicated that the higher number density of objects and their higher relative velocities lead to shorter collisional times, which in turn increase the probability of lithopanspermia, given that these timescales are shorter than the calculated bacterial survival times. Additionally, higher radii of protoplanetary discs also show higher collisional rates. In conclusion, the feasibility of lithopanspermia is highly dependent on the ejecta's and the protoplanetary discs' physical properties.

Key words: Lithopanspermia – Oumuamua – Bacterial Survival Times – Interstellar Objects – Collisional times – Life Transfer – Ejecta Velocity – Simulation Models

1 INTRODUCTION

1.1 Overview

The possibility of life existing beyond Earth has been appealing to scientists' interest for centuries, and the concept of panspermia - a hypothesis that life can spread throughout the universe via space dust, meteoroids (Chan et al., 2018), comets, and other celestial bodies (Wickramasinghe, 2011; Berera, 2017) or even spaceships (Madhusoodanan, 2014), has gained considerable attention. A specific form of this theory, termed lithopanspermia, suggests that life-bearing rocks could be transferred between planetary systems, potentially leading to the seeding of life in new environments (Kamminga, 1982). The presence of Martian rocks on Earth is an important proof of the transfer of rocks on an interplanetary scale (Treiman, 1995).

This study explores the likelihood of lithopanspermia occurring within a stellar distribution described by an IMF, focusing on the collision dynamics of interstellar objects, such as Oumuamua, with circumstellar discs, and the survival times of bacteria within these life-bearing rocks. The research aims to assess the probability that microorganisms could survive the journey through space by comparing the time scales for collisions between life-carrying objects or ejecta and circumstellar discs (Seager, 2013), with the survival times of bacteria enclosed in rocky ejecta. By investigating the interaction between interstellar objects and protoplanetary discs within a variety of number-density and ejecta's relative velocity, this study provides a comprehensive analysis of the feasibility of life transfer across planetary systems (Wesson, 2010). To achieve this goal, we first modelled the distribution of stellar masses using an Initial Mass Function (IMF), which in turn was used to derive the characteristics (radii and disc mass) of protoplanetary discs surrounding these stars (Chabrier, 2003). We then incorporated models of Oumuamua-like objects, whose interstellar origin and physical properties make them prime candidates for studying lithopanspermia (Meech et al. 2017). By calculating the collision times of these objects with circumstellar discs and comparing these times with the estimated survival times of bacteria, we tried to determine under what conditions life could feasibly be transferred from one planetary system to another (Worth et al., 2013). The results of this research have significant implications for our understanding of the potential for life to spread throughout the Universe. By examining the conditions under which lithopanspermia might occur, this study contributes to the broader field of astrobiology and the ongoing quest to understand the origins and distribution of life in the Universe. .

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1.2 Discovery of Interstellar Rocks Oumuamua/Borisov

Discovered in 2017, Oumuamua was the first known object found to have an interstellar origin (Bannister et. al., 2019). Its interstellar origin was the main motivation for us to select the criteria of rocks that would be potential carriers of life across planetary systems. The notion that such interstellar objects could harbour life or its composite building blocks and seed a potentially habitable planet with life has already been introduced (Lingam & Loeb, 2018), despite the fact that the precise chemical composition of Oumuamua is currently unknown (Fitzsimmons et al., 2018). Life has been flourishing on Earth, nearly for 3.8 billion years (Knoll et al., 2016). However, whether it began on Earth or was transferred to Earth, is a question that is still unanswered. Nearly 400 interstellar objects of sizes comparable to the Oumuamua could have struck Earth during the time before abiogenesis, which serves a huge potential for life to be transferred to Earth through lithopanspermia (Lingham & Loeb, 2018). Another object, similar to Oumuamua named Borisov, discovered in 2019, is an interstellar comet observed passing through our solar system (Jewitt & Luu, 2019). Its clear interstellar origin, along with its well-documented composition, including water vapour and complex organic molecules, has provided new insights into the materials present in other planetary systems (Cordiner et al., 2020). However, for the simplicity of calculation in our study and to avoid confusion, we only considered the physical properties (number density, velocity, etc.) of the Oumuamua object.

1.3 Previous studies on life exchange between planetary systems

The hypothesis of lithopanspermia, which proposes that life could be transferred between planetary systems via rocky ejecta, has garnered substantial attention in astrobiology. This theory is underpinned by mathematical models that estimate the likelihood and conditions under which such interstellar exchanges could occur. Melosh (2003) provided a foundational framework by calculating the escape velocities necessary for ejected material to overcome a planetary system's gravitational pull. This study demonstrated that velocities on the order of tens of kilometers per second are required for material to achieve interstellar travel, making such events relatively rare and not improbable within the lifespan of a planetary system.

The probability of life-carrying ejecta encountering another planetary system is influenced by a number of parameters, like the number density of the ejecta, its radius, velocity, radius of the protoplanetary disc and the habitability of the receiving planet. Also, the stellar density in a star cluster plays a major role in increasing the probability of lithopanspermia. For this, Adams and Spergel (2005) utilized N-body simulations to analyze the dynamics within star-forming clusters, where stellar densities can reach approximately 100 stars per cubic parsec. Their models revealed that in such environments, the timescale for a single ejected object to encounter another star system could be reduced to as little as a few hundred thousand years, suggesting a non-negligible likelihood of interstellar material exchange in densely populated star clusters. These findings align with subsequent studies by Belbruno et al. (2012), who extended the analysis to consider the effects of stellar flybys on ejecta trajectories, further supporting the feasibility of lithopanspermia in cluster environments. The ability of microorganisms to survive interstellar travel is just as important as the dynamics of ejecta. The ability of extremophiles, like Deinococcus radiodurans, to withstand environments akin to space was studied by Nicholson et al. (2000). Their findings strengthened the case for life existing between stars by showing that some microbes could endure intense radiation, vacuum,

