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Contrasting Laser Ablation and Photon Pressure Propulsion

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Abstract: In this article, we contrast laser ablation propulsion with photon pressure propulsion. LAP must use repetitive short pulses (~100 ps) for best performance, while PPP requires GW-level continuous (CW) lasers and a lightsail to receive the beam and drag the payload to relativistic speeds.

Keywords: Photon pressure propulsion, Breakthrough starshot, Laser ablation propulsion, Relativistic travel, Alpha Centauri.

1. Introduction – Comparing LAP and PPP

This idea was briefly treated in [1].

The beam parameters [2] which are important for laser propulsion are similar for laser ablation propulsion (LAP) and pure photon propulsion (PPP). These are:

Momentum coupling coefficient *Cm*,

$$C_m = F / P_{inc}, \tag{1}$$

the ratio of thrust *F* to incident laser power *Pinc*. with dimensions N/W,

For LAP, a specific impulse is given by

$$I_{sp} = v_E / g_o \tag{2}$$

exhaust velocity v_E divided by the acceleration of gravity (a rocketry term with dimensions of seconds), and Thermal coupling coefficient

$$C_{th} = Q / W \tag{3}$$

For LAP, *Cth* is important because deposited heat *Q* can melt the target before the mission is finished. For PPP it is also important to avoid melting the lightsail.

For LAP, ablation kinetic efficiency is

$$\eta_{AB} = \delta m v_E^2 / (2W) = C_m I_{sp} g_o / 2, \tag{4}$$

a dimensionless quantity where δm is the single pulse ablated mass. For PPP,

$$\eta = \gamma m_o c^2 / (Pt), \tag{5}$$

allowing for relativistic speeds, where

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}, \tag{6}$$

β = v/c, m_o is the rest mass, c is light speed, P is laser power, and t is the CW beam duration.

Figs. 1 and 2 compare the mechanics of this interaction in the two cases. $\bar{E}$ indicates the direction of the associated optical electric field, giving initial surface breakdown and plasma formation in the case of LAP, which are critical for efficient propulsion. The factor of 2 for impulse in Fig. 2 assumes perfect reflection.

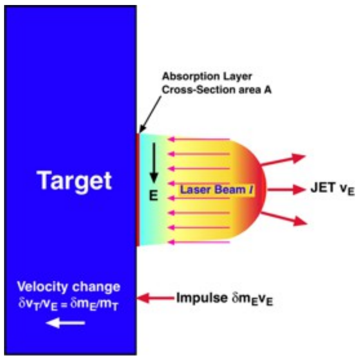

Fig. 1. Illustrating momentum generation for LAP.

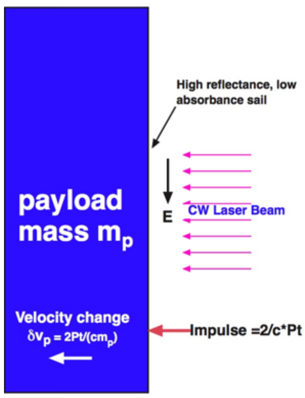

Fig. 2. Illustrating impulse for PPP for zero velocity and zero absorption.

Related quantities involving these basic parameters are:

Ablated mass depth for a single shot in LAP is

$$\delta x = C_m^2 \Phi / (2\rho_T \eta_{AB}), \tag{7}$$

where ρ_T is the target mass density, and Φ is the incident pulse fluence (J/m^2), and δx = 0 for PPP, Ablation fuel lifetime for LAP is

$$\tau_{AB} = 2M\eta_{AB} / (PC_m^2), \tag{8}$$

for LAP, where M is the ablation fuel mass. Thrust

$$F = C_m P, \tag{9}$$

for LAP. To allow for relativistic speeds, a more complicated relationship exists for PPP,

$$F = \gamma^3 m_o c \dot{\beta}, \tag{10}$$

If τ_{AB} is less than mission lifetime T, a laser-propelled craft will not reach its destination.

For PPP, $\tau = \infty$, providing care is taken with sail temperature. Therefore, relativistic speeds are possible in PPP, which is a strong advantage over LAP for some missions.

Optimum values for all these parameters can be chosen for any problem.

For LAP, there are several optima, each giving different sets of laser parameters: delivered mass ratio m/M, cost per kg and delivered mass m.

