Journal of High School Science

An analysis of interstellar exploration focused on propulsion technologies

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Submitted: November 11, 2022, Revised: version1, December 26, 2022
Accepted: December 27, 2022

Abstract
Humans have dreamed of venturing beyond our planet and solar system for thousands of years. This paper discusses how such interstellar travel can be achieved with the technology of today or that of the near future, focusing specifically on propulsion. It begins with considering the motivations behind interstellar travel, namely the wealth of scientific information it would provide on exoplanets and the interstellar medium. The paper then discusses the many challenges surrounding interstellar travel when using conventional spacecraft, including those of distance, time, and energy. However, many possible alternative propulsion technologies address these issues. The three discussed, are ion engines, nuclear pulse propulsion, and light sails. The suitability of each technology is analyzed, with a comprehensive Pugh matrix. The paper concludes that light sails are the best option for an interstellar mission due to their high specific impulse and final velocities. A foundational mission concept for a fly-by to our nearest star Proxima Centauri in under 50 years is developed using light sail technology. The mission concept includes a discussion of the lasers needed to propel the light sail, the size and mass of the probe, on-board instrumentation, the mission timeline, communications, deployment, and finally, a risk analysis. The paper concludes by presenting the future advancements and research needed for such a mission to be created.

Keywords
Interstellar travel, Propulsion, Light sail, Deep space, Mission concept, Nuclear pulse propulsion, Ion propulsion, Space exploration, Exoplanets, Lasers

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Introduction

The desire to reach the stars has propelled astronomers to study the cosmic formations within our solar system and even those beyond it. At first, this was merely through studies by the naked eye. But slowly, through the development of optical telescopes, scientists were able to observe the other planets in our solar system and far-off stars, allowing them to gain a detailed insight into the orbital mechanics of our neighboring planets. With the creation of satellite technology during the space age came another wave of information on the surface of these planets and their composition. Deep space probes such as the Voyager 1 and 2 traveling to the outer planets of our solar systems have provided astronomers with new information. Advances in telescopic technology in the past few decades have allowed for a glimpse at exoplanets light years away from Earth.

Following this natural progression of astronomical advancement, the next step is most certainly advancing interstellar exploration. This would involve sending a probe of some kind beyond our solar system, beyond the edges of the Oort cloud. Ideally, this probe would be able to visit neighboring solar systems and provide us with information currently unavailable due to distance constraints.

This paper will analyze the concept of interstellar travel. It will explore the theory along with motivations and challenges surrounding interstellar exploration. The paper will mainly focus on the propulsion technology necessary to make interstellar travel feasible. An overview of the most practical propulsion technologies for interstellar travel will be discussed, explaining how each of them work, and their suitability for such a task. By choosing the most suitable propulsion technology, a foundational mission concept for a flyby to our neighboring solar system Proxima Centauri within approximately 50 years will be presented.

Motivation

It has become clear that the universe cannot be fully understood simply through observations made here on Earth. While earth-based observations have given us a great amount of insight into the orbits, compositions, and surfaces of planets in our own solar system, they have only given us a tantalizing peak at the planets and stars beyond it. Despite the multitude of telescopes on our planet – from radio to gamma-ray – all that is known about these exoplanets is their path of orbit, potential mass or radius, and if we're lucky, information about their atmosphere (1). Using current technology, scientists are greatly limited in the information they can squeeze out of light through photometric, spectroscopic, and interferometric means.

Hence, to truly learn more about the planets beyond our solar system, interstellar travel must be undertaken. Scientists must create probes that successfully exit our solar system and fly near these exoplanets to truly understand them. Interstellar travel will provide astronomers with detailed information on the composition of exoplanets, astrophysical properties of the star system, and much more. It would even allow for the investigation of signs of life on such exoplanets, answering the age-old question "are we alone in the universe?" Not only would an interstellar mission provide insight into the genesis, composition and trajectory of planets and planetary systems, but it would also allow for studies on the mysterious interstellar medium en route to the destination. Considering that the interstellar medium is yet another section of the universe where astronomical knowledge is lacking, this further adds to the motivations for undertaking such a mission (2). When interstellar missions become a practical undertaking, mainstream astronomy will achieve an enrichment similar to, if not greater than, the one it received during the space age with the launch of the first satellites.

Though it may seem far-fetched, interstellar exploration could also allow humanity to find new planets that could support life. And as technology advances, humans may be able to reach these planets and set up colonies on their surfaces (3). The possibilities that interstellar exploration brings are endless, making it an important endeavor.

Challenges

Unfortunately, interstellar travel is fraught with non-trivial challenges. First is the matter of distance. The nearest star to our solar system is Proxima Centauri, 4.3 light years away from us, or 4.1×10^{13} km. To help put things in perspective, the Moon is 4×10^{5} km away from the Earth. The Voyager probes, the first of which was launched in 1977, flew by Pluto in 1989, which is 4×10^{9} km away - ten thousand times the distance to the Moon. The nearest star, Proxima Centauri, is ten thousand times the distance to Pluto (Figure 1) (4).

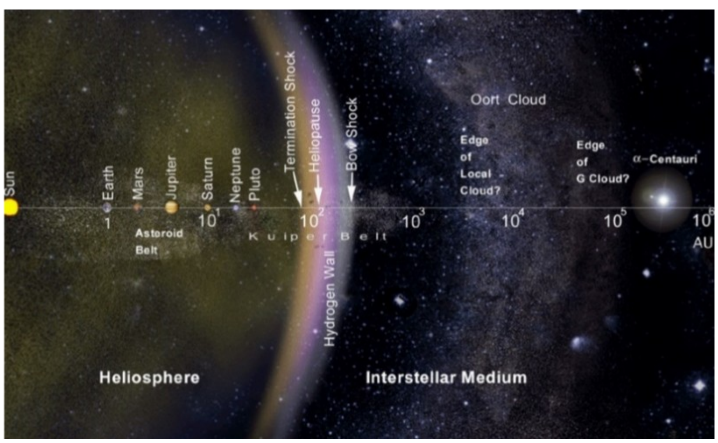

Figure 1: Scale of the Solar System
An image showing proportionally how far Proxima Centauri is to planet Earth. This distance extends past the Oort cloud well into the interstellar medium (77)