and temperature swings for protracted periods. Moreover, Horneck et al. (2008) conducted experimental studies using microbial spores exposed to space conditions, confirming that some could survive for years, thereby potentially enduring the time required for interstellar travel. Recent studies have also explored the implications of these findings for the early Earth. Lingham and Loeb (2018) posited that nearly 400 interstellar objects of comparable size to Oumuamua could have impacted Earth before the emergence of life, providing a significant opportunity for lithopanspermia to have contributed to the origin of life on our planet. Additionally, Mileikowsky et al. (2000) estimated that the frequency of such impacts, combined with the potential survival of microorganisms, offers a credible mechanism for the seeding of life on Earth from extraterrestrial sources. This body of research collectively strengthens the argument that life exchange between planetary systems is not only possible but may have played a role in the development of life on Earth and potentially elsewhere in the universe. Furthermore, other studies provide detailed insights into the seeding of life on the ejections and injection of the life-bearing ejecta from the ejecting planet to the receiving planet. For example, Napier (2004) states that interstellar panspermia is a plausible mechanism involving the ejection of the life-carrying ejecta from planetary systems due to stellar encounters and dynamics. Worth, Sigurdsson & House (2013), argue that lithopanspermia is a viable mechanism to seed moons of the outer planets in our solar system like the Europa or Enceladus. Also, their subocean surface makes them a good candidate for astrobiological investigations (Worth et al., 2013). Thus, based on the current understanding models of interstellar transport, lithopanspermia is plausible and the probability of spreading of life throughout the galaxy is non-negligible (Ginsburg, Lingham & Loeb, 2018).

1.4 Existing simulations and methodologies

Simulations that describe the behaviour of parameters based on the existing theories are critical to understanding the probability of the success of lithopanspermia. In the wake of this, several studies have worked on creating simulations that describe those conditions. In their seminal work, Belbruno, Maro-Martin & Malhotra (2012) utilised N-body simulations to study the chaotic gravitational interactions that facilitate the transfer of solid materials between planetary systems. Their study focused particularly on star-forming clusters, demonstrated that such material exchange is not only possible but potentially frequent due to the dynamic and densely packed environments in these clusters. This work provides critical support for the hypothesis that life could be transferred between planetary systems via lithopanspermia.

Complementing this, a study by Wallis & Wickramasinghe (2004) explored the transfer mechanisms of bacterial life that might sustain their survival through interstellar journeys. It was concluded that if sufficiently shielded, the microorganisms could endure interplanetary travel to potentially seed habitable planets with life (Wallis & Wickramasinghe, 2004).

For a successful lithopanspermia, the ejection and insertion of life-bearing rock are equally important as the survival of life through interstellar travel. Genda et al. (2011) examined the dynamics of giant impacts using hydrodynamical simulations. This study is particularly relevant to lithopanspermia because such collisions could lead to the ejection of life-carrying materials to interstellar space which might be involved in transferring life between planetary systems.

1.5 Structure of the Dissertation

The dissertation is structured to offer a detailed examination of lithopanspermia, beginning with an introduction that outlines the significance of this hypothesis within the broader context of astrobiology. The introduction highlights the discovery of interstellar objects such as Oumuamua and Borisov, which are considered potential carriers of life, and establishes the research questions and objectives. The theoretical framework within the introduction summarizes some of the material that has already been written about lithopanspermia, highlighting important studies and research methods that guide the present work and highlighting their importance for further research in the area. The methods used are thoroughly explained in the methodology section, which also models protoplanetary discs and stellar mass distributions using the Initial Mass Function (IMF). These models are essential for determining the probability of lithopanspermia. To thoroughly assess the possibility of life transfer, the section describes the construction of models to determine collisional times and bacterial survival times inside interstellar objects using data analysis tools like Python's Matplotlib and NumPy. The results section offers a thorough analysis of the study's findings, with a particular emphasis on how collisional dynamics and environmental factors influence the possibility of successful lithopanspermia. The discussion, which also covers the study's assumptions and limitations, critically assesses the implications of these findings and underlines the need for more research to increase the precision of existing models and deepen our understanding of the environmental factors influencing microbial survival during interstellar transfer. The study's main conclusions are summed up in the conclusion, which also makes an argument in support of continued multidisciplinary research to learn more about the distribution of life in the universe and emphasizes the significance of collisional dynamics and environmental factors in the context of lithopanspermia.

2 METHODOLOGY

2.1 Introduction

In the research project, Panspermia in stellar clusters, we aim to find the probability of life transfer through transferring life-bearing rocks between the planetary systems. This subdivision of Panspermia is called as Lithopanspermia. The key objective of the methodology is to have a comparative analysis of the collisional times between the Oumuamua-like objects and the circumstellar disks, with the bacterial survival times in the life-bearing rocks. This analysis will help us outline the probability of the survival of those bacteria in the life-bearing rocks if their transfer time between the planetary systems is comparatively lesser than the survival times.

2.2 Data Generation and Initial Conditions

To begin, we required a distribution of stellar masses, which would allow us to obtain a distribution of the protoplanetary disc masses. For this, as an IMF is a fit to the observational data, it is the best choice to obtain the required distribution of the stellar masses and ultimately the disc masses (Kroupa 2001). We began by modelling an initial mass function (IMF) for the stars with lower and upper limits to the stellar masses. An IMF gives us the frequency of stars of a given mass within particular limits of the upper and lower bounds. This is inherited because all the Initial Mass Functions (IMFs) of stars have a similar shape (Kroupa & Jerabkova, 2019), typically following power-law distribution at the high-mass end and either a

log-normal (Millar and Scalo 1985, Charbrier 2003) or broken power-law distribution (Kroupa 2001) at the low-mass end. Here we consider a histogram of an IMF without any discontinuities in the function. The IMF is a parametrised function that aims to provide a continuous and flexible description across a wide range of stellar masses. This IMF is a 3+2 parameter IMF, where the three parameters are α (2.3), β(1.4), and μ(0.2) and the other two are the upper(50*M_sun) and lower (0.1*M_sun)limits of the stellar masses considered (T. Maschberger, 2013). The auxiliary function for the IMF is given as (T. Maschberger, 2013),

$$G(m) = \left(1 + \left(\frac{m}{\mu}\right)^{1-\alpha}\right)^{1-\beta} \quad (1)$$