C_{th} is critically important for LAP because the target will melt after N_{max} pulses when it is a simple object with mass M that shares all the incident energy [1]

$$N_{max} = (2/3)^{1/3} C_p M (T_m - T_i) / (C_{th} W), \tag{11}$$

If the target is space debris, melting will create much more debris. For Al in LAP, N_{max} predicted by (11) is of order 2000 pulses, whereas millions of pulses may be required to complete some propulsion tasks. In Eq. (11), T_m is the melting temperature, and C_p is the target material's specific heat.

We have shown that reality is more complex than this in LAP, and the material can take many more pulses than in Eq. (11). At very high laser intensity, surface recession can outrun the thermal wave [2], giving

$$v_{rec} / v_{th} \propto \frac{\sqrt{\Phi} A^{1/8}}{\sqrt{\lambda \rho K} \tau^{1/4} [Z^2 (Z+1)]^{3/8}} >> 1, \tag{12}$$

and appropriately larger N_{max}. In Eq. (12), Z is the plasma atom charge state, A is atomic mass, λ is wavelength and τ is pulse duration.

For cases where we can choose a target material, we obviously want to select a material with very low thermal conductivity K and C_{th} value but very large ablation efficiency η_{AB} and large melting temperature T_m. If we select target materials like ZrO_2 or $CaCO_3$, we have shown that N_{max} can be thousands of times larger than for bulk Al [4], but only for short pulses.

In PPP, the laser is continuous (CW), and the maximum duration is governed only by lightsail temperature, limited by reradiation.

Relativistic propulsion using just pure light pressure without ablation is key to the Breakthrough Starshot proposal. This is the only way in which humans (or instruments) will explore regions within a few light years of Earth.

For PPP, given

$$D = \sqrt{\frac{1+\beta}{1-\beta}}, \tag{13}$$

for the relativistic Doppler factor of the lightsail relative to the laser, the equation of motion is

$$\frac{d\beta}{dt} = c\beta\frac{d\beta}{dz} = \frac{(A+2R)P}{c^2 m_o D^2 \gamma^3}, \tag{14}$$

where P is the laser power received by the lightsail in the laser frame with absorbance A and reflectivity R. In Eq. (14), γ is the time dilation factor in Eq. (6).

For PPP, kinetic energy is given by

$$KE = \gamma m_o c^2 \tag{15}$$

For the PPP case, in which travel beyond the solar system is the goal, we will discuss the likelihood of finding intelligent extraterrestrial life in subsequent sections.

Using parameters anticipated for Breakthrough Starshot, Table 1 shows the results for $\beta = 0.2$, Table 2 gives results for $\beta = 0.7$ and Table 3 outlines the results for $\beta = 0.99$. Table 4 is a summary.

Table 1. β= 0.2 [5].

Sail diameter (m)	4.0
Payload mass (kg)	0.0035
Energy efficiency η (%)	3.0
Laser aperture diameter (m)	180
Beam transmit duration (s)	500
Temperature limited force (N)	500
Irradiance (GW/m^2)	8.7
Peak laser power (GW)	260
Temperature limited acceleration (G)	15k
Goal (light years)	4.37
Time to goal (Earth years)	22
Cost (B$)	8.98

Table 2. β= 0.7 [5].

Sail diameter (m)	4k
Payload mass (kg)	20k
Energy efficiency η (%)	26
Laser aperture diameter (m)	1.8k
Beam transmit duration (mo)	2.7
Temperature limited force (N)	260k
Irradiance (GW/m^2)	17.5
Peak laser power (PW)	220
Temperature limited acceleration (G)	3.4
Goal (light years)	12
Time to goal (onboard years)	12
Cost (T$)	10.5

2. Details of Breakthrough Starshot Flight

This flight will be quite expensive per kg payload mass because it is the first, and a lot of infrastructure has to be built. In 500 s, the lightsail and payload will reach 0.2c and be located at about 1/3 the distance from Earth to Mars at the closest approach, way beyond the Moon. At the end of one day, the payload will be twice the distance from Earth to Pluto on its closest approach to us. Still, it will take 22 years to reach Alpha Centauri. The lightsail has to withstand 870 kW/cm^2 irradiance. In order not to burn up, the point design calls for its absorptance to be less than 10^{-8} [5]. The Starshot designers believe they can achieve this.

One thing was not made clear: to transmit photos of the Alpha Centauri region back to Earth, the payload also needs to include a 4-m diameter transmitting aperture. However, Dr Parkin tells me that will be the parabolic shape of the lightsail itself, so it will not increase payload mass and the required laser power or lightsail area.

Table 3. β= 0.99 [5].

