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Comparison of Propulsion Systems to Reach Alpha Centauri

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ABSTRACT

Today, many different propulsion systems have been developed for use in space. However, chemical propulsion systems are not considered sufficient for interstellar missions due to their low specific impulse values, while ion propulsion systems are not considered sufficient due to their low thrust levels. Although fission and fusion-based photonic propulsion systems offer high efficiency and potential speed values, due to current technological limitations and the vastness of interstellar distances, it does not seem possible for even these systems to reduce the time required to reach the nearest stars, such as Alpha Centauri, to reasonable levels. This study aims to compare different propulsion systems for the Alpha Centauri mission through numerical modeling. Speed, acceleration, and arrival times were calculated for each system, and performance analyses were conducted based on the numerical results. According to the findings, even under ideal conditions, the fusion-based propulsion system, which showed the highest performance, was calculated to take 1674 years to reach Alpha Centauri. This value reveals that both this system and other existing propulsion types are inadequate for interstellar missions when compared to the lifespan of humans.

Alpha Centauri'ye Ulaşmak için İtki Sisteminin Karşılaştırılması

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ÖZET

Günümüzde uzayda kullanılmak üzere birçok farklı itki sistemi geliştirilmiştir. Ancak kimyasal itki sitemi düşük özgül itki değerleri nedeniyle, iyon itki sitemleri ise düşük itki seviyeleri nedeniyle yıldızlararası görevler için yeterli görülmemektedir. Fisyon ve füzyon odaklı fotonik itki sistemleri ise yüksek verimlilik ve potansiyel hız değerleri sunsa da günümüz teknolojik kısıtlamaları ve yıldızlararası mesafelerin büyüklüğü nedeniyle bu sistemlerin bile Alpha Centauri gibi en yakın yıldızlara ulaşım için gerekli süreleri makul seviyelere indirmesi mümkün gözükmemektedir. Bu çalışma, Alpha Centauri görevi özelinde farklı itki sistemlerinin nümerik modelleme yoluyla karşılaştırılmasını amaçlamaktadır. Her bir sistem için hız, ivme ve varış süreleri hesaplanmış ve sayısal sonuçlar üzerinden performans analizleri yapılmıştır. Elde edilen bulgulara göre, ideal kabul edilen koşullarda dâhi en yüksek performansı gösteren füzyon odaklı itki sisteminin Alpha Centauri'ye ulaşım süresi 1674 yıl olarak hesaplanmıştır. Bu değer, insanoğlunun yaşam süresi kıyaslandığında hem bu sistemin hem de diğer mevcut itki türlerinin yıldızlararası görevlerde yetersiz olduğunu ortaya koymaktadır.

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INTRODUCTION

One of the greatest scientific goals in human history is interstellar travel. Since the launch of Sputnik-1, the first satellite, in 1957, every advancement in space exploration has continuously expanded humanity's imagination and simultaneously facilitated new ways to make new discoveries. Through probes and satellites, humanity has obtained high-resolution images of galaxies, stars, and exoplanets in the deep unknowns of space beyond our solar system. These developments have contributed to increased interest in interstellar projects (Lubin, 2016). With these new technologies, images, and experiences, it is thought that there are more than 150 stars within 20 light-years of the Sun and that some of these stars may have planetary systems. It is thought that a significant portion of these stars could host planets with stable orbits in the habitable zone (Lubin, 2016). These findings encourage in-depth research into interstellar travel and lead to its positioning as a goal.

Many propulsion methods have been proposed for interstellar travel. Historically, chemical rockets have formed the basis of all major space missions (Crawford, 1990). However, the exponential increase in the mass of fuel required in chemical propulsion systems to achieve the target final velocity demonstrates that these methods cannot be used for interstellar missions (Lingam & Loeb, 2018). Modern electric propulsion systems show promise with their high specific impulse values and have been considered as an option for spacecraft transportation (Choueiri, 2004; Moloney et al., 2019). However, the low acceleration produced by this propulsion system makes it impractical for interstellar missions. The foundations of electric propulsion date back to Goddard's 1917 application and 1920 publication of his electrostatic ion thruster patent. Although ion thrusters are widely used in satellites today, their very low thrust levels are a disadvantage of these propulsion systems (Mazouffre, 2016).