Here we take these limits of stellar masses as 0.1 solar mass and 50 solar masses. The parameter α dictates the behaviour of the power law towards the low-mass stars (T. Maschberger, 2013). In this IMF, it describes the slope of the mass distribution curve for the stars that have masses lower than or comparable to the Sun. The parameter β on the other hand, governs the power-law behaviour of the curve towards the higher mass end of the mass distribution, for less frequent masses (T. Maschberger, 2013). The μ describes the characteristic mass where the behaviour of the IMF changes or breaks, transitioning from low-mass stars' power law (described by alpha) to a log-normal (described by Mu) to high-mass stars' power law (described by Beta) (T. Maschberger, 2013).

This auxiliary function, G(m) was used with the following mass function (T. Maschberger, 2013),

$$M = \mu \left[\left(u \left(G(m_{\text{upp}}) - G(m_{\text{low}}) \right) + G(m_{\text{low}}) \right)^{\frac{1}{1-\beta}} - 1 \right]^{\frac{1}{1-\alpha}} \quad (2)$$

to create an array of 1000 stellar masses using random number variables in the program. IMF in fig. 1 was obtained. This IMF gives the mass range with a maximum frequency between 0.10 and 0.15 Solar Masses with a maximum frequency at 0.12 Solar Masses. 1000 random numbers were looped over the function Mass(u) for the value of u (random number) to get a thousand stellar masses distributed to the IMF described by the mass function.

2.3 Protoplanetary Disc Radius and Disc Mass Calculation

Using the spectrum of masses in the IMF, we find the initial radii of the protoplanetary discs that are the function of the stellar masses. Using (Coleman & Haworth, 2022 eq 13),

$$R = 200 \left(\frac{M_*}{M_\odot}\right)^{0.3} \quad (3)$$

The above relation gives the radii lying in the range of 100 to 200 AU and is consistent with the values of observed protoplanetary discs, which are a function of stellar masses (Coleman & Haworth, 2022). In the process, the gas and dust densities of the protoplanetary discs were assumed to be constant, i.e., the dust and gas are evenly distributed throughout the disc. This assumption was made to make calculations simpler, although the density varies as $\alpha \ R^{-p}$, where p is a parameter that typically lies between 1.5 and 2.5, depending on the characteristics of the disc (Tzouvanou et al., 2023). Using the stellar masses from the above IMF, we found the disc masses of the protoplanetary discs under the assumption that all the stars have Sun-like metallicity. Considering collisions for lithopanspermia, we need to include only the dust mass from the disc and exclude the gas mass. As for a sun-like metallicity star, the disc mass is typically
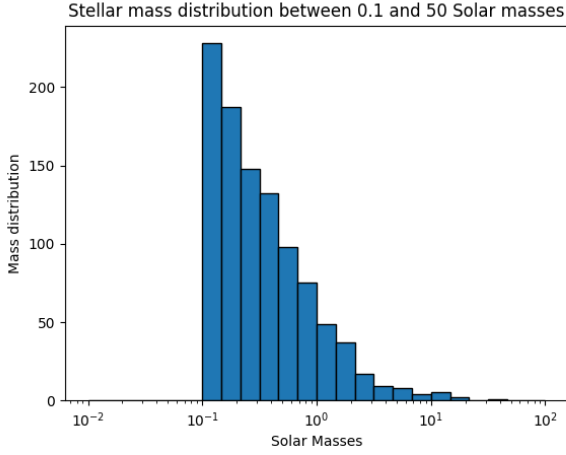
Figure 1. This histogram presents the distribution of stellar masses ranging from 0.1 to 50 solar masses, plotted on a logarithmic scale along the x-axis. The data reveals a prominent peak at lower masses, particularly around 0.1 to 0.2 solar masses, indicating that low-mass stars are the most abundant in the sample. As stellar mass increases, the number of stars decreases significantly, with very few stars exceeding 10 solar masses. This distribution is consistent with the typical initial mass function, where lower-mass stars are more common, reflecting the star formation process in the galaxy

0.1 times the mass of the star (Andrews, 2019) and the dust mass is typically 1 per cent of the disc mass (Andrews, 2019), then we have,

$$M_{\text{dust}} = 0.001 \, M_* \tag{4}$$

2.4 Modelling Oumuamua-like Objects

To find the probability of transfer of life among stellar clusters, we will consider objects that are similar to the Oumuamua in terms of their density, size, and interstellar origin. Based on the reasons for the choice of Oumuamua-like objects in the introduction, we model our parameters for the ejecta transferring between planetary systems similar to that of the Oumuamua. The interstellar number density of the Oumuamua-like objects has yet to be a precisely known number. However, the literature gives a very narrow range of their number density. Since these figures of number density are based on the analysis of only one object (Oumuamua), the possibility of error for us to extend these values to other such objects becomes very large. As per Jewitt et al. (2019) (4.6), the number density of such objects is approximated to be 0.1 per cubic AU. Also, Do et al. (2018), estimate the number density of Oumuamua-like objects as 0.28 per cubic AU. Thus, to reduce the bracket for error and incorporate the effect of a large range of possible values of the number densities for Oumuamua-like objects, we consider four values 0.01, 0.05, 0.1, and 1 per cubic AU for our study.