The issue with these huge distances is the time it will take to cover them. Consider the Voyager probes. It took Voyager 1, 35 years to simply travel beyond the solar wind. It will take Voyager 1 another 30,000 years to travel beyond the Oort cloud and truly leave the solar system. Bear in mind that Voyager 1 is the fastest spacecraft humanity has built to date, traveling at 17 km/s (5). At this speed, or even ten times this speed, interstellar travel is not feasible as it would be nearly impossible to track a mission for such a long duration. Indeed, for comparison, the longest-lasting scientific mission to date is 45 years, achieved by the Voyager probes themselves (6). Additionally, a mission spanning centuries would not be a practical use of technology as by the time such a mission is even halfway complete, scientists would likely have developed more advanced technologies that could carry out the same mission on a shorter time scale. This is known as the incessant obsolescence postulate (7). To avoid this conundrum, the mission would have to occur within about 50 years (8). This therefore indicates that if interstellar travel is to be a success within a reasonable time frame, we would have to develop spacecraft capable of traveling at least 10% of the speed of light, about 30,000 km/s. At this speed, it would take 43.5 years for the probe to visit our closest solar system, and another 4.35 years to send the data it collects back to us, allowing for a roughly 48-year-long mission (discussed in more detail in later sections), which is much more manageable than 30,000 years.

Additionally, at such high speeds, energy demand and consumption increase exponentially. The high velocity necessary for a spacecraft for such a mission is thousands of times greater than a normal spacecraft. Accelerating to just 10% of the speed of light requires at least 125 terrawatt-hours, without even factoring in the efficiency of the propulsion device, as no propulsion device can be 100% efficient (9). This amount of energy compares to almost 2.5 times the total energy consumed in New York City in 2017 (10). If a rendezvous mission is desired instead of a simple flyby, then deceleration is needed as well, doubling the required energy needed for the entire mission. Not only is generating this much energy nearly impossible but storing it presents another problem. Solid or liquid fuels are not an option, as the more fuel added to a probe, the heavier it becomes and the more fuel it needs, creating an inescapable paradox.

These issues with energy and speed make interstellar travel seem impossible and with a basic rocket, it practically is. If standard rockets are used to propel a space vehicle, the vehicle will be limited in its terminal velocity to a minuscule fraction of the speed of light. If a rocket-powered spacecraft has a human crew, the mass of the humans themselves as well as all of the necessary life support equipment will further limit the speed of the probe (4).

Additionally, there is still much unknown about the interstellar medium, which an interstellar spacecraft would have to travel through (11). A major issue with traveling at extremely high speeds is that interstellar dust may cause considerable damage to the craft. An object the size of a grain of sand moving at about 90% of the speed of light through the interstellar medium has kinetic energy corresponding to a small nuclear bomb (12, 13). Colliding with such an object during the probe's mission would be disastrous, posing another significant issue.

While interstellar travel may seem unlikely right now with our current technological capabilities, there is still hope. New, emerging technologies provide unique solutions to these challenges, that would allow us to accomplish the endeavor of interstellar travel. This paper specifically will focus on propulsion technologies needed to accomplish interstellar travel, as these technologies work on overcoming the issues of speed and energy.

Propulsion

In the past few years, many new theories and concepts for interstellar travel have been developed. Some of these concepts are theoretical such as large anti-matter ships that could travel at 90% of the speed of light even with a crew, or "planet-hopping" – using a planet's gravitational pull to fling a spacecraft from planet to planet, steadily accelerating it (14). While such theories are interesting, they are unfortunately not feasible with current technology. Even with significant technological developments, scientists may not be able to generate and store the large quantities of (as yet hypothetical) antimatter needed for an antimatter drive (15). Additionally, there simply does not exist a planet with a large enough gravitational pull within our solar system to make planet hopping an option (16). Instead, we must look at technologies for a simple, uncrewed mission if we want to achieve interstellar travel in the near decades.

With these uncrewed missions, the main question is what type of propulsion system to use. The propulsion system, after all, is what determines how fast the probe can travel as well as how much energy/what kind of energy it will require (17). Propulsion systems may be ranked by different characteristics, such as energy input, acceleration rate and power produced, among others. However, for the purposes of interstellar travel, there are two main quantities of overarching importance: the specific impulse, and the final velocity of travel. Specific impulse is a measure of efficiency for propulsion, in units of seconds. It is the change in momentum per unit of mass of engine fuels. Simply put, specific impulse is a measure of how much push (thrust) accumulates for a given quantity of fuel used/combusted (18). To achieve interstellar travel well within approximately 50 years, a specific impulse close to 400,000 seconds will be needed. And as previously touched upon, a final velocity of 0.1c will be necessary as well (19).

At present, almost all our rockets are based on chemical reactions. These chemical rockets are the technology that has the smallest specific impulse since they only operate for a few minutes. Their thrust may be measured in millions of pounds, but they operate for such a small duration that their specific impulse is quite small. Hence, as mentioned previously, these rockets are not suitable for interstellar travel (20, 21).

There are now more options available than just chemical rockets that could potentially achieve the necessary specific impulse needed for interstellar travel. The three more researched technologies are ion, nuclear, and beamed propulsion. Each of these technologies has its pros and cons alongside its many unique characteristics, which will be discussed in detail in the following sections.