	Distance (ly)	Duration seen from Earth (y)	Duration on board lightsail with braking (y)	Duration on board lightsail, no braking (y)
Acceleration	15.34	16.0	3.68	3.68
Cruise	69.32	70.0	9.78	9.88
Deceleration	15.34	16.0	3.68	2.26
Totals	100	102.0	17.14	15.81
Cost/kg	6.26B$			

Table 4. Summary [5].

	Distance (ly)	Payload Mass	Duration (yr)	Max β	Sail dia. (m)	Max G's	Cost (Capex + Opex)
Starshot	4.4	0.0035 kg	22	0.2	4	15 k	8.8 B$
Medium mass	4.4	1000 kg	58	0.075	180	20 k	535 B$
Large mas	12	20 ktons	12	0.70	4000	3.4	15 P$

Once the payload reaches Alpha Centauri, it takes another 4.4 years for the photos to return to Earth, so a total of 26.4 years after launch.

Based on the results of our panel at OPAL 2024, PCSELs (Phased Crystal Surface Emitting Lasers) are now seen to be the ideal photon source for these flights rather than individual CW lasers. Each 3-cm wafer can, in principle, produce 10 kW of light already phased.

When complete, these wafers will be the brightest source ever created. Please see Section 6 for more details on PCSELs.

3. Ways of Slowing Down in PPP

Parkin assumes a slowdown laser at the end of a PPP trip. But to use an extreme case, If I'm returning from an 1823 departure at a speed of 1/8 AU/minute, and I expect you to be there for me at this moment to actuate the slowing beam, good luck! Because we can't put a slowing laser at every possible destination, we need to be able to slow ourselves. There are ways of braking using the magnetic fields in space so that you don't have to have a "slowdown" beam waiting for you.

The secret is:

$$\overline{\mathbf{F}} = q\overline{\mathbf{v}}x\overline{\mathbf{B}}, \tag{16}$$

with q the (signed) charge on your spacecraft. This force will likely be perpendicular to the plane of your orbit around a star because the magnetic field is often radial.

You can control the sign and magnitude of magnetic force by choosing to emit electrons or protons. Near Earth, B = 60 µtesla so the force on a single milli- coulomb is 15N. This force will likely be perpendicular to the plane of your orbit around a star because the magnetic field is often radial.

By periodically creating that perpendicular velocity and reversing it, your kinetic energy is gradually given to the star that created the magnetic field. Of course, this option could take years and might be most suitable for instruments.

4. Existential Problem: Questions about Relativistic Human Travel

At $\beta = 0.7$, $\gamma = 1.96$, and time is advancing twice as fast for travelers as it is for people back home. At $\beta = 0.99$, $\gamma = 7.05$ and kinetic energy density is $7.05 m_o c^2$. Considering that in a thermonuclear explosion, only 0.7 % of hydrogen rest mass is converted to energy [8], at this speed, kinetic energy density is 1000 times larger than the energy density in a hydrogen bomb.

This fact makes it critical to design the system with international cooperation so that no one will think it is a weapon in disguise.

We must design our flight path with care! The cost per kg for this acceleration level is 6.26 B$ [7], Table 3. For a 100 ly trip, you can return home in 32 years, but all your friends will be 204 years older!

Would you like that? Some people would.

How many Earth-sized planets are inside the "Goldilocks zone" of temperature and also within 100 ly of Earth? Andrew McGregor [6] says, "Exactly one, and it wouldn't be very comfortable. One. It's called Gliese667 Cc." Gliese is 24 ly distant, and its gravity is twice that of Earth.

5. Practical Limits

a. Human travel at relativistic speeds requires a far different investment of emotional and financial effort than just going to the moon. I guess that, because of the incredible expense, it seems likely that human relativistic travel will not happen for a long time. And you can't go faster than the speed of light.
b. Funding. Capital plus operating expense to get a 10-tonne spacecraft to 0.99c. is 63 T$, or 6.3 B$/kg. That's $2200 for each inhabitant of Earth. On the other hand, we could afford to accelerate an 8 kg mass to 0.99c. So, this kind of technology is primarily useful for instrument packages now. Because 2530 is the presumed year of completion for this project, all that is required to launch the 10-tonne spacecraft 500 years from now is a 0.23 %/yr growth rate of the world's economy.
c. Psychological and emotional limits can be avoided if I travel with a tribe of rich people and don't intend to return. Even so, we would guess that a 15-year trip is the maximum investment of time for intelligent living beings, but very few billionaires could afford the cost.
d. Laser aperture for just the β = 0.7 example is 1800 km. Few places on Earth have so much empty land. Perhaps the laser could be put on the Moon, but that option would be very expensive.
e. Why haven't we actually seen extra-terrestrials originating within 100 lightyears of Earth in my lifetime, despite all the hype and hope? Why are no little green corpses at Area 51 in Nevada?
f. We are alone. The sooner we accept that and treat our civilization and its products as precious, the better. What is the chance that for advanced civilizations don't destroy themselves before traveling to us? Assume that a society which has advanced technologically to the point of making atomic weapons lasts 2000 years before self-destructing. This is a generous assumption. Assume that, like us, it takes about 4B years to evolve from slime to intelligence. Even if it's 8B years, the ratio is one in 2 million. That means that out of

