Relativistic Propulsion Using Directed Energy

Johanna Bible[a], Isabella Johansson[a], Gary B. Hughes[b], Philip M. Lubin[a]

[a]Physics Department, University of California, Santa Barbara, CA 93106-9530;
[b]Statistics Department, California Polytechnic State University, San Luis Obispo, CA 93407-0405

ABSTRACT

We propose a directed energy orbital planetary defense system capable of heating the surface of potentially hazardous objects to the evaporation point as a futuristic but feasible approach to impact risk mitigation. The system is based on recent advances in high efficiency photonic systems. The system could also be used for propulsion of kinetic or nuclear tipped asteroid interceptors or other interplanetary spacecraft. A photon drive is possible using direct photon pressure on a spacecraft similar to a solar sail. Given a laser power of 70GW, a 100 kg craft can be propelled to 1AU in approximately 3 days achieving a speed of 0.4% the speed of light, and a 10,000 kg craft in approximately 30 days. We call the system **DE-STAR** for **D**irected **E**nergy **S**ystem for **T**argeting of **A**steroids and explo**R**ation. DE-STAR is a modular phased array of solid-state lasers, powered by photovoltaic conversion of sunlight. The system is scalable and completely modular so that sub elements can be built and tested as the technology matures. The sub elements can be immediately utilized for testing as well as other applications including space debris mitigation. The ultimate objective of DE-STAR would be to begin direct asteroid vaporization and orbital modification starting at distances beyond 1 AU. Using phased array technology to focus the beam, the surface spot temperature on the asteroid can be raised to more than 3000K, allowing evaporation of all known substances. Additional scientific uses of DE-STAR are also possible.

Keywords: DE-STAR, Photon Drive, Directed Energy, Relativistic Travel, Interstellar Travel

1. INTRODUCTION

Throughout history, scientists have expended significant effort researching possible methods for relativistic travel. Though numerous concepts have been proposed, we have yet to attain macroscopic relativistic travel. To date, the maximum spacecraft speed obtained is by the Voyager 1 spacecraft, at 17km/s (relative to the sun), as of the 2013-07-05 weekly mission report by JPL. This is only $5.7 \times 10^{-5} c$.
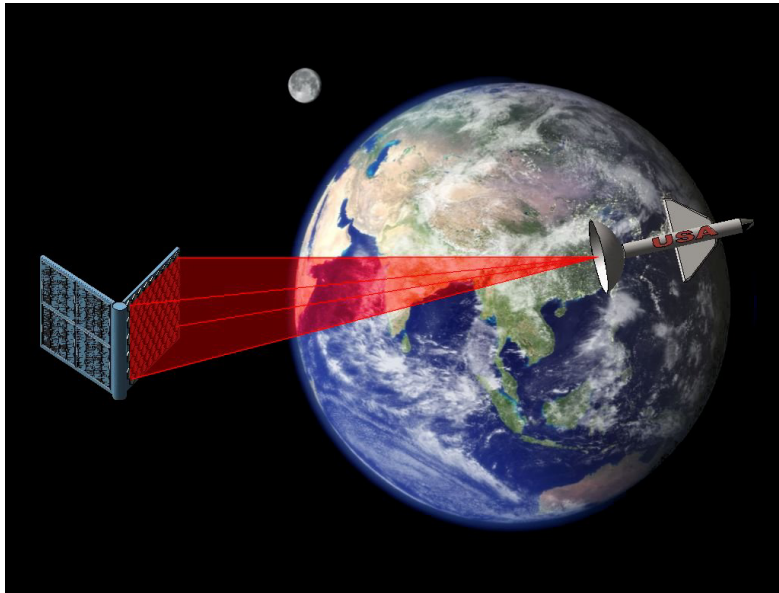

Figure 1. Artist conception of DE-STAR 4 propelling a spacecraft past Earth. DE-STAR is an orbiting platform consisting of a solar PV array, and a phased array of fiber laser amplifiers used primarily for asteroid orbit deflection. Reaction to

ejected material provides a thrust that deflects the asteroid's orbit. It could also be used for other scientific purposes, such as spacecraft propulsion, powering interplanetary spacecraft, asteroid composition interrogation, and space debris de-orbiting.