Ion Engines

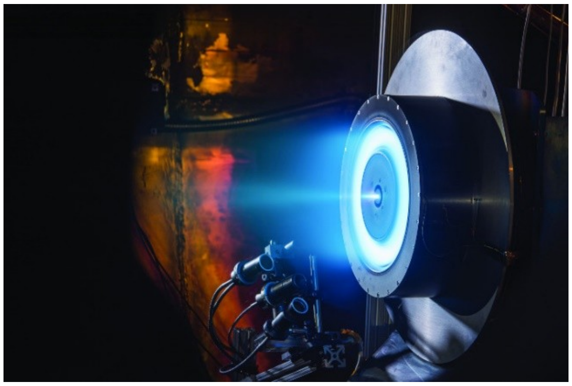

Figure 2: Ion Engine
NASA Evolutionary Xenon Thruster (NEXT) ion thruster in operation. The blue light is the plasma produced by the engine (78)

Ion thrusters use beams of ions – electrically charged atoms or molecules – to generate thrust per the principles of momentum conservation (Figure 2). The most conventional version of the ion engine acquires its electric power from photovoltaic panels. It is a squat cylinder, not much larger than a bucket, that is set at the rear of a spacecraft. Inside the bucket, xenon gas from the propellant tank flows into an ionization chamber. Here, an electromagnetic field tears electrons off the xenon gas atoms to create a plasma. The plasma's positive ions are then extracted and accelerated to high speeds via an electric field that is applied between two electrode grids. The positive ions in the field feel a strong tug from the aft-mounted, negatively charged electrode and therefore accelerate rearward (22). The positive ions in the exhaust exit the spacecraft with a negative net charge. If this charge were to accumulate, it would attract the ions back to the spacecraft and negate the thrust produced. To prevent this, an external electron source (a negative cathode or an electron gun) injects electrons into the positive flow to electrically neutralize it, thus leaving the spacecraft with a neutral charge (23).

Ion thrusters have higher specific impulses than chemical rockets, so they require significantly less propellant for a given mission than a chemical rocket would need (24). Additionally, ion engines operate for a much longer time than traditional chemical rockets. This means they can continue to accelerate for tens of years, achieving top speeds of up to 90 km/s compared to the 20 km/s obtained by chemical rocketry.

Ion thrust engines are practical only in the vacuum of space and cannot take vehicles through the Earth’s atmosphere because ion engines do not work in the presence of ions outside the engine (25). However, considering that in this case the spacecraft would only be operating in deep space, never near an atmosphere, this does not pose a problem in terms of application. It does mean that the spacecraft cannot generate sufficient thrust to achieve the initial liftoff of the Earth. Instead, it must rely on other methods such as conventional chemical rockets or non-rocket launch technologies to reach its initial position. Subsequently, it can execute the rest of the mission using ion thrusters (26).

However, ion engines suffer from one major shortcoming: they generate very little thrust. Just how little thrust ion engines generate can be demonstrated by how much the palm of the hand is weighed down by the weight of 10 quarters (27). This is due to a phenomenon known as “space-charge limitation”, which is when a positive charge builds up as the positive ions pass between the electrostatic grids in an ion engine. This buildup of charge limits the electric field attainable for driving the acceleration (28).

The drawback of this low thrust is less acceleration. While the continuous operating period does allow for this weak acceleration to manifest into a significant velocity, it takes an extremely long time for this to occur. An ion drive would require two days to accelerate a car to highway speed in a vacuum (29). At this rate, it would take many years to accelerate to top speed, which draws out an interstellar mission farther out than is practical. Furthermore, the current top speeds of ion engines are still not fast enough to complete an interstellar mission within approximately 50 years, because a top speed of 90 km/s is only 0.03% of the speed of light. Recall that we need to reach at least 10% of the speed of light to achieve interstellar travel within a reasonable time frame.

A variation of the ion thruster known as a Hall thruster may avoid the space-charge limitation and therefore be able to accelerate a vessel to high speeds quicker. This system relies on the “Hall Effect,” which arises when electric and magnetic fields are set perpendicular to each other inside a conductor. It results in an electric current (called the Hall current) that flows in a direction perpendicular to both fields (30).

In a Hall thruster, an electric discharge between an internal positive anode and an external negative cathode ionizes a neutral gas inside the device to generate plasma. This plasma fluid is then accelerated out of the cylindrical engine by the Lorentz force. The Lorentz force is the force exerted on a charged particle moving through an applied radial magnetic field and an electric current (in this case, the Hall current) that flows in an azimuthal direction (31). This form of ion rocket avoids a space-charge buildup by accelerating the entire plasma (both the positive ions and negative electrons). This results in a thrust force many times that of an ion engine of the same size, with a specific impulse of up to 8,000 seconds (32).

The Hall thrusters available today are rather small and only operate for a few months. Hence, they are not suitable for deep space missions. However, engineers are now trying to scale up today's rather small Hall thrusters so that they can handle higher amounts of power to generate greater exhaust speeds and thrust levels, and therefore generate greater specific impulses as well. (33).

Nuclear Pulse

Nuclear pulse propulsion is a theoretical method of spacecraft propulsion that uses nuclear explosions for thrust (Figure 3). There are two categories of nuclear pulse spacecraft technology: external pulse and internal pulse. These options differ in how the momentum from the nuclear explosion is converted into thrust. However, they both operate on the same basic concept. In both cases, an individual explosive device (some sort of pellet or pulse unit) is ejected from the vehicle and detonated at a predetermined standoff distance from the rear. The resulting explosion vaporizes the entire pellet and generates a high-energy plasma, which expands and acts as the “propellant”. Some of that plasma then interacts with the vehicle, providing thrust. A large number of pulses would need to occur, ideally at equal intervals (34).

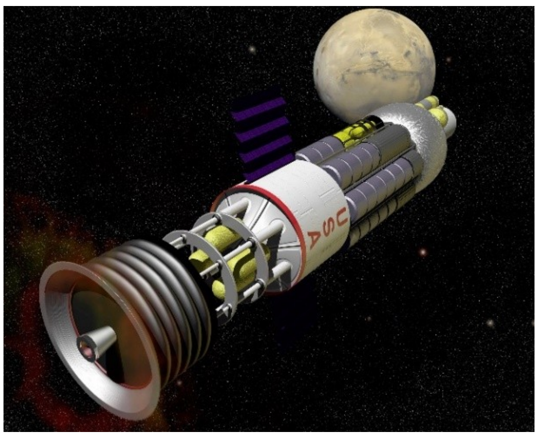

Figure 3: Nuclear Pulse Propulsion Spacecraft
A CAD model of what a nuclear pulse spacecraft would look like. The actual nuclear pulse mechanism is at the bottom of the craft (79)

In the case of an external pulse, the pulse takes place at some distance from a pusher plate at the very rear of the craft. This pusher plate intercepts and absorbs the shock of the explosion. A momentum conditioning unit is used to smooth out the momentum transfer between pulses, allowing a nearly constant acceleration while also returning the plate to its proper location for the next pulse (35). The advantage of this approach is that no attempt is made to confine the explosion. Hence the material limits associated with confined concepts such as solid core rockets are avoided. The actual interaction time between the plasma propellant and the vehicle is fleeting, as short as 0.1 milliseconds (36). This results in essentially no heat transfer occurring. Hence, while the temperatures in the propellant cloud may be as high as a million degrees Kelvin, the momentary interaction time means that only a small amount of material is ablated and lost. This pulsed nature allows this approach to be achievable, else a sustained application of such high temperatures would surely lead to sustained vehicle damage.