2 million Earthlike exoplanets, one now has intelligent life. If intelligent beings will not want to travel further than 15 ly to find intelligent neighbors, and if there's just one planet in the Goldilocks zone in our 200 light-year diameter sphere, the chances of finding intelligent life nearby or of having it threaten us are vanishing.

6. PCSELs – Lasers for Breakthrough Starshot

6.1. Current State-of-the-art in Light Propulsion

We are still discussing and working on laser sources that could be applied for photon propulsion. Solar light is used to validate the technology. The most recent NASA experiment demonstrates a solar sail that uses light pressure acting on a large 80 m^2 reflective polymer sheet to provide propulsion for a small 12U satellite with a weight of 4.6 kg for future space missions [10].

The Breakthrough Starshot mission seeks to send a gram-scale chip satellite with a 4 m^2 light sail propelled by an Earth-based laser [11]. It is estimated that millions of kW-class lasers with an overall power of 100 GW working for 10 minutes are needed to speed up the sail to 20 % of the speed of light (0.2c). At the end of the acceleration stage, the sail will be at a distance of 15 million km. Therefore, the diffraction of the beam should be managed, requiring a kilometer-scale laser source if operating at a 1-micron wavelength. This could be achieved only by coherently combining multiple light emitters.

6.2. Progress in Laser Beam Combining

There are two main techniques for coherent laser beam combining [12]:

- Side-by-side combining a phased array of lasers, leading to a larger beam size. By synchronizing their optical phases, the joint large beam could have a reduced beam divergence;
- Filled-aperture techniques, where several beams are combined into a single beam with the same beam size and divergence, using diffraction grating or similar optical element.

Most of the experiments are made with fiber lasers. A coherent beam combining using a grating up to 5 kW laser power at 82 % efficiency was shown [13]. G. Mourou et al. [14] proposed an approach combining 30,000 phase-locked fiber lasers to achieve a 100-petawatt laser beam. The method was tested experimentally with 64 phased fibers, and a phase map was captured every ~30 ms. M. Shpakovich et al. [15] proposed the dynamic phase control of a laser beam array based on a simple neural network included in a phase correction loop. Experiments demonstrated the high performance and scalability of the scheme with an array of up to 100 laser beams and a phase setting at $\lambda/30$. A real high-power laser system should include electro-optic modulators distributed on the inputs of an amplifier array to lock the output beams on desired phase relationships. C. P. Bandutunga et al. present a photonic solution for optical phase sensing and control to enable the coherent combination of order 10^8 individual lasers, including the ability to sense and compensate for atmospheric distortions, assuming the laser system is ground-based [16]. To limit losses due to atmospheric turbulence, the laser beamer will require an adaptive optics system, and 10^8 piston-phase actuators with relevant sensing are required per square kilometer of array size.

6.3. Lasers

Various types of lasers are considered a potential choice for getting 100 GW power. Selection criteria include cost per watt, the ability of coherent combining, wall-plug efficiency, size, cooling, etc. Solid-state lasers could hardly meet cost, efficiency and size requirements. Fiber lasers look more promising, but there are challenges in upscaling the manufacturing. Their cost highly depends on the cost of laser diodes used to pump fiber lasers. Permanent progress and scaling manufacturing of laser diodes leads to a constant drop in their price. It is expected that the target price of 0.1-0.01 USD/Watt will be reached by 2040 [17].

Keeping in mind high wall-plug efficiency and direct emission of coherent light, other types of semiconductor (diode) lasers are under consideration for light sail propulsion. An array of electrically pumped vertical external cavity surface-emitting lasers (VECSELs) can be of long coherence and provide sufficient power density at 100 mW per 1 mm emitter [11]. Single-mode VECSELs with a power of 500 mW have been demonstrated at 500 mW [18]. The high areal fill factor required for efficient energy transfer to the sail could be achieved. However, it remains unclear if billions of VECSELs can be incorporated into an architecture that maintains coherence and phase over these spatial scales.