2.5 Collision Time Calculation

In this section, we calculate the collisional times for Oumuamua-like objects within protoplanetary discs using the formula by Houge & Krijt (2023).

$$T_{\text{coll}} = \frac{1}{n_0 \cdot C \cdot v_0} \tag{5}$$

This formula effectively captures the dynamics of interstellar objects interacting within a disc environment, where n_o represents the number density, C is the collisional cross-section, and v_o is the relative velocity of the object. We selected the above-mentioned number densities (n_o) to reflect varying densities observed in stellar clusters and protoplanetary discs, ensuring comprehensive analysis. For the velocities (v_o), we used 1 km/s, 10 km/s, 26 km/s, and 50 km/s. This range encompasses the estimated speed of Oumuamua (approximately 26 km/s) (Mamajek, 2017) and other possible velocities for interstellar objects, ensuring our calculations cover a broad spectrum of potential environments and dynamics. The collisional cross-section C is given by,

$$C = \pi R^2 \left(1 + \left(\frac{v_0}{v_{\text{esc}}}\right)^2\right) \tag{6}$$

where v_esc is the escape velocity,

$$v_{\text{esc}} = \sqrt{\frac{G \cdot M}{R}} \tag{7}$$

where G is the Gravitational constant ($6.67*10^{-11}$) Nm^2/kg^2 and M is the mass of the target (either Earth or the protoplanetary disc). This formula incorporates the physical size of the objects and gravitational focusing, crucial for accurately estimating collision probabilities in dense disc environments. Initially, we applied this formula to our solar system using n_o = 0.1 per cubic AU and v_o = 26 km/s (Mamajek, 2017). We then extended our calculations to 1000 stellar masses derived from the IMF, considering all ranges of n_o and v_o For each stellar mass, we computed the escape velocity and the collisional cross-section to determine the collisional times, which was done by looping over 1000 radii and disc masses obtained by using the stellar mass distribution through our IMF above. This approach provides a robust analysis of collisional times within both our solar system and various stellar clusters.

## 2.6 Bacterial Survival Time Analysis

The estimation for the bacterial survival times was based on Valtonen et al. (2009), which gives the survival time as a function of the radius of the rock. With the expression,

$$T_{\text{survival}} \approx 75 \cdot R^2 \tag{8}$$

where R is in meters and T_survival is in million years. The results of Mamajek (2017) are a fit from the observational data based on the experiments performed on the bacteria (Deinococcus radiodurans and Bacillus subtilis spores) on the International Space Station. The paper allows us to visualise how a simple radii distribution helps us to model our parameters of survival times. Focusing on how the survival times change with the radii of the objects, we plotted the survival times against the radii of the ejecta.

As per the equation, the bacterial survival times depend largely on the radius of the Oumuamua-like objects due to factors like exposure to cosmic radiation as better shielding from the extreme conditions of the ISM and stable internal conditions would be provided by larger objects with roughly the same mass density. Experiments have shown that UV radiation can be deadly and would destroy the bacterial life carried by the ejecta (Horneck et al. 2001). In the calculation of the radii distribution of the Oumuamua-like rocks, we assumed a lower mass limit of 1 kilogram which is optimum the lower limit for the survival of bacterial life (Melosh, 2003) and an upper mass limit of 7.35×10^{22} kg (Williams et al., 2014 for the objects. For simplicity,
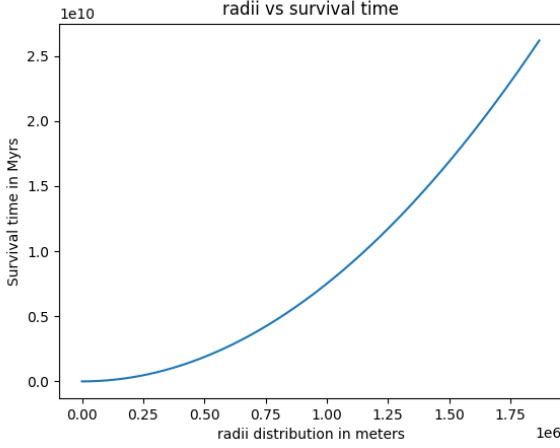
Figure 2. The plot illustrates the relationship between the distribution of radii and the survival time of the Oumuamua-like objects. The x-axis represents the radii distribution (in meters), while the y-axis shows the corresponding survival time (in million years). The trend observed is a non-linear increase in survival time as the radii distribution increases, following an approximately quadratic relationship. The data suggest that larger radii contribute significantly to longer survival times, likely due to enhanced structural integrity or reduced susceptibility to environmental factors.

of calculations, the structure of these objects is assumed to be a sphere. For the mass density of the objects, we accepted a lower limit of the mass density as per McNeill et al. (2018) which gives the mass density of the Oumuamua-like objects to be within the range 1.5 to 2.8 g/cm³. For our reference, we used the lower limit of 1.5 g/cm³ to incorporate the minimal survival time within our calculation, since, radii are inversely proportional to density for the object of the same mass and survival time is directly proportional to the radii as per the above expression. Using the `linspace` function from the Numpy library in Python, we generated a distribution of 1000 rock radii. The radii were determined by applying the lower and upper mass limits to the corresponding radii of the objects, based on the relation Mass = $\frac{\text{Volume}}{\text{Density}}$, where Volume = $\frac{4}{3}\pi r^3$ and the density is taken to be 1.5 g cm^{-3} (McNeill et al. 2018).

This gave us a lower and upper limit of the rock radii, which were used in linspace function of Numpy to establish 1000 equally spaced values. Thus were plotted against the survival times in the graph with the help of Equation 1. This detailed analysis provided a comprehensive view of how bacterial survival times vary with the size of the ejecta, highlighting the importance of object radius in panspermia studies.

