Fuel Effective Photonic Propulsion

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Abstract: With the entry of miniaturization in electronics and ultra-small light-weight materials, energy efficient propulsion techniques for space travel can soon be possible. We need to go for such high speeds so that the generation’s time long interstellar missions can be done in incredibly short time. Also renewable energy like sunlight, nuclear energy can be used for propulsion instead of fuel. These propulsion techniques are being worked on currently. The recently proposed photon propulsion concepts are reviewed, that utilize momentum of photons generated by sunlight or onboard photon generators, such as blackbody radiation or lasers, powered by nuclear or solar power. With the understanding of nuclear photonic propulsion, in this paper, a rough estimate of nuclear fuel required to achieve the escape velocity of Earth is done. An overview of the IKAROS space mission for interplanetary travel by JAXA, that was successful in demonstrating that photonic propulsion works and also generated additional solar power on board, is provided; which can be used as a case study. An extension of this idea for interstellar travel, termed as ‘Star Shot’, aims to send a nanocraft to an exoplanet in the nearest star system, which could be potentially habitable. A brief overview of the idea is presented.

1. Introduction
Mankind has always wanted to go beyond the solar system on an interstellar travel. But the nearest stars to the Sun (Alpha Centauri) are located 4.4 light years away. Using conventional spacecrafts, reaching the interstellar systems would not be possible even in a generation’s time. This is because of the slow speeds of our crafts. So, the speed of the craft needs to be increased. According to Dr. Robert Frisbee of NASA's Jet Propulsion Laboratory, the fuel takes up almost 2/3rd of the craft’s mass and is stopping us from reaching higher speeds. If we can find other alternatives for fuel, science fiction levels of speeds can be attained. Utilization of the energy of light (Photonic propulsion) strangely proposes a good solution as it allows very little or no fuel to be carried along with the spacecraft. Photons do not have mass, but they have energy and momentum. When they get reflected off an object, that momentum is transferred into a little push (thrust). The thrust depends only on power and not wavelength. Clearly, these spacecrafts needs to be very small in size and cannot be used for manned missions.

2. Motivation
The present near-earth space endeavors are limited fundamentally by the following factors [1]: (1) Extremely high construction/operation cost, (2) Fuel limited mission lifetime and operation capability, (3) High environmental impact.
How important is that this problem is addressed? Mankind is one step ahead of exploring potentially habitable planets in the universe. If this problem is overcome, interstellar travel can be possible in unimaginable less time and open new gateways for space exploration.

3. Sunlight for photonic propulsion

This fuel-independent technique utilizes momentum of sunlight that has the greatest specific impulse. Specific impulse is a measure of the efficiency of rocket and jet engines. Here, since the output has no (rest) mass and is not expended fuel; if we take the momentum per inertia of the photons, the specific impulse is just the speed of light. The spacecraft that incorporates this kind of propulsion is called solar sail. The sail is made up of or coated with highly reflective material, like aluminium. The coating is made over plastic medium for mechanical support.

Figure 1. Force on sail due to photon repulsion

3.1. Sail parameters [2],[3]:

- Sail loading $\sigma$ is the areal density: $\sigma = \frac{\text{mass of sail}}{\text{sail area}}$ (2)
- Characteristic acceleration $a_c$ is related to $\sigma$ as $a_c = \frac{\text{efficiency}}{\sigma}$ (3)
- Lightness number $\lambda$ relates the craft’s maximum acceleration and the Sun’s local acceleration due to gravity ($5.93 \text{ms}^{-2}$).

$$\lambda = \frac{\text{maximum acceleration of craft}}{5.93}$$ (4)

There are different types of solar sails based on their structure and appearance whose sail parameters are given in the Table 1.

| Type               | $\sigma (g/m^2)$ | $a_c (\text{mm/s}^2)$ | $\lambda$ |
|--------------------|------------------|------------------------|-----------|
| Square sail [4]    | 5.27             | 1.56                   | 0.26      |
| Helio-gyro [5]     | 18.3             | 0.5                    | 0.03      |

4. Laser For Photonic Propulsion

The LASER Photonic Propulsion uses direct momentum transfer of photons generated by LASER source. These LASER sources can be Earth-based, placed in space or on board generated using solar or nuclear power. The craft is first suspended in space using a rocket, and then a powerful LASER beam is directed at it from the Earth to propel it forward. It requires beaming of laser photons over astronomical distances to the craft, amplification using two highly reflective mirrors [6], and reflection that pushes the craft. “Fig. 2” shows the schematic of LASER propulsion.

4.1. Challenges and overcoming:
• **It needs ultra-large, thin space optics[7]:**
  A new emerging technology to fabricate ultra large adaptive space mirrors using the Photonic Muscle has been proposed [8] that allows shaping to smaller sizes.