These limitations have led researchers to explore higher-density energy sources. Continued interest in space exploration has driven humanity to investigate new and different propulsion systems. National Aeronautics and Space Administration (NASA) and the United States of America (U.S.) Department of Energy have collaborated on developing fission power technology to enable future space energy systems for scientific exploration (Mason et al., 2013). A more traditional energy fission-focused photonic propulsion system, using liquid metal-cooled reactors and dynamic energy conversion, is suitable for lunar and Martian surface power generation or nuclear electric propulsion (NEP) vehicles (Mason et al., 2013). However, while nuclear fission makes missions into the depths of space possible, it is still insufficient for missions over interstellar distances of approximately 4 light-years (Long, 2022). Fusion energy has become an energy source that attracts humanity because of its high-power density (Meschini et al., 2023). Today, research is being conducted on small-scale nuclear fusion reactor designs based on the Princeton Field Reverse Configuration (PFRC), one of the objectives of which is to enable the use of fusion energy in space (Galea et al., 2023). Therefore, alternative methods such as fusion and photonics-focused photonic propulsion with higher energy density have been explored for interstellar missions.

Although photonic propulsion systems powered by solar energy are promising, they are not practical for interstellar travel. Such systems have low energy density and are dependent on an energy source such as the Sun or a source that generates photon pressure. As distance from the Sun increases, the pressure decreases according to the inverse square law; for example, at 1 AU (Astronomical Unit), a very small pressure of approximately $9.12\ \left(\frac{N}{km^2}\right)$ is obtained for an ideal reflective surface. Since the Sun's effect will be lost at long distances during interstellar travel, such systems do not appear suitable for interstellar travel (Savelev & Shumeiko, 2025). The concept of combining photon propulsion with a high-energy-density fusion source independent of the Sun is considered a potential approach that, while not technologically feasible today, warrants future research. This system could enable us to take a significant step forward in interstellar travel.

Within the scope of this study, the propulsion systems have been examined. The structures, speeds, accelerations, and arrival times of these propulsion systems to Alpha Centauri have been investigated. As a result of the numerical models created, the performance of these systems in the travel plan to Alpha Centauri has been examined and their suitability has been compared.

In this study, propulsion technologies that are currently available and those anticipated to be used in the future have been examined within the same framework under optimistic assumptions, unlike the approaches that are generally addressed separately in the literature; the feasibility of these technologies for interstellar travel has been comparatively evaluated. In light of the obtained data, it is discussed why quantum-based approaches previously addressed theoretically in the literature, as well as similar novel ideas, should be reconsidered for future interstellar missions.

First Level Subheading

First level subheadings should be capitalized, bold, in Times New Roman font and 11-point font size. A 12k space should be defined before headings. Headings and paragraphs should start with a 1cm indent. Line spacing should be 1.15k. There should be a 6k space above each paragraph. You can do these operations using the line spacing menu.

PROPULSION SYSTEMS

Today, many different propulsion systems have been developed for use in space missions. Advances in this field have led to the development of more efficient motor designs that produce higher thrust and perform better under operating conditions. Therefore, different propulsion systems and different design approaches have been considered, and efforts have been made to develop propulsion systems. This study will present general information on four different propulsion systems and evaluate these systems based on performance parameters such as efficiency, speed, acceleration, and distance traveled.

Chemical Propulsion Systems

Chemical propulsion systems are systems that convert the energy released by the combustion reaction of fuel and oxidizer into a high-temperature gas flow, ejecting it at high speed through a nozzle to generate thrust. The working principle is based on Newton's third law; the expulsion of exhaust gases causes the engine to produce a reaction force in the opposite direction. The performance of this propulsion system is mostly characterized by specific impulse (I_{sp}). Specific impulse is a fundamental performance metric that indicates how long propulsion can be generated per unit mass of fuel and is directly dependent on exhaust velocity. In chemical propulsion systems, I_{sp} typically ranges from 200 to 468 s (Sutton & Biblarz, 2011); these values are quite low compared to the high exhaust velocities required for interstellar missions.

The total thrust produced in a chemical rocket engine is given as:

$$F = \dot{m} v_e + (p_e + p_a) A_e \tag{1}$$

where $\dot{m}$ is the fuel mass flow rate, v_e is the exit velocity of the gases, p_e is the exit pressure, p_a is the ambient pressure, and A_e is the nozzle area at the exit (Sutton & Biblarz, 2011). The exhaust velocity is related to the specific impulse is:

$$v_e = I_{sp} g_0 \tag{2}$$

where I_{sp} is the specific impulse, and g_0 is the gravitational constant.

Therefore, the physical limits of the exhaust velocity in a chemical propulsion system are approximately 2-3.45 $\left(\frac{km}{s}\right)$ (Sutton & Biblarz, 2011). These velocities are insufficient for interstellar missions, making chemical propulsion systems impractical for missions targeting destinations such as Alpha Centauri. In equation 2 used for v_e the value I_{sp} represents the specific impulse and g_0 represents the gravitational acceleration.