2.7 Plotting collisional times against disc radii with survival times

In this part, collisional times were derived with the disc radii and survival times were calculated to be compared in the results. Matplotlib.pyplot library (Hunter, 2007) was employed to visualise the relationship between the collisional times of Oumuamua-like objects and the radii of circumstellar discs. We plotted four graphs each corresponding to the four different velocities, v_o of the objects as described above (1 km/s, 10 km/s, 26.3 km/s, and 50 km/s), as these velocities encompass a wide range of dynamically active objects; from slower-moving interstellar objects to highly dynamic

environments. In each plot, the collision times are displayed as a set of scattering points for different radii, calculated with ranges from 100 AU up to 300 AU. This range was not manually set up but was a result of the stellar mass range of the IMF (0.1*M_sun to 50*M_sun) and the ratio of radii to disc mass as per equation 3. The collisional times were plotted as a function of these radii, for different number densities of Oumuamua-like objects. For the reasons mentioned in section 1.5, we took the four densities 0.01, 0.05, 0.1, and 1 per cubic AU, respectively, corresponding roughly to stellar clusters and interstellar space. To put in comparison, we added the horizontal lines giving the range of bacterial survival times from equation 8. These lines show the lower, middle, and upper bounds of the survival times as indicated by the radii of the ejecta. The outcome is a series of general plots that show dependencies of collisional times on disc radii and object velocities while at the same time giving a reference to the survival times of bacteria. These plots show, through a quick visual guide, that one can estimate the probability of life-bearing rocks surviving transport between stellar systems, thus providing very valuable insight into the feasibility of lithopanspermia.

2.8 Simulation tools

The realization of this project has been majorly done with the help of Python programming in model simulation and data analysis. Some core libraries are NumPy (Van der Walt et al. 2011), used for the performance of numerical computations and the processing of data, and Matplotlib (Hunter, 2007), for the visualization of data. Important applications of NumPy include the simulation of random distributions, statistical operations, and efficient handling of large datasets. Mass distributions and collisional times in stellar environments are plotted using Matplotlib. The analyses are done inside the Jupyter Notebook interactive environment, which means interactive coding is supported in every stage: debugging and visualization.

3 RESULTS

3.1 Introduction to Results

This section will present the results of our study, mainly focusing on the graphical analysis of collisional times vs circumstellar disc radii with horizontally plotted bacterial survival times. This comparison between collisional times of Oumuamua-like objects with circumstellar discs and the survival times of bacteria within these objects will help us achieve the aim of the study.

3.2 Collisional Time Calculations

The collisional times of Oumuamua-like objects were calculated for the above velocities (v_o) and number densities (n_o) across a range of circumstellar disc radii as mentioned in the methodology. The results, as visualized in the attached plots, demonstrate that collisional times vary inversely with both velocity and density. The radii range of the protoplanetary disc is dictated by the lower (0.1 M_sun) and upper (50 M_sun) limits of the stellar masses that were chosen for the study. This range, distributed by equation 2 in methodology, sets the lower protoplanetary radii limit as 100 AU. Although, as per the equation, the upper limit of the y-axis is set to be higher (~500 AU), we set the upper radii limit to be 300 AU.
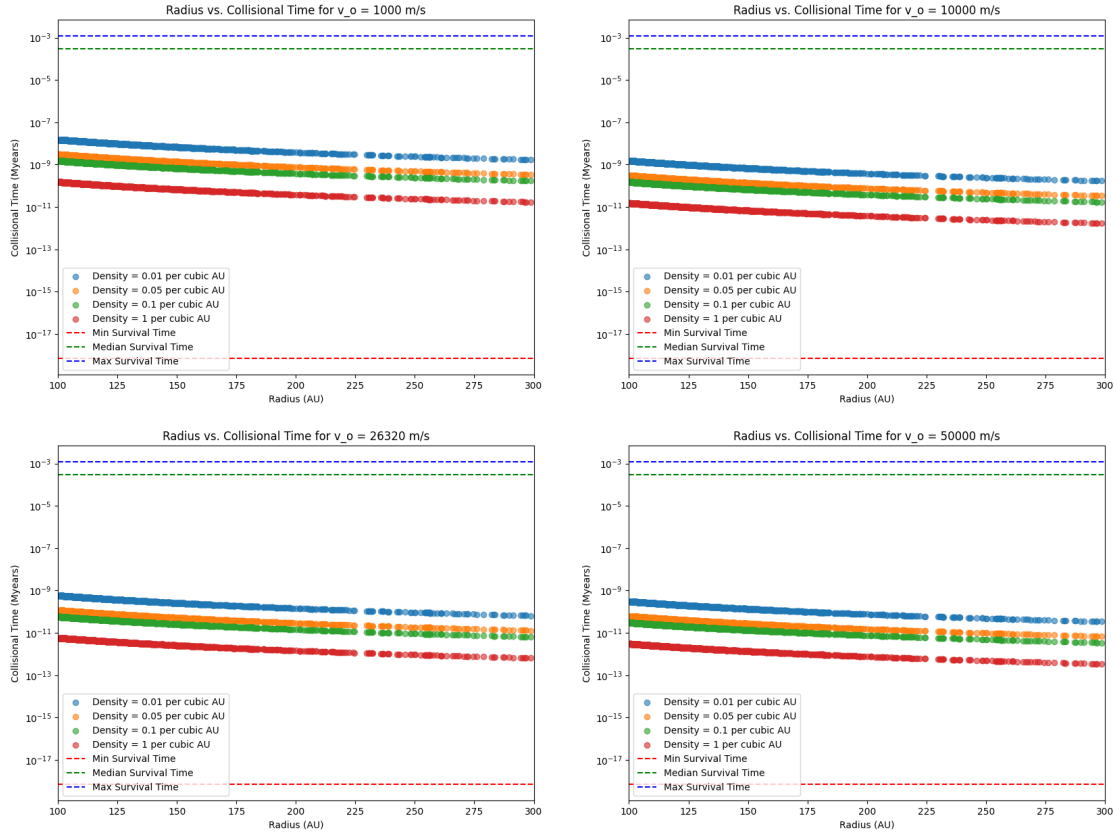
Figure 3. The plots depict the relationship between the radius of the protoplnetary discs and its collisional time with the Oumumua-like rocks for different their velocities (v_o) and number densities (n_o). Four scenarios are considered, corresponding to relative velocities of 1000 m/s (top-left), 10,000 m/s (top-right), 26,320 m/s (bottom-left), and 50,000 m/s (bottom-right). In each plot, the collisional time (in million years) is plotted on a logarithmic scale against the object's radius (in astronomical units, AU), ranging from 100 AU to 300 AU. Different number densities, represented as Oumuamua-like objects per cubic AU, are colour-coded: 0.01 (blue), 0.05 (orange), 0.1 (green), and 1 (red). The survival times of interest - minimum, median, and maximum - are depicted as dashed lines: minimum survival time (red), median survival time (green), and maximum survival time (blue). The data shows that collisional time decreases as the radius of the protoplanetary disc increases and that denser environments correspond to shorter collisional times. This behavior is consistent across all initial velocities, with faster velocities generally yielding shorter collisional times for the same radius and density. The plots illustrate that objects in denser regions of the ISM or moving at higher velocities face a significantly increased likelihood of collision.

