Assessment of an Interstellar Photon Propulsion Concept

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John E. Sinko[1] and Tyler R. Baxter[2]
St. Cloud State University, St. Cloud, Minnesota, 56301, USA

Abstract: In the past decade, solar sail propulsion has been successfully demonstrated in space. In this paper, we propose a new type of interstellar propulsion system and critically examine its physical feasibility in the context of modern photovoltaic and solar sail technologies. This paper analyzes the viability of a spherical interstellar propulsion concept, and explores its physical parameters and the limitations against its practical implementation. The proposed system would use a spherical, thin film photovoltaic structure, relying on ambient light in the astrophysical environment for power and ultimately, thrust generation. Integrated diode lasers powered by the photovoltaic structure would produce a net unidirectional thrust in an adjustable direction with no onboard propellant. Compared to planar solar sails, there would seem to be inherent promise for niche applications where the distribution of radiant power sources is roughly isotropic, such as propulsion between stars or within a luminous nebula. However, our analysis indicates that the device is impractical as an interstellar propulsion system, primarily due to low thrust and long transit times that would exceed component lifetimes by orders of magnitude.

Nomenclature

λ	=	Wavelength [m]
σ	=	Areal density [g/m^2]
τ	=	Thrust [N]
A	=	Area [m^2]
c	=	Speed of light in the vacuum [m/s]
f	=	Repetitive pulse frequency [Hz]
E	=	Energy [J]
E_g	=	Band gap energy [J]
F	=	A unitless temperature-dependent function of temperature related to laser diodes
h	=	Planck’s constant [J s]
I	=	Total impulse [N s]
k_B	=	Boltzmann’s constant [J/K]
K	=	A material-dependent constant
$MTTF$	=	Mean time to failure [s]
N	=	Number of photons
p	=	Momentum [N s]
P	=	Power [W]
P_0	=	Optical peak power [W]
P_{output}	=	Stellar power output [W]
r	=	Radius [m]

[1] Assistant Professor, Department of Physics and Astronomy, jesinko@stcloudstate.edu
[2] Undergraduate student, Department of Physics and Astronomy, baty1102@stcloudstate.edu

t	=	Time [s]
t_L	=	Laser pulse length [s]
T	=	Temperature [K]
w	=	Laser emitter width [m]

I. Introduction

IF humans are to eventually travel between stars, we must consider non-traditional methods of propulsion. For interstellar travel, reducing mass and increasing specific impulse are critical steps. One way to reduce propellant mass is to use massless photons as the propellant. Photon thrust, predicted by Kepler,[1] is a well-established concept in which by absorption or reflection, a number of photons N delivers a total impulse I. When delivered in a time interval Δt, this process results in an average thrust τ. The de Broglie momentum for a photon is:

$$p = \frac{h}{\lambda} \tag{1}$$

for a single photon with wavelength λ and Planck's constant ($h \approx 6.626\times10^{-34}$ J·s). Absorptive thrust is then:

$$\tau \approx \frac{I}{\Delta t} = \frac{Nh}{\lambda \Delta t}, \tag{2}$$

and considering the energy of a single photon is $E = c\,p$, then the thrust obtained under radiative power P is:

$$\tau \approx \frac{P}{c} \tag{3}$$

An increase of roughly a factor of 2 can be obtained by using photon reflection instead of absorption, but given that $c \approx 3\times10^{8}$ m/s, photon thrust will still be small compared to rocket thrust (i.e. exhaust of material with mass), even for significant optical power. These observations apply to all photon sails.

The concept explored in this paper deviates from typical sails in that it uses photon emission for thrust generation (instead of reflection or absorption). Ultimately, though, this concept must face the same inherent challenges. As background for our concept, we will begin the paper with a discussion of a few solar sail missions and concepts for beamed power photon sails. We will discuss the 'state of the art' of thin film photovoltaic power. Finally, we will analyze a concept for a spherical power array that feeds a laser 'photon thruster'. We will attempt to integrate the disparate components and finally consider whether a spherical, laser-driven, photon-momentum-based propulsion system could be viable for interstellar travel.

II. Context: Traditional Solar Sails

The vehicle concept presented in this paper draws heavily from existing solar sails and solar sail concepts. Consideration of the existing literature will help inform design and analysis.

A. Solar Sail Missions

International interest in solar sail technology has recently surged. Maturation of manufacturing processes for thin films and new schemes for sail deployment have contributed to this rise in interest; however, progress in solar sails has seen its share of setbacks.