Ion Propulsion Systems

Ion propulsion systems are the most efficient systems compared to other propulsion systems (chemical, etc.) (ranging from 60% to 80%) and have very high specific impulse (I_{sp}) values (Goebel & Katz, 2008). Ion propulsion systems operate by ionizing the fuel. High-speed electrons emitted by the cathode collide with neutral fuel atoms, initiating ionization, and ionized fuel and free electrons are formed in the plasma chamber. The resulting ions are accelerated to high speeds by grids that apply an electrostatic field and are ejected.

Electrons are supplied by a neutralizer cathode placed at the engine outlet to prevent positively charged ions separated from the exhaust from disrupting the vehicle's electrical charge balance. These electrons neutralize the ions, ensuring that the engine and spacecraft remain electrically balanced. This process enables thrust to be provided directly through high-speed ions; since energy losses are low, the specific thrust is very high. Therefore, the ion propulsion system is ideal for long-duration, low-mass consumption deep space missions.

The efficiency of the propulsion system, η, is defined by equation 3 as the ratio of the kinetic energy generated by the exhaust gas to the total electrical power applied to the propulsion system (Sutton & Biblarz, 2011):

$$\eta = \frac{\frac{1}{2}\dot{m}v_e^2}{\sum IV} \tag{3}$$

where $\dot{m}$ is flow rate $\left(\frac{kg}{s}\right)$, v_e is exit velocity $\left(\frac{m}{s}\right)$, I is ion current (A), V is acceleration voltage (V).

The equation 4 gives the exit velocity of ions after they are separated from the plasma. The exhaust velocity directly determines the thrust and specific impulse produced by the engine.

$$v_e = \sqrt{\frac{2eV}{\mu}} \tag{4}$$

where e is the electron charge(C), V accelerating voltage(V), μ is the ion mass (kg).

The equation (5) allows the separation rate of ionized fuel from the plasma and the ion current produced by the engine to be calculated. Ion current is a fundamental quantity for both thrust and power calculations.

$$I = \dot{m}\left(\frac{e}{\mu}\right) \tag{5}$$

The equation (6) shows how efficiently the ion engine converts fuel into thrust. If the exhaust velocity is high, I_{sp} is also high; this indicates that the engine is suitable for long-duration deep space missions:

$$I_{sp} = \frac{v_e}{g_0} \tag{6}$$

where g_0 is the gravitational constant.

When the ion current and exit velocity is known, the thrust produced by the motor can be calculated directly. This allows for the evaluation of motor performance during the simulation and design stages.

$$F = \dot{m}v_e = I\sqrt{\frac{2\mu V}{e}} \tag{7}$$

The force was calculated using the following simplified formula:

$$F = \frac{2\eta P}{v_e} \tag{8}$$

In this paper, NASA's NEXT ion engine data is used in that the I_{sp}, η and P (W) values are $4190\ s,\ 0.71,\ 6.9\ kW$ respectively (Herman et al., 2007).

Fission-Driven Photonic Propulsion

A comprehensive overview of photonic laser propulsion reveals that the search for non-rocket propulsion solutions continues, driven by the decades-long challenge of overcoming the limitations of traditional propulsion systems. Among these conceptual pioneers, photonic laser propulsion stands out as a promising light in the search for innovative propulsion methods (Bae, 2025). Photonic laser propulsion has brought about a profound change by providing propulsive force to spacecraft via a circulating laser beam generated from a power station (Bae, 2025).

In such propulsion systems, thrust is derived from the momentum of photons. Light is emitted through a laser, providing thrust to the spacecraft. These propulsion systems operate without expelling gas from the spacecraft. Non-propellant systems generate thrust through the propagation or reflection of light (Levchenko et al., 2018). This also means that in propellant-free systems, the primary mechanism for generating thrust is the momentum exchange between photons and the spacecraft's components. Internal (i.e., nuclear reaction-based) or external (i.e., lasers mounted on another spacecraft or on the surface of the Moon or Earth) power sources can be used to generate light energy and create thrust (Levchenko et al., 2018). The magnitude of thrust depends on the power of the laser used and is fundamentally defined by the following equation:

$$F = \frac{P}{c} = \frac{Nhf}{c} \tag{9}$$

where F is the photon momentum (photon beam) (N), N is the photon number beam $\left(\frac{1}{s}\right)$, h is Planck's constant (Js), f is the photon frequency (Hz), P is the laser power (W), and c is the speed of light $\left(\frac{m}{s}\right)$.