3.3 Impact of velocity on collisional times

In the top left panel of Fig. 3 we plot the collisional timescales as a function of radii of the protoplanetary disc, for different assumed number density of the interstellar rocks. At lower velocities, v_o = 1 km/s (top-left subplot) of the ejecta (Oumuamua-like) objects, the collisional times vary within 10^{-10} Myrs to $10^{-7.5}$ Myrs for number densities 1 and 0.01 per cu AU at the circumstellar radii ~100 AU. At the same radii value, the collisional times for the number density 0.1 and 0.05 are 10^{-9} and $10^{-8.5}$, respectively. This indicates that at velocities closer to this, the collisional timescales are relatively higher for all the considered number densities. This being said, as we move in the positive x-axis direction, that is towards increasing circumstellar disc radii, the collisional times have a downward slope. This implies, that with increasing disc radii, the collision between the ejecta and the disc becomes more frequent.

At the next step-up for the relative velocity, v_o = 10 km/s (top-right subplot), for the same number of densities, the collisional timescales are shifted by ~10^{-1} Myrs downwards. For this sub-plot, at radii 100 AU, the collisional timescale varies within the range 10^{-11} Myrs and $10^{-8.5}$ Myrs for n_o = 1 and 0.01 per cu AU, respectively. For the other two number densities, 0.05 and 0.1 per cu AU, the function of the collisional time varies around 10^{-10} Myrs and $10^{-9.5}$) Myrs, at radii ~100 AU. Similar to the first subplot, proceeding towards the right on the x-axis, results in a slope in the collisional time scale lines, indicating lower collisional timescales (higher collisional rates) at protoplanetary discs of higher radii.

At a velocity of v_o = 26.32 km/s (bottom-left subplot), the collisional timescales decrease further compared to the previous velocities. At a circumstellar radius of around 100 AU, the collisional timescales range between $10^{-11.5}$ Myrs and 10^{-9} Myrs for the dif-

ferent number densities. Specifically, for a number density of 1 per cubic AU, the collisional time is around $10^{-11.5}$ Myrs, while for a density of 0.1 per cubic AU, it is closer to $10^{-10.5}$ Myrs. The other two number densities, 0.05 and 0.01 per cubic AU, show collisional times of about 10^{-10} Myrs and 10^{-9} Myrs, respectively. As with the previous velocities, increasing the circumstellar radius results in a decrease in collisional times, indicating more frequent collisions for discs of higher radii and hence higher cross-section.

For the highest velocity of v_o = 50 km/s (bottom-right subplot) of the study, the collisional timescales decrease even more drastically. At a circumstellar radius of approximately 100 AU, the collisional times become significantly shorter. The collisional time for a number density of 1 per cubic AU drops to around 10^{-12} Myrs, while for a density of 0.1 per cubic AU, it is about $10^{-10.5}$ Myrs. The densities of 0.05 and 0.01 per cubic AU show collisional timescales of approximately 10^{-10} Myrs and $10^{-9.5}$ Myrs, respectively. As in the other subplots, increasing the circumstellar radius leads to a downward slope in the collisional timescale, showing that at this high velocity, collisions are more frequent.

3.4 Impact of Number Density on collisional timescales

Analytically, it is evident from the graph that the number density of Oumuamua-like objects also has a major influence on the collisional rates with the protoplanetary discs. Essentially, as the number of objects in a given space increases, the time it takes for them to collide (collisional time) decreases noticeably.

For example, we consider the graph at a velocity of 10,000 m/s. When the density is high, around 1 object per cubic AU, the collisional time is quite short, roughly about 10^{-10} million years. This tells us that in a more crowded environment, collisions happen much sooner. A similar trend follows in the graphs with all the other velocities in the study.

For a much lower number density, 0.01 objects per cubic AU, the collisional time stretches out significantly, reaching around 10^{-8} Myrs. In this less populated setting, objects have more room to move, so it takes longer for them to bump into each other.

The graphs make it clear: the higher number density of the Oumuamua-like objects in the ISM, the higher the collisional rate. This trend holds across all the velocities studied. In simpler terms, the more packed the environment, the less time each object has before it potentially crashes into another. The difference in timescales, from 10^{-10} to 10^{-8} Myrs, highlights how crucial density is in determining the likelihood and timing of these collisions.

3.5 Comparison with Bacterial Survival Times

We compared the bacterial survival times, based on the formula from Valtonen et al., 2009, with the collisional times of the ejecta. The survival times, which were calculated as per equation 8. Where R is in meters, were plotted against the radii of the ejecta to assess whether bacteria could survive long enough to be transferred to another planetary system.

These survival times varied widely depending on the radius of the ejecta. For instance, the largest radius of our study, ~1.87e6, offers significantly longer survival times of up to 10^{-3} million years due to better shielding from cosmic radiation. Although this result from Valtonen et al., 2009 is valid only for a small range of radii (0.26m - 2.26m), we have extrapolated this result to our radii range.

Based on the bacterial survival time values in the graph, the minimum, maximum and median survival times were calculated to be

around $6.9 * 10^{-19}$ Myrs, $1.12 * 10^{-3}$ Myrs and $3.03 * 10^{-4}$ Myrs, respectively. These values were plotted on the Y axis of the collisional times vs disc radii plots and compared with the values of collisional times.