The specific impulse attainable by this external design is proportional to the impingement velocity of the propellant against the pusher plate. This quantity is limited by the ablation of the pusher plate. The maximum specific impulse is estimated to be about 270,000 seconds, indicating that this design is highly efficient when it comes to producing thrust (37).

The other option is the internal pulse design. In this concept, the nuclear explosion takes place inside a pressure vessel in which heated propellant is expanded through a conventional nozzle. Liquid hydrogen or water serves as a propellant and is fed into the pressure vessel radially through the walls to simultaneously serve as a coolant. The explosion occurs at the center of the vessel, generating a shock wave that spreads through the plasma propellant until it is reflected from the walls. This wave is reflected back and forth in the vessel increasing the internal energy of the hydrogen until equilibrium is established. All of this only takes a few milliseconds, and then the vessel is refilled with propellant. The expansion process is continued until the former initial conditions in the vessel are restored, and the whole cycle is repeated (36).

However, internal pulse designs have one significant drawback. For a specific impulse of greater than 1,400 seconds, they would require extremely heavy engines. This greatly increases the mass of the probe and hence makes it difficult for it to travel at the speeds needed for interstellar travel (38). Hence, when it comes to nuclear pulse concepts, the external pulse is the superior option of the two. Its high specific impulse allows for acceleration much faster than both ion engines and chemical rockets, an attribute ideal for interstellar travel.

Furthermore, there have been further developments in recent years to external nuclear pulse engines by the use of externally triggered inertial confinement fusion (39). This involves producing fusion explosions via compressing fusion fuel pellets, likely made of lithium deuteride, with high-powered electron beams (40). Since then, lasers, ion beams, neutral particle beams, and hyper-kinetic projectiles have been suggested to produce nuclear pulses for propulsion purposes (41). This further increases the specific impulse of external nuclear pulse engines, as well as the amount of thrust they can produce.

In fact, for the purposes of interstellar travel, it has been theorized that an external nuclear pulse engine would use deuterium fusion detonations with a very high fuel-burn up fraction. Studies have shown that a Teller-Ulam-style powered nuclear spacecraft could achieve a top speed of 8-10% of the speed of light (42).

However, even though most of the technology required to implement such a spacecraft has been actualized, implementation remains difficult. A current impediment to the development of any nuclear-explosion-powered spacecraft is the 1963 Partial Test Ban Treaty, which includes a prohibition on the detonation of any nuclear devices (even non-weapon based) in outer space (43). Many other nations have internal restraints on the use of nuclear technology as well. If a nuclear-pulse spacecraft were to be created, this treaty along with many other laws and regulations would have to be renegotiated.

Light sails

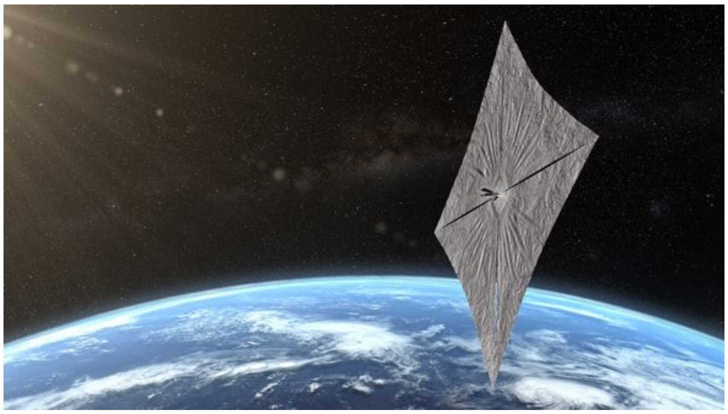

Figure 4: Light sail probe in Earth Orbit
An artist's rendition of Light Sail 2 in Earth orbit. Note that the light sail is highly reflective and the largest component of the spacecraft (80)

Light sails (also known as solar sails, photon sails, or laser sails) are a method of "beamed" power propulsion (Figure 4). This means that instead of using liquid or even atomic fuel, this propulsion system uses light/photons as its main source of power. Photons carry a momentum of hv/c, where h is Planck's constant, v is the frequency of the light, and c is the speed of light (44). Hence, a light sail could harness this momentum to propel a spacecraft, similar to how sailboats harness the wind to glide across the water. The photons travel through space towards the probe where they are then reflected off giant, mirror-like sails made of a lightweight material 40 to 100 times thinner than a piece of printer paper. The push from the photons is unceasing, allowing for continued thrust and acceleration (45).

The most unique feature of this propulsion system is that its "engines" – its light source – are left behind in the solar system and the power is instead transmitted out to the rest of the vehicle that carries the payload. This means light sails technically have an infinite specific impulse, as the reaction mass is not onboard the craft (46). Additionally, since the probe does not have to carry any fuel, all the "heavy" parts associated with chemical rockets are detached, allowing the probe to have a much smaller mass and achieve greater velocities.

There are two main options for the light source for solar/light sails. The first is the sun, which readily provides a constant stream of sunlight. The perks of using sunlight to propel a probe are that it already exists and is self-reliant. Humans do not need to construct any structures or make sure the sun has enough power to keep generating light. Hence, it is cheaper as well. However, while the sun does generate abundant power, this power is disseminated throughout the entire solar system. It is not pointed directly at the probe, and hence at the Earth's distance away from the sun, solar sails are a low-thrust propulsion system, similar to spacecraft propelled by electric engines (47). They are still able to achieve higher velocities than chemical rockets due to their lower mass, on the scale of 30 km/sec (48). However, this is still far too less for interstellar travel.