If the surface is perfectly reflective, the magnitude of the thrust doubles because the momentum transfer doubles.

$$F = \frac{2P}{c} \tag{10}$$

In equality (10) express the doubling of power is due to both the absorption and reflection of light. However, for this system to work, an external laser source that provides total reflection and suitable optical surfaces are required.

In a photon engine, the value of I_{sp} is expressed as follows:

$$I_{sp} = \frac{F}{g\dot{m}} \tag{11}$$

where $\dot{m}$ flow rate $\left(\frac{kg}{s}\right)$ and g $\left(\frac{m}{s^2}\right)$ is the gravitational constant.

In fission reactions, the incoming neutron enters the heavy target nucleus and excites the nucleus to such a high energy level ($E_{exc} > E_{crit}$) that the nucleus splits into two large fragments and several neutrons (fission occurs). The recoverable energy per fission is assumed to be approximately 200 MeV. In the absence of more precise data, this value is normally used at least in preliminary calculations (Lamarsh & Melkonian, 1977).

$${}_0^1n + {}_{92}^{235}U \rightarrow ({}_{92}^{235}U)^* \rightarrow {}_{55}^{140}Cs + {}_{37}^{93}Rb + 3({}_0^1n) \tag{12}$$

Finally, a large amount of energy, radiation, and particles are released. To find the energy released per kilogram, the following steps are followed ($1eV = 1.602 \times 10^{-19}j$, $200\ MeV = 3.204 \times 10^{11}J$).

To find the energy per kilogram, follow these steps:

$$N = \frac{1kg}{M_U} N_A = \frac{1kg}{235 \cdot 10^{-3} \frac{kg}{mol}} * 6.022 \cdot 10^{23} mol^{-1} = 2.5626 \cdot 10^{24} \tag{13}$$

$$E_{kg} = N * 200\ MeV = 2.5626 \cdot 10^{24} * 3.204 \cdot 10^{-11} J = 8.21 \cdot 10^{13} \frac{J}{kg} \tag{14}$$

$$P = \dot{m}E_{kg} = 1 \cdot 10^{-6} \left(\frac{kg}{s}\right) * 8.21 \cdot 10^{13} \frac{J}{kg} = 8.21 \cdot 10^{7}\ W \tag{15}$$

where N is the total number of atoms in 1 kg, N_A Avagadro number, M_U is the molar mass of uranium and P is the power.

In the subsequent sections of the article, it is assumed that the satellite has a fission-based power source, and that this power source has a fuel consumption rate of $\dot{m} = 1 \cdot 10^{-6} \left(\frac{kg}{s}\right)$, it was found that it produced a laser power of magnitude $P = 8.21 \cdot 10^{7}\ (W)$ using the above formulas, and it was assumed that the energy produced for this laser power was converted to laser energy with 100% efficiency.

Fusion-Driven Photonic Propulsion

In the previous section, the photonic laser propulsion system was explained, and its basic principles were presented. In this section, the same photonic propulsion mechanisms are retained, but only the power source, a fusion-based energy production system, will be discussed. The photonic propulsion equations (9-11) will remain valid since the system is the same; however, the system's performance will differ accordingly because the power levels produced by the fission reactor will be much higher.

A deuterium-tritium fusion is as follows: (Kikuchi, 2002). ($E_{rxn} = 17.6\ MeV = 2.8198 \cdot 10^{-12}\ J$)

$$D + T \rightarrow He\ (3.5\ MeV) + n\ (14.1\ MeV) \tag{16}$$

The total mass per fuel unit $(D + T)$ is approximately $5u$ (atomic mass units), where $1\,u = 1.66054 \times 10^{-27}$.

$$m_{rxn} = 5u = 5 * 1.66054 \cdot 10^{-27}\,kg \tag{17}$$

$$E_{per\;kg} = \frac{E_{rxn}}{m_{xrn}} = \frac{2.8198 \cdot 10^{-12}\,J}{5 * 1.66054 \cdot 10^{-27}\,kg} = 3.396 \cdot 10^{14}\,\frac{J}{kg} \tag{18}$$