When these survival times are compared with the collisional times, we see an interesting pattern. At lower velocities, around 1,000 m/s, collisional times are generally closer to the survival times, which suggests that the chances of bacteria surviving long enough for successful lithopanspermia (the transfer of life between planets) are relatively low. However, at much higher velocities, like 50,000 m/s, the situation changes dramatically. Here, the collisional times are much shorter, often less than the bacterial survival times, particularly for larger radii. This suggests a higher potential for bacteria to survive and be successfully transferred to another planetary system, making the concept of lithopanspermia more viable under these conditions.

3.6 Summary

Our analysis demonstrates that, under certain conditions, particularly those involving high velocities and large radii, lithopanspermia is a plausible mechanism for the transfer of life between planetary systems. The difference between bacterial survival times and collisional times at higher velocities supports the hypothesis that interstellar objects like Oumuamua could serve as possible transporters for life across planetary systems. However, only a very small fraction of the ejecta will be life -bearing and if they are, they may not collide with the habitable zones of the protoplanetary discs. This reduces the plausibility of lithopanspermia. And, the varying results across different parameters highlight the need for further study to refine these estimates and better understand the conditions that would facilitate lithopanspermia.

4 DISCUSSIONS

4.1 Introduction to Discussion

This research aimed to assess the possibility of lithopanspermia by comparing the time it takes for Oumuamua-like objects to collide with protoplanetary discs, with the survival duration of bacteria inside these objects. By examining different number densities of Oumuamua-like rocks and their characteristics (radius, mass density, relative velocity) we aimed to determine how likely it is for life-carrying rocks to transfer successfully between planetary systems. The importance of this study lies in its contribution to understanding panspermia and the circumstances that could make it more feasible.

4.2 Interpretation of Findings

Under sections 3.2.1 and 3.2.3, our results clarify that the collisional times between Oumuamua-like objects and protoplanetary discs are greatly influenced by factors such as the object's number density (n_o), velocity (v_o) and protoplanetary disc radii(r). Specifically, higher object number densities and faster velocities result in shorter collision times, potentially increasing the chances of lithopanspermia. This implies that, in conditions dictated by these values (number densities and velocities) given the bacterial survival times are comparatively longer than the collisional times, collisions tend to occur more frequently which could aid in life transfer between different planetary systems.

Furthermore, our results imply that collision times decrease as the radius of the protoplanetary disc increases. We have assumed a

simplified geometry of the protoplanetary discs in which the discs have a circular cross-section. Thus the effective protoplanetary disc area for head-on collisions increases as a square of the radii because of this simple geometry. This means that, for discs with higher radius, the area increases as its square, which in turn increases the chance of collisions with the Oumuamua-like objects, thereby reducing the collisional time.

This correlation becomes more pronounced at higher velocities, where an increase in disc radii leads to a rise in collision frequency (Houge & Krijt, 2023). The survival durations of bacteria, contingent, on ejecta radius play a role in this comparison point.

The research shows that larger ejecta tend to result in survival times offering improved protection against cosmic radiation. As the size of the rock increases, given the same density, there is simply more material working as a shield against the outer environment.

This suggests that larger objects have a higher likelihood of successfully transferring life across stellar systems, provided they collide with a protoplanetary disc within a timeframe shorter than their survival time.

4.3 Comparison with Previous Studies

Our study has given results that are in line with earlier studies that have investigated the dynamics of interstellar objects and their possible role in life transfer. For example, Grimaldi et al., 2021 discuss how the microbial survival times along with the spatial dispersion of the ejecta (here, Oumuamua-like objects) influences the probability of the lithopanspermia. Grimaldi et al., 2021 p 5, also discuss that the survival times of bacteria more than 1 Myrs are possible with the ejecta of size more than or equal to 1 m, which again is nearly consistent as per Fig. 2 of our result.

Moreover, our results, which signify the decrease in collisional timescales with increasing relative velocity of the ejecta, are in agreement with Mukherjee et al., 2023. Fig. 4 from the paper Mukherjee et al., 2023, quantifies that with increasing velocity of the ejecta, the capture cross-section of close encounters decreases, which means a higher probability of close encounters with increasing object velocities, aligning with our result of increasing collisions with increasing relative velocity of the ejecta. Although in this section Mukherjee et al. 2023 state this result for close Earth orbits and the Earth-Moon system, our analysis confirms that this result can be extended to distances comparable to the radii of the protoplanetary discs in our simulation.

In our calculation, we incorporated the gravitational effect of protoplanetary discs on the collisional rates between the ejecta and the discs with equation 6, in which the second term, called the collisional cross section, dictates the gravitational effect of the star's and discs' mass over the ejecta, which in turn affects the considered collision rates (Adam & Napier, 2022).

The results of the study align with previous studies that have investigated the dynamics of interstellar objects and their possible role in life transfer. However, this research gives a more in-depth examination of the relationship between collisional times and bacterial survival, covering different velocities and object densities. What is innovative about this study is that it presents a complete model to create a stellar system simulation based on the IMF as well as object properties, which provides a much stronger estimate of chances for lithopanspermia.

4.4 Limitations of the study

Although the study provides valuable insights into the potential of lithopanspermia, it considers a few assumptions which impose several limitations on the results of our study. When considering Oumuamua-like objects, we considered four values for the number density [0.01, 0.05, 0.1, 1] per cubic AU. Although these values wander around the number density provided by papers like Jewitt et al., 2019 and Do et al., 2018, these values are obtained with the observation of only one interstellar object (Oumuamua). This lack of statistics with multiple interstellar objects makes the value less reliable, where the actual value may vary widely.