• **High powered LASER:**
  The LASER power required for an interstellar mission could be reduced from 64GW to **448 MW** by the use of a dielectric sail [9] with high emissivity and low absorption.

• **Large thrust:**
  Using Photonic Laser Thrusters (PLT), Direct energy (DE) can be used for momentum beaming [2]. Optical resonator can be used for LASER propulsion [10]. Thin Disk Laser can produce PLT thrust of 5mN [11].

The idea of ‘Starwisp’ proposed by Robert.L.Forward aims at using MASER placed on the Moon[12] that will guide a spacecraft weighing only a few kilograms [13].

![Figure 2. LASER Propelled Light Schematic](image)

### 5. Nuclear Photonic Propulsion

Nuclear energy is converted into blackbody radiation that is similar to photons (EM-waves) that can be used for propulsion. Such a craft is nuclear photonic rocket. Since it requires some amount of fuel to be taken along with the craft to produce power for thrusting, this method fuel-dependent [14].

#### 5.1. **Power requirement calculation**

The power per thrust required for a perfectly collimated output beam is 300 MW/N (1N of thrust requires 300 MW of energy [15].)

**Example to compute T/W value:**

The Russian-made RD-180 rocket engine produces 3,820 kN of sea-level thrust and has a dry mass of 5,307 kg. Using the Earth acceleration due to gravity of 9.807 m/s², the sea-level thrust-to-weight ratio is computed as follows [16]:

\[
\frac{T}{W} = \frac{3820 \text{ kN}}{5307 \text{ kg} \times 9.807 \text{ m/s}^2} = 73.40.
\]

This value for jet and rocket engines vary from 1.8 to 180 that are used for propelling rockets. For the aircraft having least T/W ratio (RD-0410 nuclear rocket engine), it requires 35.2 kN of thrust for mass of 2000 kg. For photonic sails, the weight is only in grams or a few kilograms, say 5 kg. This requires: \(\frac{35.2 \text{ kN} \times 5 \text{ kg}}{2000 \text{ kg}} = 88 \text{ N of thrust, that would be provided by:} \)

\[
\frac{300 \text{ MW} \times 88 \text{ N}}{1 \text{ N}} = 26400 \text{ MW} = 26.4 \text{ GW of power.}
\]

#### 5.2. **Fuel requirement calculation**

| Symbol | Description |
|--------|-------------|
| \(E_{ph}\) | Photon energy available for propulsion |
| \(M\) | Mass of rocket |
| \(\alpha\) | Mass ratio of fuel to rocket (\(\alpha < 1\)) |
| \(c\) | Speed of light |
| \(\delta\) | Propulsion system energy to photon energy conversion efficiency (\(\delta < 1\)) |
| \(\gamma\) | Fuel mass to propulsion system energy conversion efficiency |
| \(T_{ph}\) | Total photon thrust |
| \(V_{max}\) | Maximum attainable velocity |
Here, $\alpha M$ the total mass of the fuel. Considering the above notations, \[7\]
\[E_{ph} = \frac{M c^2}{\alpha \delta \gamma}\]  
\[T_{ph} = \frac{E_{ph}}{M}\]  
\[V_{max} \approx \frac{f_{ph}}{M} = \alpha \delta \gamma c\]  
We know that $T_{ph}$ is 88N and mass is approximately 5kg.

So, $V_{max} \approx \frac{T_{ph}}{M} = \frac{88}{59.8} = 1.79 \text{ m/s}$  
\[E_{ph} = T_{ph} c = 88 \times 3 \times 10^9 = 2.64 \times 10^{10} = 26400 \text{ MJ}\]  
Assuming 10% of fuel is effectively converted into propulsion energy, $\gamma = \frac{10}{100} = 0.1$;
\[\alpha = \frac{E_{ph}}{M c^2 \gamma} = \frac{26400 \text{ MJ}}{59.8 \times 9.8 \times g \times (3 \times 10^8)^2 m/s \times 0.1 \times 0.1} = 1.197 \times 10^{-7}\]  
(for $\delta = 0.5$) (using eqn.5)
Thus, $1.197 \times 10^{-7} \times 5 \times 9.8 = 5.86 \times 10^{-3} \text{ g of fuel is required.}$