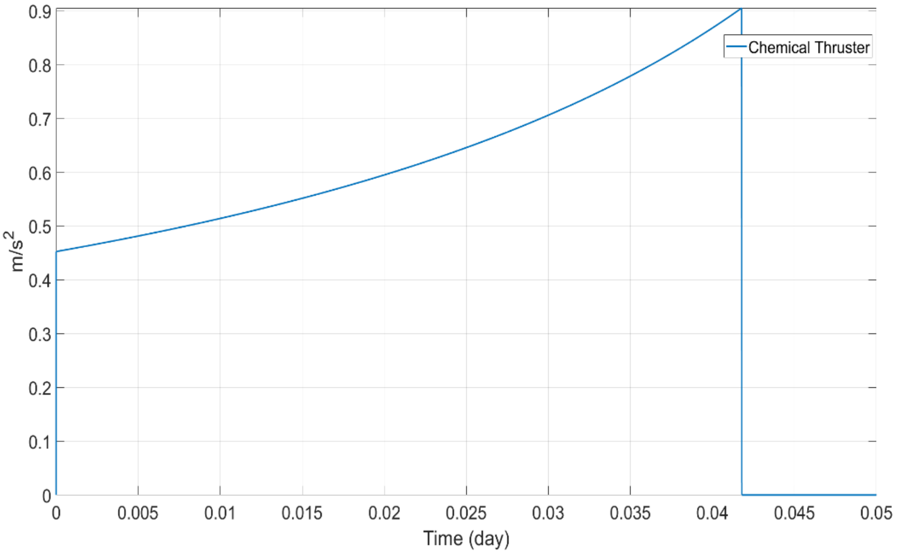
$$P = \dot{m}E_{per\;kg} = 1.0 * 10^{-6}(\frac{kg}{s}) * 3.396 \cdot 10^{14}\left(\frac{j}{kg}\right) = 3.396 \cdot 10^{8}\,W \tag{19}$$

In the later sections of the article, it is assumed that the satellite contains a fusion-based power source, and that this power source, with a fuel consumption rate of $\dot{m} = 1 \times 10^{-6}\,\frac{kg}{s}$, generates a laser power of $P = 3.396 \times 10^{8}\,W$, calculated using the formulas above. It is also assumed that the energy produced for this laser power is converted into laser energy with 100% efficiency.

The fundamental propulsion equations provided in the literature for chemical, ion, and photonic propulsion systems were used in the modeling. The propulsion force, specific impulse, and fuel consumption of each system were calculated using a time-stepped numerical solution method.

Figure 1

Acceleration Graphic of a Spacecraft Propelled by a Chemical Thruster



RESULTS

This section presents velocity, acceleration, and distance profiles obtained from modeling studies conducted using numerical solutions for different propulsion systems. These data are evaluated comparatively in terms of the Alpha Centauri mission. For a fair comparison, the total mass of the spacecraft excluding fuel is assumed to be 1000 kg for all four propulsion tests, and the total fuel is assumed to be 1000 kg. Therefore, the mass of the spacecraft is 2000 kg when it first takes off, and its mass decreases over time until it reaches 1000 kg.

As shown in Figure 1, chemical propulsion systems have very short acceleration times despite their high acceleration values. Besides, they have very low I_{sp} values. Chemically propelled spacecraft consume their total fuel load of 1000 kg in 0.044 days. Therefore, despite the high acceleration in Figure 1 and the high initial velocity in Figure 2, they cannot be used for interstellar space travel due to their low specific thrust and the fuel and mass limitations in space travel.