Photonic-crystal surface-emitting lasers (PCSEL) are a new promising candidate to be a building block for kilometer-sized laser arrays [4, 19].

PCSELs are single-mode semiconductor lasers capable of high power and high beam quality and can deliver a laser power of up to 1 kW from a 1 cm-sized emitter with an experimentally shown brightness of ~1 GW/cm^2/sr [20]. The authors expect to make 3-cm diameter lasers with output powers exceeding 10 kW and brightness up to 1,000 GW/cm^2/sr [21].

Even though 3-cm-sized 10 kW PCSEL lasers are still a dream, we could consider manufacturing capabilities. Ten million 10 kW PCSEL lasers are needed for the required 100 GW laser power. A 12-inch-diameter wafer could incorporate 65 lasers.

This corresponds to 155,000 12-inch wafers – a small amount compared to the annual capacity of the manufacturing facilities managed by TSMC and its subsidiaries only, which exceeded 16 million 12-inch equivalent wafers in 2023 [22]. Therefore, manufacturing this kind of laser chips would not be a problem even with today's capacities. Challenges could be in their packaging and electrical supplies. The PCSEL emitters themselves could fit into an area of 120×120 sq. meters.

However, the open question remains: Are PCSEL-type lasers easy to control by phase? How is that opportunity preserved by upscaling the single laser power?

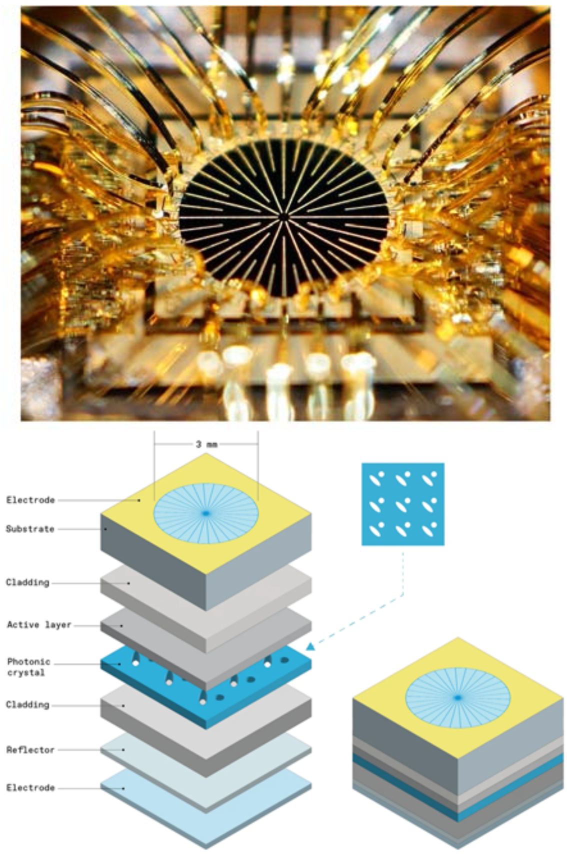

Fig. 3. Photonic-crystal surface-emitting laser [4].

7. Conclusions

- Relativistic laser space propulsion is just around the corner. Plans are underway to launch a probe to Alpha Centauri at 20 % of the speed of light using a giant CW laser;
- This probe can return at least one photo to Earth with reasonably sized apertures. The 1-meter aperture for doing that needs to be considered as part of the payload. Dr Parkin believes the lightsail itself can redirect photos to the Earth;
- The same technology can be used to launch instrument packages across the near universe.

Support for laser development is the key. As Prof. Raciukaitis pointed out in his presentation ("With Lasers to the Stars") at our panel in OPAL 2024, [8], PCSELs (Photonic Crystal Surface Emitting Laser) can have a brightness of 1GW/cm^2/sr, brighter than any laser existing today [4]. A 3 cm diameter PCSEL wafer can potentially emit 10 kW of automatically phased light. These can be phased together in a plane wavefront, or a parabolic wavefront for focusing, and such a plane wave can be instantaneously steered. This is how we can create a single 250 GW beam, such as is required for Breakthough Starshot.

Acknowledgments

For the discussion of PPP, Claude Phipps is deeply indebted to calculations by and discussions with Dr Kevin Parkin. My conclusions about PPP are more skeptical than his. Dr. Parkin firmly believes in the future of all aspects of this field, including human travel. I hope he's right. I sincerely thank Séverine Boyer, CNRS, for her support in this work.

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