In June 2005, Cosmos 1, a solar sail produced by the Planetary Society, was launched on a Volna rocket.[2] The payload had a mass of about 100 kg; its sail, made of aluminized PET, had an area of 600 m^2. Its expected acceleration was 5×10^{-5} m/s^2. The anticipated mission lifetime was 30 days, with the intent of executing an orbit-raising maneuver as a technology demonstration. It failed to reach orbit.

In 2008, NASA also made an effort at launching a solar sail. The NanoSail-D mission would have tested solar sail propulsion with a 4 kg payload and 10 m^2 area, but the satellite was lost shortly after launch due to a malfunction of the Falcon-1 launch vehicle.[3] The subsequent Nanosail-D2[4] was more or less a duplicate of the original. Successfully launched from a Minotaur IV rocket in November 2010, Nanosail-D2 had a square, 7.5 µm-thick, 10 m^2 sail, intended to demonstrate sail deployment technology. It re-entered Earth's atmosphere in late 2011.

In May 2010, JAXA launched IKAROS (Interplanetary Kite-craft Accelerated by Radiation of the Sun), which successfully demonstrated solar sail propulsion, passing Venus around December 2010.[5] The square sail had about 200 m^2 area, 300 kg total mass with a 7.5 μm-thick sail composed of aluminum-coated polyimide. It was used in a hybrid propulsion scheme combining photon propulsion and thin film photovoltaic-driven ion propulsion. About 5% of the sail area was devoted to solar cells which generated about 500 W, used to drive the ion engine.

NASA had been developing a solar sail mission called Sunjammer,[6] which had been planned to include a 5 μm-thick sail with 1200 m^2 area, and about 9 mN thrust. It was canceled in 2014.

The missions in the last 10 years indicate that at least part of the world aerospace sector is excited about research in solar sails. However, unless solar sail missions can demonstrate significant advantages compared to conventional propulsion methods, the technology is unlikely to be enthusiastically adopted for future missions. This situation motivates our attempt to apply solar sail technology to interstellar propulsion.

B. Beamed Sails

The beamed sail concept was probably first proposed by Forward in 1962[7] and Marx in 1966.[8] Instead of sunlight, beamed sails incorporate a terrestrial or space-based power source, probably a laser, to propel the sail with larger thrust than possible with solar radiation alone. Although Marx's original idea to use a 1-km wide, hard x-ray laser beam is not currently feasible, visible lasers with 10-100 kW total output power are now commonplace. Realization of beamed photon sails is challenged by the basic limitations of diffraction; namely, large aperture and small wavelength are needed.

Beamed sail vehicle concepts are essentially identical to those for solar sails. Such topics have been explored conceptually, for instance by Landis.[9] Experimentally, Myrabo, et al.[10] investigated laser-driven carbon fabric sputtered with molybdenum under vacuum, measuring about 10 dynes thrust from 10 kW incident irradiation by a CO_2 laser. In the process, they raised the sail material to temperatures around 2500 K, with significant ablation of the sail observed above about 13 kW irradiated power. An upper limit on allowable irradiance may be inferred for beamed sails and solar sails. An alternative realization of a beamed sail arises in the efforts of Bae[11] towards an intracavity laser-driven 'photonic thruster'. Yet, the use of a remote laser in beamed energy propulsion for sail missions is still 'diffraction limited'. A laser is of doubtful use at interstellar distances due to the rapid falloff of transferred power over light years. Can the sail itself be used as a practical power source in interstellar space?

III. Solar Sail Power Sources and Power Management

Photon sail vehicle concepts require an external power source. As discussed above, the source could be the Sun, a laser beam, or some more exotic radiator. Towards considering interstellar photon propulsion, interesting non-traditional options for power sources are stars and radiant interplanetary gases. We will now consider whether these sources are sufficient to be utilized for propulsion purposes. Light from point-like sources dissipates according to the inverse square law; however, an interstellar vehicle surrounded by stars can in principle be considered to rest in an isotropic radiation environment. Let this vehicle lie at some arbitrary position near, but outside of, our solar system. Considering the vast distances, how much power can be intercepted from stars in our astrophysical locale? Table 1 indicates relevant properties of the nearest 10 stars including Hertzsprung-Russel classification, power output, rough distance from Earth, and irradiance (computed as P_{output} divided by spherical area at the indicated distance). The irradiances from these remote sources at best are on the order of 10^{-7} W/m^2. This situation sets extreme limits on the power available to the spacecraft, and suggest that the design for the propulsion system be trimmed back as far as possible, for example by reducing mass to maximize acceleration.