Figure 1

Acceleration Graphic of a Spacecraft Propelled by a Chemical Thruster

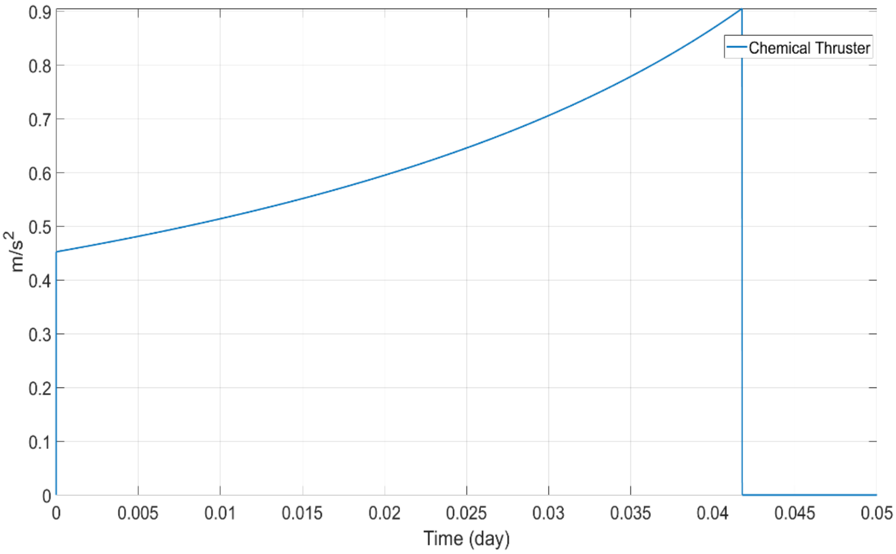
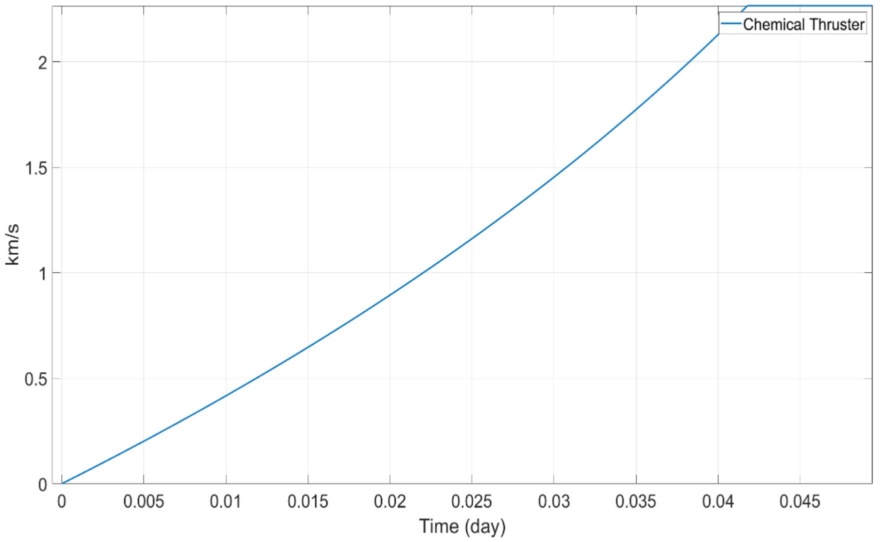


Figure 2

Velocity Graphic of a Spacecraft Propelled by a Chemical Thruster

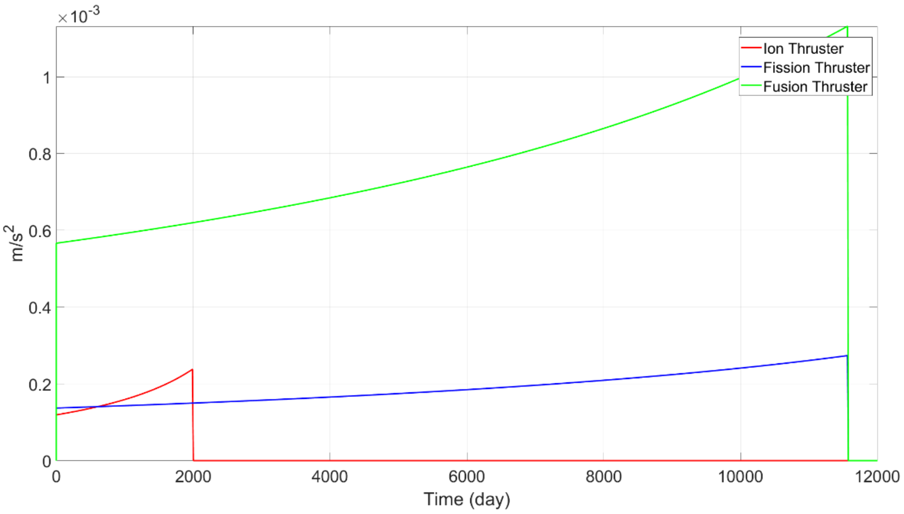


As shown in Figure 1, The acceleration curve exhibits a sharp initial peak corresponding to the high thrust produced during ignition. As the propellant mass rapidly decreases, the total mass of the spacecraft also decreases, causing a slight increase in instantaneous acceleration during the combustion phase. However, since the entire 1000 kg of fuel is consumed in only a very short period of time, the thrust phase ends abruptly, and acceleration drops to zero immediately after the fuel is exhausted.

As shown in Figure 2, Due to the high initial acceleration, the velocity profile increases rapidly during the short combustion period. When the fuel is exhausted, the velocity reaches its maximum value and remains constant. Although the slope of the velocity curve is steep at the beginning, the limited combustion period significantly reduces the total velocity gain.