The second option for the light source, lasers, is able to generate much more concentrated power. Unlike the sun where the energy generated propagates throughout the entire solar system, lasers allow for the energy to be specifically pointed at the probe and therefore allow for the probe to receive more energy, and therefore generate more thrust (49). Lasers also avoid the inverse-square dependence of the intensity of sunlight with distance (50). A laser suitable for powering an interstellar spacecraft would have to have a large diameter beam so only a small portion of the light misses the craft due to diffraction. Alternatively, an array of lasers could be used to power the probe. The lasers must have strong pointing stability capabilities so that the craft can continuously follow the center of the beam, thereby complicating its engineering (51).

Admittedly, creating such powerful lasers is a challenging task, in and of itself. The laser would have to be huge, with the base of an array on the order of 1 km^2. It would have to generate a vast amount of energy, a minimum of 10 gigawatts and potentially up to 100 gigawatts (52). If this array is built on the moon, the requirements to generate electricity to power such a laser would need to be harnessed; presumably from the lunar surface or atmosphere using a self-propagating reaction. This clearly complicates the development of a laser-propelled interstellar probe. However, this paper focuses on the propulsion technology itself, not the construction of the laser source.

Light sail propelled probes allow for much customization as well. A 100 m^2 sail could be used to propel a 1kg CubeSat at ~ 10% of the speed of light. Increasing the size of the solar sail to the scale of kilometers allows for a much greater payload mass, on the order of about 1000 kg (53). This would allow for much more equipment to be transported on the probe, without significantly increasing the mission time.

The light sail's material is also of great importance. The material's properties have a significant effect on the performance of the proposed mission and influence the payload. As mentioned, the material of the light sail would have to be extremely thin. However, the material must not be so thin so as to allow light to pass through it, as the material must reflect as much light as possible to properly harness the energy of the photons (54). A thin layer of aluminum coating on a polymer (plastic) sheet, such as aluminized Mylar® , is currently the most common material used in solar sail designs. The polymer provides mechanical support along with some flexibility, and the thin layer of metal provides the necessary reflectivity (46).

In recent years, new, alternative materials have been suggested. Certain carbon fiber materials may be useful in solar sails. Although the material is over 200 times thicker than conventional solar sail designs, it is so porous that it has the same mass. The rigidity and durability of this material could make solar sails that are significantly sturdier than plastic films. The material could self-deploy and withstand higher temperatures as well (55). Graphene is another distinct possibility for future light sail materials, as it is much thinner and lighter than aluminized Mylar®. However, both these options are not as reflective (56).

One of the advantages of light sails is that they are highly customizable in terms of interstellar mission design. The technology is hence suited for smaller probes intended for cursory exploration, or to a larger probe designed for detailed measurements (57).

Table 1: Pugh Matrix of Propulsion Technologies

Key: -- = extremely difficult, - = difficult, + = feasible, ++ = highly feasible				
Requirement	Importance Weighting (1-5)	Ion Engines – Hall Thruster	Nuclear Pulse – External	Light sails – Laser Propelled
Sufficient Velocity (>0.1c)	5	-	+	++
Appropriate Specific Impulse (>400,000 sec)	5	--	+	++
Experimentally tested	3	++	--	+
Design size appropriate for construction	4	+	+	-
Supplemental engineering structures required	3	+	+	--
Political constraints	1	++	--	++
Power required	4	+	-	--
Mission Risk	2	-	-	-
Totals (with weightage)		**2**	**3**	**5**

The disadvantage of light sails is that it is difficult to decelerate them on interstellar voyages. Turning off the lasers would simply cause the spacecraft to coast at a constant velocity. Instead, for deceleration to occur, the spacecraft would have to use some other technology added onto the probe to slow down, stop or change directions. A small electromagnetic or chemical propulsion unit could potentially be used but this would add mass to the probe, making it heavier and requiring more energy to propel (58). Thus, when it comes to light sails, a flyby mission becomes much more feasible than a rendezvous. The latter is certainly possible, it would however require much more engineering and material, and likely take a much longer time.

Overall, considering the various characteristics of all the propulsion options discussed, light sails are the most suitable for implementation in interstellar probes. This conclusion is highlighted in Table 1. For a more detailed presentation of this information with explanations, see Appendix 1.

Based on the propulsion technologies analysis discussed, a foundational mission concept laying out an ideal plan for an interstellar voyage to Proxima Centauri using light sail technology is demonstrated to be the most viable option. The following section will further discuss the requirements and specifications of the mission concept.

Mission Concept

For this mission, the spacecraft will travel to our nearest extra-solar star Proxima Centauri and its two planets 4 light years away in ~ 50 years. The mission will be a flyby. The probe will be equipped with a payload containing multiple scientific instruments that will be used to take pictures and measurements of both the interstellar medium and the Proxima Centauri system. The probe will use light sail technology.

Thrust Mechanism

The probe will be propelled by lasers, as this will allow for the most concentrated energy source and greater control as previously explained. The Alpha Centauri system has an inclination of −60° and is visible in latitudes smaller than 30° South on Earth (59). If the laser were to be constructed on Earth, it would have to be assembled near the South Pole. While the construction and energy resources needed for such lasers are available on Earth, the losses and pointing disturbances encountered while traversing the atmosphere suggest that placing the lasers in space would be much more feasible and economical. For these reasons, this laser system would be built on the Moon (60).

To determine the total amount of energy the laser base must produce, we must first calculate the necessary acceleration of the probe for it to accomplish the interstellar mission within 50 years. To do this, one of Forward’s equations may be applied

$$a = \frac{4\sigma\epsilon\eta T^4}{c\alpha\beta}$$ Equation 1

Where T is the maximum operating temperature, α is the absorption, $\epsilon$is the emissivity, c is the speed of light, η is the reflectance of the sail, β is the same areal density, and σ is the Stephan Boltzmann constant. The maximum operating temperature can be assumed to be 600 Kelvin. The speed of light and the Stephan Boltzmann constant are known to be 299,792,458 m/s and 5.67×10^{-8} $W/m^2 K^4$ respectively (58). The graphene sandwich material has a reflectivity of 0.82, slightly less than aluminum. Its absorbance is assumed to be 0.135 and its emissivity to be 0.06 (58). These values compute the thermally limited acceleration to be 0.36 m/s^2.