5.3. Comparison with conventional propulsion

It requires 35.2 kN of thrust for mass of 2000 kg for conventional rockets. That would be provided by:
\[\frac{300 \text{ MW}}{35200 \text{ N}} = 10500 \text{ GW} = 10.5 \text{ TW of power.}\]
\[V_{max} \approx \frac{T_{ph}}{M} = \frac{35200}{2000 \times 9.8} = 1.79 \text{ m/s}\]  
\[E_{ph} = T_{ph} c = 35200 \times 3 \times 10^9 = 105.6 \times 10^{11} \text{ J}\]  
Assuming 10% of fuel is effectively converted into propulsion energy, $\gamma = \frac{10}{100} = 0.1$
\[\alpha = \frac{E_{ph}}{M c^2 \gamma} = \frac{105.6 \times 10^{11}}{2000 \times 9.8 \times g \times (3 \times 10^8)^2 m/s \times 0.1 \times 0.1} = 1.197 \times 10^{-7}\]  
(for $\delta = 0.5$) (using eqn.5)
Thus, $1.197 \times 10^{-7} \times 2000 \times 9.8 = 2.34 \times 10^{-3} \text{ kg = 2.34g of fuel is required.}$

5.4. Results:

It is seen that the fuel requirement for nuclear photonic propulsion is lesser than that of conventional methods. **Weight of fuel saved is 2.33414 grams.**

A broad comparison between the conventional and photonic propulsion techniques is given in Table.2.

| Table 2. Comparison of conventional and photonic propulsion |
|------------------------------------------------------------|
| **Conventional propulsion** | **Photonic propulsion** |
| 1. Fuel takes most of the craft weight | 1. Can be completely fuel-independent. |
| 2. For manned missions. | 2. For unmanned missions. |
| 3. 3% of the speed of light can be achieved. | 3. 10-30% of that of light can be achieved. |
| 4. Interstellar missions are impossible within a generation’s time. | 4. Interstellar missions are possible within a generation’s time. |
| 5. Uses non-renewable sources of energy. | 5. Uses renewable sources of energy. |

6. **IKAROS Mission Overview**

The IKAROS (Interplanetary Kite craft Accelerated by Radiation Of Sun) is a Japanese spacecraft, deployed on May 21st, 2010. It is the first spacecraft to successfully demonstrate solar sail technology as the main propulsion. It currently explores interplanetary space in orbit between Venus and Earth. It successfully completed following missions [17]: deploying a large membrane sail, generating electricity by thin film solar cells, check if photon propulsion works.

6.1. **Sail Layout**

- **Membrane:** The membrane is square shaped whose diagonal distance is 20cm made of polyimide.
• **Thin film solar cell**: Si solar cells attached to some areas of the membrane generate almost 500W.
• **Steering device**: Placed at the tips of the membrane, they can be used to control the spin direction.
• **Dust counter**: PVDF film is attached for dust counter.
• **Tip mass**: Four small masses (0.5 kg) attached to the tips of the membrane to adjust its centrifugal force. [18]
• **Tether**: The membrane is attached to the main body by tethers.

The **sail layout** is shown in “Fig. 3”.

6.2. Propulsion system
The highly reflective material of the craft was used for pushing by sunlight photonic propulsion. Additionally, solar cells made from silica generated 500 W onboard the craft.

![Figure 3. Sail layout](image-url)

7. Breakthrough ‘Starshot’ Overview
The ‘Starshot’ is a breakthrough idea for interstellar travel to nearby galaxies, probably to Alpha Centauri system which is 4.4 light years away [9]. These projects require technological breakthrough, and long-term economic interest and investment [7].

7.1. Sail layout proposal
The sail is proposed to be a **nanocraft** consisting of a single wafer of electronics with cameras, sensors, communication devices, small LASERS for thrusters and a small nuclear battery.

7.2. Propulsion
The craft can be accelerated upto **20% the speed of light using** onboard LASERs and nuclear fuel.

7.3. Reaching the star system and time estimate
This technology is expected to come in 20 years, 20 years to reach Alpha Centauri, 4.4 years to beam data to Earth = **45 to 50 years to get information about the galaxy**.

7.4. Challenges Ahead and Recently Proposed Solutions:
• **The craft should withstand cosmic dust and turbulence**: Three methods are proposed: Route Adjustment, Protective shielding, On-Chip Healing.
• **Miniaturization of electronics**: We cannot reduce the size of electronics beyond a certain limit because quantum tunneling effects come into existence (end of Moore’s law) [19]. The base resins for IC is selected by moisture performance and fluidity. [20]
• **Pointing the LASER** array towards the tiny spacecraft is a huge challenge.
8. Conclusion
The power that lies dormant within photons could be mankind’s future towards energy efficient flight. Information about other galaxies can be acquired, that is nowhere as good as those acquired by conventional and other observation methods. This technique makes space travel less-dependent on conventional resources by relying more on renewable energy like Sunlight. Thus, if long-term research of photonic propulsion is fueled by constant economic interest and investment, it would take us on the ultimate path to fuel independence for spaceflight.

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