Figure 3

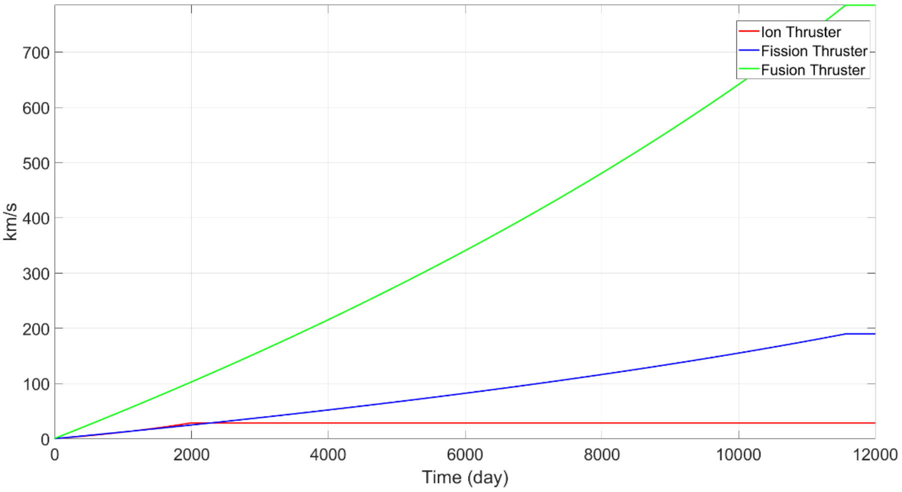
Acceleration Graphic of a Spacecraft Propelled by an Ion, Fission and Fusion Thrusters



As shown in Figure 3, Acceleration curves show significant differences between propulsion types. The ion and fission propulsion systems maintain low acceleration levels. The ion propulsion system depletes quickly due to mass loss, while the fission propulsion system has a longer acceleration duration. In contrast, the fusion-based photonic system produces significantly higher acceleration values.

Figure 4

Velocity Graphic of a Spacecraft Propelled by an Ion, Fission and Fusion Thrusters



As shown in Figure 4, Speed-time curves further highlight long-term performance differences. The ion propulsion system shows a continuous increase in speed over thousands of days. Meanwhile, the fission-based photonic system has a steeper velocity curve than the ion propulsion system due to its higher acceleration level and fuel consumption time. The fusion-based photonic propulsion system exhibits the steepest velocity increase due to its higher power output per unit mass. Over time, the difference between the curves becomes increasingly apparent.

A comparative analysis of the velocity-time and acceleration-time graphs obtained Figure 1 and Figure 2 have been omitted and shown separately in order to maintain meaningfulness in the graphs, due to the very low level of chemical fuel compared to other fuels. Ion, fission-based photonic, and fusion-based photonic propulsion systems graph is presented. All propulsion systems were modeled using a common time scale generated by numerical analysis under the same mission profile. This allows for fair comparison of their performance for the Alpha Centauri mission.

As shown in Figure 3, the ion thruster consumes all its fuel in 1994 days. During this period, it produces a thrust force of $0.2385\ (N)$. For this reason, the acceleration, which was $1.19 \cdot 10^{-4} \left(\frac{m}{s^2}\right)$ at the start of the journey, increased over time to $2.38 \cdot 10^{-4} \left(\frac{m}{s^2}\right)$ due to the decrease in mass. So, as shown in Figure 4, its velocity increased to $28.58\ \left(\frac{m}{s}\right)$ until the fuel was depleted, and it continued its journey at this constant velocity.

The fission-based photonic propulsion system produced much higher thrust than the ion propulsion systems and shifted the velocity curve upward at a steeper angle as seen in Figure 4. The main reason for this is the direct reflection of the high-power output provided by the reactor on the laser propulsion performance. However, the total laser power that the system can produce is still limited compared to the fusion-based model. The main reason for this is that fusion energy releases much higher energy than fission energy.

The fusion-based photonic propulsion system has demonstrated the highest performance metrics compared to the three models as seen in Figure 3 and Figure 4. In the graph, this curve clearly stands out from other propulsion systems, showing the highest acceleration value and acceleration characteristic. This makes this propulsion system the most viable propulsion system among other propulsion systems for interstellar missions.

Table 1
Performances of Thrusters

Typesof Propulsion Systems	$\dot{\mathrm{m}} \left(\frac{\boldsymbol{kg}}{\boldsymbol{s}}\right)$	$\boldsymbol{V}_{\mathbf{max}} \left(\frac{\mathbf{km}}{\boldsymbol{s}}\right)$	Fuel Depletion Time(day)	Reaching Time (year)
Chemical Thruster	0.277	2.265	0.042	575266
Ion Thruster	$1.33 \cdot 10^{-4}$	28.584	1994	45486
Fission Thruster	$1.0 \cdot 10^{-6}$	189.754	11574	6869
Fusion Thruster	$1.0 \cdot 10^{-6}$	784.903	11574	1674

As shown in Table 1, chemical propulsion systems have the lowest maximum speed despite their high fuel consumption. This is because the fuel is depleted in a very short time. For this reason, the acceleration time is very short, and the spacecraft cannot reach very high speeds. Compared to other propulsion systems, the chemical thruster is the system that takes the longest time to reach Alpha Centauri.