Now that the required acceleration has been calculated, another one of Forward's equations may be used to calculate the power required.

$$P = \frac{mca}{2\eta}$$ Equation 2

Where P is the power required, m is the total mass of 1000 kg, c is the speed of light, a is the acceleration, and η is the reflectance of the sail. Plugging these values into equation 3 gives us a required power of 65 gigawatts (58). This is the power required for the physical propulsion of the craft. Additional power would be needed for operating the instruments on board and sending data back to Earth. However, in comparison to the amount of power required to accelerate the probe, the power needed for operating instrumentation is quite minor, on the scale of kilowatts as opposed to gigawatts.

Furthermore, not all of the energy produced by the laser beam will be captured by the probe. In fact, due to pointing losses, it is estimated that only about 84% of the energy generated by a laser base will be able to reach the probe over long distances (61). With this efficiency, the total power that must be generated by the laser base may be calculated.

$$P_{generated} = \frac{P_{required}}{e} = \frac{65\,GW}{0.84} = 77\,GW$$ Equation 3

Hence the laser base must generate 77 GW of energy to power this mission. Of course, this is the minimum amount required and assumes no significant deviations from the probe's orbital path or obstruction by interstellar dust particles or larger celestial objects, both of which would require a laser source producing more than the minimum amount of power. To account for the possibility of such events occurring, a laser base capable of generating around 125% of the minimum required power, ~ 97 GW in this case, should be built (62).

While 97 GW may sound extreme, high-power scientific lasers in the desired 100 GW range are currently available (63). However, they are solely pulsed lasers. For an interstellar mission, a continuous wave laser would be required to reduce loads on the sail (64). It would be ideal to develop multiples different applications for high-powered continuous wave lasers to make the construction of such a laser base more economically feasible, as it would not be practical to create such a base for just one mission.

With NASA's renewed interest in the Moon and potentially creating a Moon base through the Artemis missions, a laser base on the Moon is not outside the realm of possibility (65). The exact science and planning of the laser system is outside the scope of this paper. Instead, it will be assumed that such a base is already built and in operation. The paper will instead focus on the creation of the probe itself, examining different parameters.

Materials

As previously discussed, aluminized Mylar® and graphene are the two possible options, with the former being the more reflective and the latter being much lighter. By itself, graphene's low density cannot compensate for its low reflectivity. To overcome the high transmittance of graphene, a sandwich structure composed of graphene sandwiched between two appropriate monolayers has been proposed. Adding alkali atoms to the outer surface (the one facing the light) increases the reflectivity. This comes at the expense of higher density but demonstrates a much better acceleration potential (56).

If used in a sandwich structure, the properties of the graphene sail improve, leading to a better performance than aluminized Mylar®. Matloff has calculated the acceleration distance required to reach 0.05c for different spacecraft masses. The acceleration distances for 0.1c are proportional to those of 0.05c. Smaller distances are favorable to avoid pointing and beam spread losses (66).

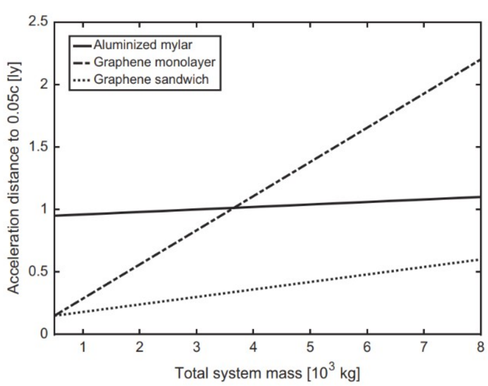

Figure 5: Materials Comparison.
A comparison of light sail materials with acceleration needed to reach 0.05c as a function of the spacecraft mass. The three materials compared are aluminized mylar®, graphene monolayer, and graphene sandwich (67)

The graphene sandwich has the least acceleration distance for a wide range of system masses, and hence it is the ideal choice for the solar sail material (Figure 5).

Size and Mass

The size and mass of the probe and solar sail must be considered as well. The sail itself will have a circular configuration as opposed to a rectangle or other shape. The circular shape avoids the problems with bending loads associated with rectangular sails (68). Additionally, unlike rectangular sails, circular sails do not require heavy booms for support (69). These booms add mass that could instead be dedicated to instrumentation, hence rendering circular light sails the most advantageous for this mission.

The size of the solar sail is directly dependent on the mass of the system, as the greater the mass, the larger the sail required to accelerate it. This relationship can be modeled with the equation derived from Forward's calculations (59).

$$d=\left(\frac{4\,m}{\pi\beta}\right)^{1/2} \qquad \text{Equation 4}$$

Where d is the diameter of the sail, m is the total mass of the probe β is the areal density of the sail, structure, and payload. For our case, we will assume an areal density of 0.1 g/m^2 based on past solar sail missions. Setting the probe to a mass of 1000 kg, the diameter of the solar sail would be 3.6 km. While this may sound extremely large, note that the solar sail would not be opened during the time of launch. Instead, the solar sail would be compactly folded, and then unfurled in space where there is ample room. Of course, these sail deployment mechanics would take up mass on the probe (68). Additionally, the position determination and control system, data handling system, power system, communication system, and the actual light sail itself all contribute to the mass of the probe (67). Therefore, instead of the usual 1/3 of the total mass being set aside for the payload, it would be more accurate to assume a payload fraction of about 1/5 of the total mass, or 200 kg (70).

Instrumentation

The maximum payload mass for this mission concept has been set to 200 kg, as detailed in the previous section. This payload will consist of scientific instrumentation, such as a Geiger counter or solid-state detector and a telescope equipped with a camera. To minimize mass and size, the smallest possible instruments will be used. Near-future developments will result in the further miniaturization of some instruments (71).

Studies of the interstellar medium will involve taking a survey of the different levels of electromagnetic radiation throughout, often in the radio wavelength. This requires the least sophisticated instruments. Hence, the Geiger or solid-state detector will be used to measure the radiation level and other characteristics of the interstellar medium as the probe is traveling to Proxima Centauri (72). These instruments have a high potential for miniaturization as well, meaning they will only contribute marginally to the total payload mass.