Table 1. Properties of the 10 nearest stars.[12]

Star	Type	P_{output} (W)	Distance (m)	Irradiance (W/m^2), at Earth
Sol	G2V	3.9×10^{26}	1.49×10^{11}	1.4×10^{3}
Proxima Centauri	M5.0V	6.3×10^{23}	4.01×10^{16}	3.1×10^{-11}
α Centauri A α Centauri B	G2V K0V	5.9×10^{26} 2.0×10^{26}	4.16×10^{16}	2.7×10^{-8} 9.2×10^{-9}
Barnard's Star	M4V	1.3×10^{24}	5.67×10^{16}	3.2×10^{-11}
Wolf 359	M5.5V	5.5×10^{23}	7.38×10^{16}	8.0×10^{-12}
Lalande 21185	M2V	1.2×10^{25}	7.85×10^{16}	1.6×10^{-10}
Sirius A Sirius B	A1V DA2	9.9×10^{27} 9.9×10^{24}	8.13×10^{16}	1.2×10^{-7} 1.2×10^{-10}
Luyten 726-8 A Luyten 726-8 B	M5.5V M6V	3.5×10^{23} 1.5×10^{22}	8.23×10^{16}	4.1×10^{-12} 1.8×10^{-13}
Ross 154	M3.5V	2.5×10^{24}	9.17×10^{16}	2.4×10^{-11}
Ross 248	M5.5V	5.5×10^{23}	9.74×10^{16}	4.6×10^{-12}

Table 2 indicates expected irradiances from the sun at significant distances. In consideration of the results of Myrabo, et al.,[10] it is likely that sails activated within the orbit of Mercury would suffer unduly from ablation. Outside of over-irradiance, the sun probably remains the best fixed single source of radiant power up to about 1 light year from Earth. On the other hand, the fixed stars are not the only possible sources of radiant power. Table 3 lists a few other sources, which are (roughly) isotropically distributed.

In theory, a single-directional, planar sail effectively intercepts light from 2π steradians at perfect efficiency. In reality, additional losses will be present, for instance when not at normal incidence, due to the Lambert cosine factor. If the sail material is reflective in one direction but absorbing in the other, it will still generate thrust when illuminated isotropically, as long as it is not in thermal equilibrium with its isotropic radiation environment. Happily, this would not be the case for a sail, since the thermal environment is roughly at 2.7 K, whereas the typical photon temperature in the visible spectrum is roughly ~5000-6000 K.

Table 2. Irradiances at Distances from Sol.[12]

Location	Solar 'altitude'	Irradiance
	[m]	[W/m^2]
Solar surface	0	6.4×10^{6}
Mercury	5.8×10^{10}	9.3×10^{3}
Venus	1.1×10^{11}	2.7×10^{3}
Earth	1.5×10^{11}	1.4×10^{3}
Mars	2.3×10^{11}	6.0×10^{2}
Jupiter	7.8×10^{11}	5.1×10^{1}
Saturn	1.4×10^{12}	1.5×10^{1}
Uranus	2.9×10^{12}	3.7×10^{0}
Neptune	4.5×10^{12}	1.5×10^{0}
1 light year	9.5×10^{15}	3.4×10^{-7}

Table 3. Astrophysical Radiation Sources[13]

Isotropic Source	Irradiance (W/m^2)
Zodiacal light	1.2×10^{-7}
Integrated starlight	3.0×10^{-8}
Diffuse galactic light	9.1×10^{-9}
Cosmic light	9.1×10^{-10}

Thin film photovoltaic devices and semiconductor materials are under intense scrutiny at present for their potential use in optics, photonics, and commercial solar power.[14] Thin film photovoltaic materials composed of silicon, copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) are approaching opto-electrical efficiencies of 20%. Table 4 provides a few details about these thin film photovoltaic materials in terms of mass, cost, and efficiency.

A 10 m^2 array of any the materials in Table 4 will produce on the order of 1 kW electrical power in Earth orbit. Although other types of thin film photovoltaic materials and devices are currently under development, the above may be considered representative of the 'state of the art' for photovoltaic power.

We will now attempt an integration of photovoltaic materials into our interstellar propulsion concept.