Ion propulsion systems consume fuel much more slowly than chemical fuels and, thanks to their high I_{sp} values, can reach much higher speeds than chemical systems. This is because the fuel depletion time is longer, resulting in a longer acceleration time.

Fission-based photonic propulsion has demonstrated much more successful performance compared to chemical and ion thrusters. The high speeds it achieves have resulted in significant time savings for reaching Alpha Centauri. This is due to the magnitude of energy obtained from fission. The fission-powered photonic propulsion system achieved 9580 days more acceleration time than ion propulsion in the Alpha Centauri mission. This is because it consumes significantly less fuel than ion propulsion systems. Fission-based propulsion systems, reaching high speeds of $189.75\ \frac{km}{s}$, achieved a much better arrival time of 6869 days compared to ion propulsion in the Alpha Centauri mission.

As shown in Table 1, the fusion-based photonic propulsion system is the system that delivers the highest performance for reaching Alpha Centauri. Despite consuming the same amount of fuel per unit time, it has achieved much higher speeds compared to the fission-based photonic propulsion system and has significantly reduced the arrival time. The main reason for this is that fusion reactions release much more energy from the same fuel mass than fission. This high energy density has enabled the fusion-based photonic propulsion system to reach a speed of approximately $784.9\ \frac{km}{s}$. Therefore, the fusion-based photonic propulsion system stands out as the most effective option for interstellar travel compared to fission-based photonic propulsion, ion propulsion, and chemical propulsion systems.

CONCLUSION

In this study, propulsion technologies that are currently available and those anticipated to be used in the future have been examined within the same framework under optimistic assumptions, unlike the approaches that are generally addressed separately in the literature; the feasibility of these technologies for interstellar travel has been comparatively evaluated.

Under ideal mission conditions, the estimated travel time to reach Alpha Centauri would be approximately 575000 years using chemical propulsion, approximately 45000 years using ion propulsion, approximately 7000 years using nuclear fission propulsion, and approximately 1700 years using nuclear fusion propulsion.

The time required for the propulsion systems examined to reach Alpha Centauri for an interstellar mission is far too long to fall within a human lifetime. Even fusion-based photonic propulsion, which is currently under development and has the highest theoretical potential among the propulsion systems discussed in this paper, cannot provide sufficient efficiency for practical interstellar travel. These results demonstrate that current technology is not yet adequate for interstellar missions and therefore highlight the necessity of developing next-generation propulsion concepts that go beyond traditional propulsion systems.

In this context, quantum mechanics–based propulsion systems are included in the literature as conceptual approaches that aim to generate thrust through phenomena such as quantum vacuum fluctuations, the Casimir effect, and dynamic vacuum–field interactions. These concepts are noteworthy in that they address vacuum energy density and field effects within a framework different from classical systems.

Although such quantum-based propulsion systems currently involve significant uncertainties in terms of experimental validation, energy efficiency, and engineering feasibility, considering the limitations of existing propulsion technologies, they may be regarded as a potential field of future research for long-term deep space missions.

Consequently, researching innovative propulsion technologies for future interstellar missions is critical. So, revolutionary ideas such as quantum propulsion systems and antimatter systems are needed. As future work, it is planned to investigate generating thrust using quantum mechanics.

Ethical Committee Approval

No human or animal subjects requiring ethical committee approval were used in this study. The research was conducted using publicly available data sets, literature reviews, or theoretical analyses. In accordance with ethical rules, full compliance with academic honesty and scientific ethical principles was maintained at every stage of the research process. Therefore, ethical committee approval was not required.

Author Contributions

Research Design (CRediT 1) Muhammet Enes ŞAHİN (50%) –Muhammet ÖZTÜRK (50%)

Data Collection (CRediT 2) Muhammet Enes ŞAHİN (50%) –Muhammet ÖZTÜRK (50%)

Research - Data Analysis - Validation (CRediT 3-4-6-11) Muhammet Enes ŞAHİN (50%) – Muhammet ÖZTÜRK (50%)

Writing of the Article (CRediT 12-13) Muhammet Enes ŞAHİN (50%) –Muhammet ÖZTÜRK (50%)

Text Revision and Improvement (CRediT 14) Muhammet Enes ŞAHİN (50%) –Muhammet ÖZTÜRK (50%)

Conflict of Interest

There is no conflict of interest

Sustainable Development Goals (SDG)

Sustainable Development Goals: 9 Industry, innovation and infrastructure

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