The optical cameras and telescope would take a variety of close-up images of the Proxima Centauri system. This has never been done before and would reveal a wealth of information about our nearest solar system. However, the miniaturization of optical instruments is severely limited by physics, as the achievable resolution directly depends on the observable wavelength and the mirror or lens diameter. Achieving a higher-resolution image requires increasing the size of the mirror or lens, which leads to an increase in mass. The image resolution needed will depend on the orbital height of the probe as it flies by by Proxima Centauri and its two exoplanets. The closer the probe is able to get to the planets, the less powerful the optical instrumentation would need to be. However, a closer flyby will require more power as well as more refined sail control mechanisms (67). This trade off will have to be considered when developing the instrumentation for the probe.

Timeline

To determine the total time of the mission we must calculate the time of acceleration needed to reach the necessary cruising velocity plus the cruising time to reach Proxima Centauri. With the acceleration determined in the previous section, a velocity of 10% of the speed of light will be reached in a certain amount of time. This time, and the distance at which this velocity is achieved, is calculated using basic kinematic equations.

$$t=\frac{v}{a}=\frac{0.1c}{0.36} = 8.3 \text{ x } 10^7 \text{ seconds} = 32 \text{ months} \quad \text{Equation 5}$$

$$s=0.5at^2=0.5 * 0.36 * 8.3 * 10^7=0.13ly \quad \text{Equation 6}$$

Therefore, it will take 32 months to reach a traveling (coasting) velocity of 30,000 km/s (Equation 5). The distance at which this velocity will be achieved is calculated using Equation 6.

Hence the probe will be cruising over a distance of 4.22 light years, which will take 42.2 years at 0.1c. The total mission time is then 2.6 + 42.2 = 44.8 years, well within the 50-year cap and hence practical for scientists and researchers to keep track of. Note that data would continue to be transmitted beyond this mission time frame.

Communications

The probe will also require a means to send the data collected back to Earth. This would require a powerful laser based communication system. As the spacecraft is already being propelled by lasers, this is a convenient option for the mission. Laser communications have a larger bandwidth than the tried-and-tested radio frequencies and can hence transmit larger volumes of scientific data. Much like fiber optics replacing old telephone wires, going from radio communications to laser communications will allow increased data rates up to 100 times the capacity of state-of-the-art radio systems currently used by spacecraft (73).

A laser base would be required to receive the data sent back by the probe, but this would not require any additional construction as a laser base would already be built to power the probe. Laser communications are currently undergoing rapid development, with theoretical technologies allowing for near light speed communication of images and data back to Earth. Simple, lightweight communication systems can easily send back data at 10 bps over 4.35 light years. More advanced systems can do this at rates of 100 bps over 4.35 light years (74). The data from the instruments used to measure the interstellar medium will be continuously sent back by the probe, however, the images of Proxima Centauri and its exoplanets will only be taken and sent back after the probe completes its flyby, thereby adding at least 4.35 years to the total mission, depending on how advanced the communication technology is.

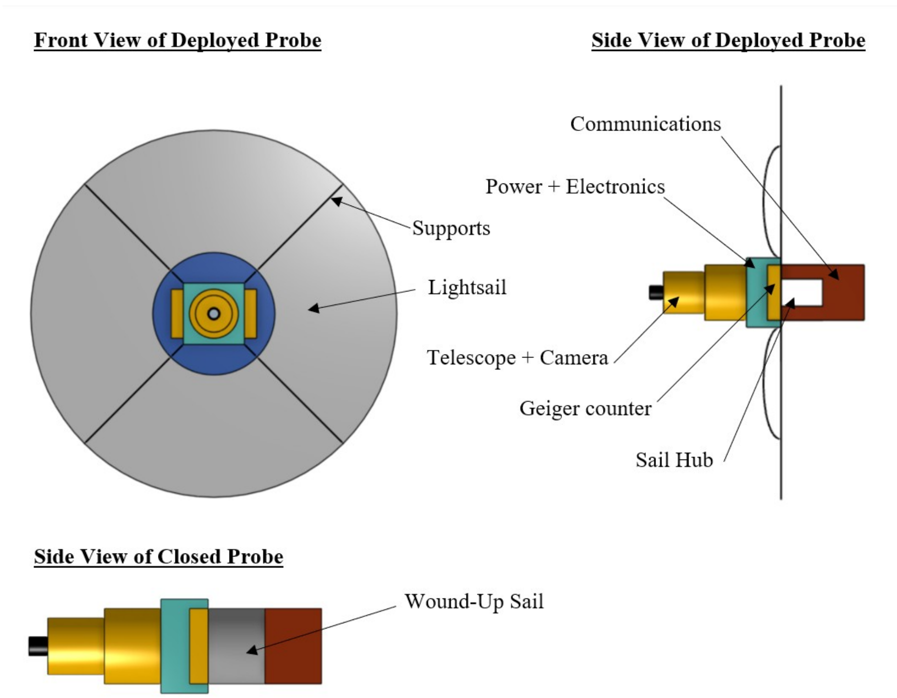

Figure 6: CAD Model
A basic CAD model of the outlined spacecraft, with front and side views. The sail hub is where the sail itself would be folded up for manufacturing and launch. The telescope and camera are the main instrumentation on the probe, with the Geiger counters simply on the side. Note that the sail diameter is not drawn to scale.

Deployment

The solar sail itself will have to be deployed in space, as it will be compactly folded prior to and during launch. In the case of a circular solar sail, the sail will have flexible radial spars to provide some stiffness in the sail disc during precession. These spars will have small bending loads and be wound around the central sail hub during the manufacturing process. The elastic energy stored in the spars would then drive the deployment, unfurling the sail film in the process. This passive deployment scheme is another advantage of using circular solar sails (75). Figure 6 shows an approximate CAD model of what the spacecraft would look like, before and after deployment.

Risks

Such a mission is not without risks. The main risk associated with this mission is the possibility of a collision with either a micrometeorite or a piece of orbital debris. As mentioned at the beginning of the paper, a collision with one of these objects can release energy equal to a small nuclear bomb, and hence a single collision has the potential to terminate a mission (13, 15). Unfortunately, the path such a spacecraft would take to get to Proxima Centauri has not been meticulously charted, and it is difficult to predict where potential groups of particles could be. However, the odds of colliding with a particle are still rather small (75).