Table 4. Photovoltaic Thin Film Properties.[15-17]

	Areal density (g/m^2)	Areal cost ($US/m^2)	Efficiency (%)
Si	5	~200	10-12
CdTe	5-6	~50	9
Cd	5-6		
Te	0.04		
CIGS	6	~6	10-20
Cu	2.53		
In	3.16		
Ga	0.76		

IV. The Proposed Interstellar Vehicle Concept

The concept proposed in this paper is a photovoltaic laser thruster. Rather than operating by absorbing or reflecting photons, the idea is to operate by absorbing power and then emitting photons in a single direction to generate momentum. The collector would be realized by wrapping a thin film photovoltaic 'sail' on the surface of a spheroid. The intent would be flexibility to use either directional or isotropic sources of radiation for power.

A. Possible Modes of Operation

For operational parameters, two thrust modes are suggested by this situation. The first mode would be used when the craft was primarily irradiated from a single direction. This mode resembles that of photon sail propulsion, in that the craft could generate thrust by photon reflection and/or absorption. However, thrust for attitude control could be delivered using the onboard laser, powered by the energy of the same photons generating momentum by absorption, and approaching the 2× factor on thrust achieved by photon reflection in typical sails. This concept is shown diagrammatically in Fig. 1. It should be clear from the figure that some efficiency factor will be necessary due to the Lambertian character of irradiation onto the oblate spheroid.

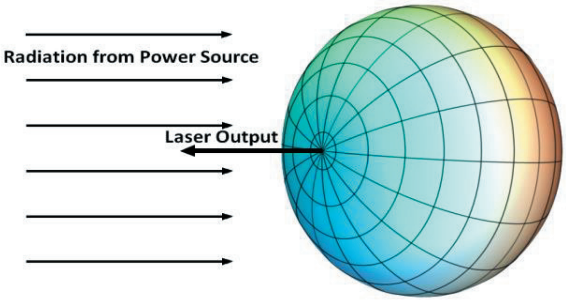

Figure 1. Directional power configuration.

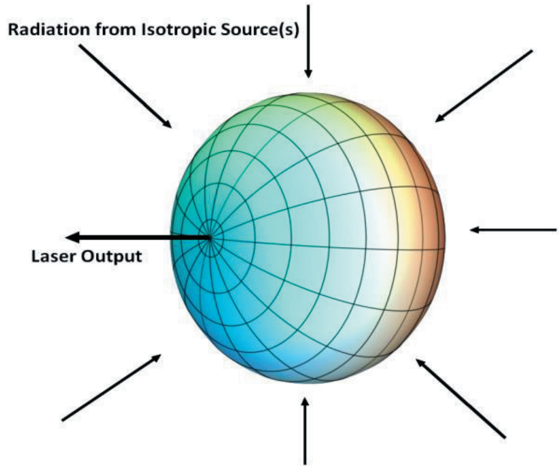

Figure 2. Isotropic power configuration.

The second mode would be used when the craft was far from any single power source, so that diffuse power sources dominated. Isotropically-intercepted incident photons would generate insignificant net thrust by momentum transfer due to net cancellation. However, power harvested from these photons would be routed to the lasers to generate directional thrust, as imagined in Fig. 2. In either usage, there would be power loss due to the electrical-optical efficiency of the laser. It might also be necessary in the case of low power, to cycle the lasers using an onboard power storage system.

B. Laser Emitters for Thrust

In considering this propulsion concept, the thrust mechanism is important. Possible options for photon emitters include laser diodes and diode-pumped solid state (DPSS) lasers, both of which have made steady inroads into worldwide commercial markets due to small size, low cost, high power output, and high electrical-optical efficiency.

Laser diodes may be the best option for a system, due to their simplicity of use, high efficiency, and long lifetimes. Several common kinds of laser diodes and corresponding wavelengths and wall plug efficiencies (optical output/electrical input) are tabulated in Table 5.

Table 5. Common laser diode parameters.[18-21]

Laser diode type	λ (nm)	Wallplug efficiency
InGaN	405	~25%
GaN	450	~12%
GaAs	650	~30%
AlGaAs/GaAs	808	~50-60%
GaAs	940-980	~70%
InP	1530	~50%

Compared to laser diodes, DPSS systems have better output coherence, but suffer additional losses to efficiency. A few possible candidate processes based on AlGaAs pump diodes, with corresponding output wavelengths and efficiencies, are tabulated in Table 6.