While conducting the calculations for the survival times, we used equation 8 (Valtonen et al., 2009). Based on the experiments performed on the bacteria (Deinococcus radiodurans and Bacillus subtilis spores) on the International Space Station, the expression for the survival times is applicable only for rock radii lying within 0.67 meters and 2.67 meters (Valtonen et al., 2009). However, in our data, we extrapolated these results to the radii corresponding to 1 kg rock with a mass density (Oumuamua-like) of 1.5 g/cm^3 (McNeill et al., 2018) which is equal to the lower limit of our radii range to be r_low (0.05m). And, similarly, the upper limit, for the rock radii, corresponding to the moon's mass as r_upp (1868km) (Rambaux and Williams, 2010). This extrapolation of the result of Valtonen et al., 2009 to such high values makes the values of the survival times of our study susceptible to a bigger margin of error and the survival times may vary differently in the radii range we considered.

During the last four billion years, nearly $4 * 10^{12}$ ejecta were ejected from the planet Mars in all directions (Mileikowsky et al. 2000). Such ejecta must leave the solar system to successfully transfer life across planetary systems. Nearly 50% of the ejecta leave the solar system within the first 50 Myr (Melosh, 2003). This reduces the fraction of the ejecta that would contribute to a successful lithopanspermia. Having said that, even out of these, not all the colliding ejecta will contain the bacterial life embedded inside. Out of the total ejecta, the fraction of the life-carrying ejecta will be nearly 10^{-6} (Valtonen et al., 2009). Which, in turn again adds up to the reduction of the probability of a successful lithopanspermia.

Further on, out of this fraction, a yet smaller fraction will be colliding with parts of the protoplanetary discs, which are in habitable zones around the star and may contain water in liquid form on a terrestrial planet. For a typical MS star, the habitable zone (HZ) in a protoplanetary disc covers nearly 1% of the entire area (Kopparapu et al., 2013). For a successful lithopanspermia, if a life-carrying ejecta collides with the disc, it either needs to collide within the habitable zone or migrate to the habitable zone of the protoplanetary disc.

Additionally, several other factors contribute to the uncertainty of our findings. One of the most significant issues is the unknown number density of 'Oumuamua-like objects. This estimate is primarily based on the observation of a single interstellar object, meaning the actual number density could vary widely, which introduces considerable uncertainty to our calculations (Jewitt et al., 2019; Do et al., 2018). Also, our models assume constant gas and dust densities within protoplanetary discs; a simplification that overlooks the inherent complexity and variability within the protoplanetary discs. This assumption could lead to inaccuracies in our predictions about the conditions necessary for lithopanspermia (Hegner, 2020).

When estimating the survival duration of bacteria within the ejecta, we used specific models that do not fully account for all environmental factors, such as variations in radiation levels or the presence of shielding materials within the ejecta (Valtonen et al., 2009). These unconsidered factors could either overestimate or underestimate the

survival times, affecting our conclusions about the likelihood of successful life transfer (Miller & Thompson, 2018).

4.5 Implications for Lithopanspermia

With several factors affecting whether life can be transferred from one planetary system to another, the context specificity of a successful Lithopanspermia appears to be quite high. In interstellar environments where object number densities and velocities are higher, the likelihood of lithopanspermia increases significantly (Adam & Napier, 2022). On the other hand, in less dense environments, where the collisional times are largely longer, the possibility diminishes unless the bacterial survival times are exceptionally longer than the considered collisional times (Melosh, 2003). This in turn would require massive ejecta with larger radii (Valtonen et al., 2009). These findings have important implications for understanding how life may spread through the galaxies and some parts of the galaxies (with suitable number densities and object velocities) could prove to be more conducive to lithopanspermia than others (Belbruno et al., 2012).

Additionally, as mentioned in section 4.4, the study is based on a number of assumptions and model parameters that restrict the implications of the results. For example, the exact number density of 'Oumuamua-like objects remains unknown, and variations in these densities could significantly affect collisional times (Mamajek, 2017). Additionally, our model assumes protoplanetary discs with constant gas and dust densities in order to simplify the calculations. An accurate representation of a complex system as a protoplanetary disc would not assume such a simple structure (Brauer et al., 2008) and hence limits the implications of our study. The survival duration of bacteria was also estimated using specific models that may not account for all environmental factors (Horneck et al., 2008). These limitations indicate that while the research provides valuable insights, caution is needed when generalizing its outcomes.

5 CONCLUSION

5.1 Summary of Key Findings

We have investigated the feasibility of lithopanspermia, the hypothesis that life can be transferred between planetary systems via ejected rocks. Key findings of the study reveal that the dynamics of collisions involving Oumuamua-like objects and circumstellar discs are critical in determining the likelihood of life transfer. The study demonstrated that higher number densities and relative velocities of interstellar objects lead to shorter collisional times, which significantly increase the probability of lithopanspermia, provided these timescales are shorter than the bacterial survival times. Additionally, the research highlighted that the physical properties of ejecta, such as size and mass, play a vital role in the survival of microbial life during interstellar travel.

The primary research questions addressed were: 1. How do the dynamics of collisions influence the transfer of life-bearing materials between planetary systems? 2. What environmental factors affect the survival of microbial life during interstellar travel?

The findings indicate that the dynamics of collisions, influenced by the density and velocity of interstellar objects, are crucial for the successful transfer of life. Specifically, environments with high stellar densities and velocities are more conducive to lithopanspermia, while lower densities pose significant challenges due to longer collisional times. Furthermore, the survival of microbial life is contingent upon

the duration of transit and the protective conditions during ejection and travel, underscoring the complexity of interstellar life transfer.

5.2 Implications for Future Research

This research carries significant implications for our understanding of the possibility of life beyond Earth. Future investigations should aim to refine models of collision dynamics and bacterial survival, utilizing more sophisticated simulations that better capture the unpredictable nature of interstellar environments. Additionally, examining a wider range of protoplanetary discs and their properties could offer valuable insights into the conditions that make lithopanspermia more likely. As advancements in observational technologies continue, our ability to assess interstellar object densities and compositions will improve, further shaping our understanding of the potential for life transfer across the universe. Ultimately, this dissertation adds to the expanding knowledge of how life might be distributed throughout the cosmos, highlighting the importance of interdisciplinary research that combines astrophysics, biology, and planetary science.

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