Such particles also pose an issue when it comes to the laser base. As discussed previously, interstellar dust, orbital debris, or larger celestial objects may interfere with or obscure the laser beam, preventing the probe from receiving power (76). Again, the risk of this is rather minor and can largely be mitigated with the creation of a laser base that produces ~125% of the power required.

The interstellar plasma also needs consideration. The continued assault on the spacecraft by the protons and ions within the interstellar plasma has the potential to cause damage to the probe. Hence some sort of protective layer would need to be added, but this would then add mass, creating a rather fragile balance (75).

Conclusion

The concept of interstellar exploration is full of possibilities. Interstellar travel will allow us to learn more about exoplanets, the interstellar medium, and astrobiology. However interstellar travel has significant challenges associated with distance, time, and energy requirements. Our nearest exoplanet is over 4 light years away, which will take hundreds of thousands of years to reach using chemical rockets and require vast amounts of energy.

While interstellar travel may seem impossible with chemical rocketry, new and emerging propulsion technologies address many of these challenges. The three most relevant and promising propulsion technologies are ion engines, nuclear pulse propulsion, and light sails. Ion engines use beams of ions accelerated by electric fields as the propellant. Nuclear pulse propulsion involves regular nuclear explosions near the rear of the spacecraft to push it forward. Light sails harness the momentum of photons to accelerate a spacecraft.

Light sails are the most suitable for the task of interstellar travel because they have the greatest specific impulse and final velocity. A mission for interstellar travel could be accomplished using light sails for propulsion. Such a mission may be a spacecraft that would fly-by our nearest star Proxima Centauri within 50 years, taking images and readings along the way. The craft would be propelled using a circular solar sail composed of a graphene sandwich material, accelerated by light from a large laser base, likely placed on the Moon. The probe would have a total mass of 1000 kg, consisting of the sail itself, sail deployment mechanisms, with a payload of 200 kg. The payload would consist of the sail itself, its deployment mechanisms, communication equipment, auxillary power systems and basic instrumentation such as Geiger counters and a telescope equipped with an optical camera; among others.

With current technology and science, an interstellar probe could indeed be created. However, to make such a mission concept feasible, further research – and eventual execution - is needed on many topics such as continuous wave high wattage lasers, lunar base construction and habitat, energy harvesting, self propagating and self contained mechanisms, optical communication systems, interstellar dust mitigation, and orbital mechanics. As an example, orbital mechanics can be used to analyze the specific path of travel such a craft would take, to ensure that the probe does not encounter major obstacles, such as asteroids in the Oort cloud. The launch angle and launch window would need to be calculated to allow for the most ideal approach to the Proxima Centauri system, as the probe will need to get as close as it can to the exoplanets of the Proxima Centauri system to allow for the best imaging in the shortest mission time frame.

Numerous difficult; but not insurmountable; technology advances need to occur before interstellar exploration becomes feasible using the mission concept formulated in this paper. Interstellar exploration will; in turn; provide a foundation for future developments and get us one step closer to venturing beyond the stars.

Acknowledgments
I would like to acknowledge my mentor Ariana Bueno, University of Michigan, for helping me write and revise this paper.

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Appendix 1: Propulsion Technology Summary Table

Requirement	Ion Engines – Hall Thruster	Nuclear Pulse – External	Light sails – Laser Propelled
Velocity of at least 10% of the speed of light can be reached.	**No** The rate of acceleration is far too slow for such a probe to realize a speed of 0.1c.	**Yes** The maximum speed of a nuclear pulse engine is 0.08-0.1c, and with the proper engineering and subsystems, it could reach 0.1c.	**Yes** Depending on the mass of the payload, size of the sail, and power source, light sails can go up to 0.2c, easily making them the best candidate.
Specific impulse of over 400,000 seconds is attainable	**No** The maximum specific impulse for Hall Thrusters today is only 8,000 seconds. Even with significant advancements, a specific impulse of over 400,000 is unlikely to be achieved in the near future	**No** The maximum specific impulse for External Nuclear pulse engines is about 270,000 seconds, still too far from the necessary 400,000. Though with advancement the specific impulse may be much closer.	**Yes** Light sails technically have infinite specific impulses since they produce thrust with no use of (onboard) reaction mass

Technology has been experimentally tested.	**Yes** NASA has extensively used ion engine technology such as in the DAWN mission.	**No** Although there has been much theoretical work done on nuclear pulse engines, none have been created or tested due to bans on nuclear testing.	**Yes** Light sail technology has been used in the IKAROS spacecraft and laser driven light sails have been tested on a smaller scale as well.
Craft size and mass are appropriate for construction	**Yes** Ion engines are small enough to be of satisfactory size and mass for an interstellar voyage, and the and the particles needed to serve as fuel are of negligible mass, rendering it a suitable mass as well.	**No** With current nuclear technology, the reactors needed for such a craft are far too large and far too heavy for an interstellar probe. However, with advancements in nuclear technology, this constraint could be potentially met.	**Yes** Light sails spacecraft can be made in a variety of sizes and dimensions, from a sail just a few meters wide to kilometers wide. Plus, the sail may be opened in space, solving sizing issues for launch purposes.
Supplemental engineering of other structures is not required	**Yes** Ion engines do not need any supporting infrastructure to operate, apart from an initial launch vehicle. The probe itself contains all necessary parts.	**Yes** Nuclear pulse technology technically does not require supplemental engineering, however the engineering of the nuclear reaction chamber would likely require the creation of a new nuclear test facility	**No** An lightsail probe capable of completing an interstellar mission in a timely manner would require a large laser for energy, necessitating the creation of a laser base.
Technology is free of political constraints	**Yes** There are no political limitations on the creation and operation of ion engines	**No** The partial nuclear test ban treaty imposes an international ban on nuclear space technology	**Yes** There are no political limitations on the creation and operation of light sails
Associated risk is minimal	**No** The interstellar medium is full of unknowns, making an ion engine interstellar mission rather risky	**No** The interstellar medium is full of unknowns, making a nuclear pulse interstellar mission rather risky	**No** The interstellar medium is full of unknowns, making a light sail interstellar mission rather risky