Table 6. Parameters of a few common DPSS lasers.[22]

Process	λ (nm)	Ideal efficiency
AlGaAs→$NdYVO_4$	594	1%
AlGaAs→$NdYVO_4$→KTP	532	48%
AlGaAs→$NdYVO_4$→BBO	473	5%
AlGaAs→BBO	404	12%

As discussed by Davarcioglu,[22] the lifetime of a laser diode is typically limited to 10,000-30,000 hours of operation. The failure likelihood is described by a 'bathtub curve' – initially high failure rates ('infant failures') give way exponentially to an essentially flat, low probability of random failures, until device end of life approaches, when the failure rate increases more or less exponentially again as the device ages.[23] The useful life of the device is thus in the flat part of the 'bathtub'. Migration of aluminum ions within AlGaAs diodes can eventually culminate in device failure. It may therefore be wise, in going forward, to choose an alternative diode laser source, such as a system based on gallium nitride. Diode laser lifetime is sometimes estimated in the industry based on mean time to failure (MTTF):[24]

$$MTTF = \frac{Kw^6 F(T)}{f P_0^6 t_L^2} . \qquad (4)$$

Here, K is a material-dependent constant (e.g., 7×10^{19}), w is the width of the laser emitter, $F(T)$ is a function of temperature ($F(T)$=1 at 25°C), f is the repetitive pulse frequency, P_0 is optical peak power, and t_L is the laser pulse length. The empirical relationship $F(T) \propto e^{E_g / k_B T}$ has been observed,[25] so operation at high temperature will tend to reduce *MTTF*. Leuzinger[23] notes that lifetimes can be extended up to millions of hours (on the order of 50 years), for instance using single emitters that operate at multi-Watt output. Considering the latter diodes are designed for reliable industrial use, a similar technology might be appropriate for our application. Our proposal is for a long-range device that could traverse interstellar distances. Component lifetimes are crucial because an arbitrarily long trip time assures eventual component failures. An interesting question is whether it would be wiser to optimize for a single long-life emitter, or to include multiple, low-mass emitters that are replaced as the trip progresses.

An important factor significantly influencing the device lifetime, which we have so far neglected, is radiation from the ambient environment. This topic was explored in detail by Phifer,[26] and more recently by Galofaro.[27] Radiation effects on semiconductor devices are often deleterious for a number of reasons, but in some cases can actually result in improvements in performance. Such effects would need to be studied in detail for an interstellar mission, since radiative degradation of either the photovoltaic cells or the laser diodes could preclude long-term functionality of the system. In concluding this discussion, it is worth noting that the output power of the laser device would necessarily vary along the vehicle trajectory as incident power fluctuated.

C. Scaling for a Practical Spherical Photon Thruster

Now that the state of the art in thin film photovoltaic technology has been introduced, let us generally apply the benchmark values so far to our spherical photon thruster concept for analysis. Based on the previously stated values for thin film materials, assume an areal density $\sigma \approx 5$ g/m^2, photovoltaic efficiency of 10%, solar irradiance (around Earth orbit) of 1.4 kW/m^2, and laser electrical-optical efficiency of 40%. Based on solar sail technology, our consideration of the maximum practical radius for the device will be held to 1 km. Table 7 is intended to provide a context of expected intercepted power and thrust for various sized conventional solar sails. Table 7 reinforces the idea that photon thrust from a traditional solar sail is reasonable (if still small) when operated close to a power source; i.e., a star.

Table 7. Scaling for a Planar Solar Sail.

Radius (m)	Mass (kg)	P, Earth (πR^2) (kW)	Thrust (N)
0.9	0.05	0.32	4.7×10^{-7}
2.8	0.5	3.2	4.7×10^{-6}
8.9	5	32	4.7×10^{-5}
28.2	50	320	4.7×10^{-4}
1000	62,800	4.1×10^{6}	5.9×10^{-1}

Turning back to our proposed spherical photon propulsion device, we wish to consider a limit of operation far from any single powerful radiation source, e.g., interstellar space. Considering the factor of $1/c$ that reduces intercepted power to thrust, one might assume that the surface area needs to be as large as possible to increase thrust to a reasonable level. However, Newton's second law indicates that scaling up the area will *not* result in improvement in acceleration because mass and intercepted power (and therefore emitted power, and thrust) also scale directly with area. Increases in acceleration can thus only be achieved by reducing the thin film photovoltaic thickness or by improving efficiencies.

Table 8 summarizes, in analogy to Table 7, the thrust scaling for a spherical photon thruster. Note that even for a hypothetical radius of nearly 200 km, the intercepted power does not provide significant thrust. Although deficiency in intercepted power can – to an extent – be offset by reduction of mass, the deficit will likely remain too great for practical use of this system. This trouble is exacerbated because the expected lifetimes of the component devices (e.g., 10-50 years) that compose the system are much shorter than the trip time, imposed by low acceleration. Can reduction of the system thickness make this propulsion system feasible? Commercial thin film photovoltaics weigh around 1-10 g/m^2, and although new materials may drive down the lower limit of this range, it is likely to be at a cost in photovoltaic efficiency. Table 9 helps evaluate the situation, assuming a spherical surface area of 1.3×10^{7} m^2 corresponding to a thrust of 2.8×10^{-10} N, as noted in Table 8. At the smallest considered areal density (1.0×10^{-3} g/m^2) assuming the material has volume density around

Table 8. Area Scaling for Spherical Propulsion System.

Radius (m)	Area ($4\pi r^2$) (m^2)	Mass (kg)	Power emitted (W)	Thrust (N)
$\mathbf{9.0\times10^{-1}}$	1.0×10^{1}	5.0×10^{-2}	6.4×10^{-8}	2.1×10^{-16}
$\mathbf{2.8\times10^{0}}$	9.9×10^{1}	5.0×10^{-1}	6.3×10^{-7}	2.1×10^{-15}
$\mathbf{8.9\times10^{0}}$	1.0×10^{3}	5.0×10^{0}	6.4×10^{-6}	2.1×10^{-14}
$\mathbf{2.8\times10^{1}}$	9.9×10^{3}	5.0×10^{1}	6.3×10^{-5}	2.1×10^{-13}
$\mathbf{1.0\times10^{3}}$	1.3×10^{7}	6.5×10^{4}	8.3×10^{-2}	2.8×10^{-10}
$\mathbf{1.9\times10^{3}}$	4.5×10^{7}	2.3×10^{5}	2.9×10^{-1}	9.7×10^{-10}
$\mathbf{6.1\times10^{4}}$	4.7×10^{10}	2.4×10^{8}	3.0×10^{2}	1.0×10^{-6}
$\mathbf{1.9\times10^{5}}$	4.5×10^{11}	2.3×10^{9}	2.9×10^{3}	9.7×10^{-6}

5 g/cm^3, the thickness would be only 2.0×10^{-10} m. Considering the matching acceleration in Table 9, even with a single-atom-thickness, the proposed system will still not produce sufficient thrust to make the device practical as an interstellar propulsion method.

Table 9. Area Density-Dependent Acceleration Performance

Area Density (g/m^2)	Total Mass (kg)	Acceleration (m/s^2)	Time to 1 m/s (years)
1.0×10^1	1.3×10^5	2.2×10^{-15}	1.4×10^7
1.0×10^0	1.3×10^4	2.2×10^{-14}	1.4×10^6
1.0×10^{-1}	1.3×10^3	2.2×10^{-13}	1.4×10^5
1.0×10^{-2}	1.3×10^2	2.2×10^{-12}	1.4×10^4
1.0×10^{-3}	1.3×10^1	2.2×10^{-11}	1.4×10^3

Our main conclusion from this study is that the spherical photon propulsion concept is not appropriate for interstellar propulsion. However, the possibility is left open that the system might find use in a different isotropic environment, for instance within a cloud of luminous gas. Further, incorporating a moveable diode laser into a traditional planar solar sail could be a valuable method to produce thrust redirection without changing the orientation of the entire sail.

V. Conclusion

In this paper, we examined an interstellar propulsion concept that uses a thin film photovoltaic array to power a laser and produce thrust based on photon momentum. The system would draw power in an isotropic radiation environment to produce propellant-less, directional thrust. Although the concept seems interesting, insurmountable challenges prevent its realization. Existing solar sails are capable of acceleration on the order of 1×10^{-6} m/s^2 in the solar environment. Our analysis indicates that in interstellar space, optimistically, an interstellar spherical propulsion system like the one described in this paper would have a maximum acceleration about 6 orders of magnitude less than traditional solar sails. This limitation effectively precludes its intended use as an interstellar propulsion system, since the trip times, even to nearby stars, are unreasonably long – and, since the component devices would only function for a small fraction of the trip. However, our research suggests that implementation of diode lasers with conventional sails is not out of the question, and may enable better sail control via steering with photons emitted from a diode laser.

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