1.1 History of Relativistic Propulsion Research

One of the earliest projects focused on relativistic travel was Project Orion[1], studied in the early 1950s at Los Alamos National Laboratory. This proposed spacecraft used nuclear pulse propulsion, that is atomic bombs exploding behind the spacecraft, as their propulsion source. The resultant vehicle velocity expectation was between 0.08c and 0.1c. Concern regarding potential radioactive contamination resulted in the cancellation of the project. In 1973, the British Interplanetary Society initiated design of an unmanned interstellar spacecraft known as Project Daedalus[2]. The project, utilizing then current technology, proposed traveling 6 light years in approximately 50 years. Daedalus was a two-stage spacecraft design that employed fusion rockets. The first rocket stage obtained a projected speed of 0.071c over two years, and the second stage, spanning 1.8 years, achieved a cruising speed of 0.12c. The proposed Daedalus payload of 450 tons made it ideal for scientific research. The Daedalus project concluded that Interstellar flight is achievable. Between 1987 and 1988, the US Naval Academy and NASA developed Project Longshot[3], a spacecraft utilizing nuclear pulse propulsion powered by nuclear fission. Project Longshot proposed a prospective trip to Alpha Centauri B at 0.045c, spanning 100 years. Other more exotic propulsion systems include antimatter propulsion such as the system proposed by Robert Forward of Hughes Research Laboratories[4]. Antimatter annihilation emits pions whose kinetic energy is then converted into thrust. The Marshall Space Flight Center has built antimatter traps[5] (HiPAT), necessary for this engine, which store antiprotons for later use. Other areas of current thought that hold academic interest include gravity manipulation and warping of space-time.

1.2 History of Photon Propulsion

The method of using a laser to propel spacecraft is not new, one proposed method would be to use a terrestrial laser[6], while another method proposed by Robert L. Forward[7] in 1984 suggests using a solar pumped laser. Forward proposes using a 1000km diameter Fresnel zone lens to focus the laser beam on the spacecraft composed of a mirror system weighing 1000kg. Further discussion by Young K. Bae[8] describes the advantages of using a Photonic Laser Thruster (PLT) as opposed to more conventional engines to build an Interstellar Photonic Railway. This futuristic railway would compose of multiple manned space structures located along the "tracks" and used to propel spacecraft onward.

2. METHODOLOGY

2.1 DE-STAR

While there have been many suggested methods of interstellar travel, the method we propose, in particular does not require on-board engines. Utilization of the DE-STAR 4, a conceptual space-based laser system[9], as a photon drive, propels a 100kg spacecraft with a 30m diameter reflector to 0.6% the speed of light at the edge of the solar system. If we assume full reflector illumination at the edge of the solar system (roughly 900m diameter reflector) then we obtain 2% c, which is increased to 3% ($2^{1/2}$ times 2% c, see Section 2.3) with continued partial illumination for large distances. DE-STAR is a proposed modular system composed of an array of phase-locked lasers and powered by solar panels. With current technology, a DE-STAR 4 (10^4m per side) outputs an average of 70GW laser power. A reflector mounted at the rear of the spacecraft reflects incoming photons generating 470N thrust. In this paper, we demonstrate how directed energy from a DE-STAR could be used as a mechanism for relativistic propulsion, as depicted in Fig. 1.

2.2 Case I: Spot Size Smaller Than Reflector ($D_s < D$)

As the spacecraft travels away from DE-STAR the spot size of the lasers will grow and eventually be larger than the reflector on the spacecraft. While the spot size is smaller than the reflector, it is straightforward to solve for time as a function of velocity. We know that the force due to the radiation pressure of the reflected laser beam is

$$F = \frac{P\varepsilon_r}{c} \tag{1}$$

where P is the power at the spacecraft, and $\varepsilon_r = 1 + \varepsilon$ where ε is the reflection coefficient, $\varepsilon = 0$ for no reflection (absorption) and $\varepsilon = 1$ for complete reflection. We note that given an initial power, P_0, from DE-STAR, relativistic effects must be taken into account. That is:

$$F = \frac{P_0 \varepsilon_r}{\gamma c} \tag{2}$$

Since it is known that force is the derivative of the momentum, $\rho = m_0 \gamma v$, where m_0 is the resting mass.

$$\frac{P_0 \varepsilon_r}{\gamma c} = \frac{d\rho}{dt} \tag{3}$$

$$\frac{P_0 \varepsilon_r}{\gamma c} = m_0 \left(\frac{d\gamma}{dv} v + \gamma \right) \frac{dv}{dt} \tag{4}$$

Further simplifying, we obtain t in terms of the relativistic speed $\beta = v / c$

$$t = \frac{m_0 c^2}{P_0 \varepsilon_r} \int \frac{d\beta}{(1 - \beta^2)^2} \tag{5}$$

Which then solves to the analytical form

$$t = \frac{m_0 c^2}{2 P_0 \varepsilon_r} \left(\frac{\beta}{1 - \beta^2} + \frac{1}{2} \ln \left| \frac{1 + \beta}{1 - \beta} \right| \right) \tag{6}$$

$$t = \frac{m_0 c^2}{2 P_0 \varepsilon_r} \left(\frac{\beta}{1 - \beta^2} + \tanh^{-1}(\beta) \right) \tag{7}$$

We now can now invert our equation and obtain plots of β versus time.

We plot the speed achieved by a 100kg spacecraft during various time intervals after initial propulsion by DE-STAR 4 in Fig. 2. The velocity is non-relativistic at early times followed by the transition to relativistic travel and ultimately reaching the relativistic limit.
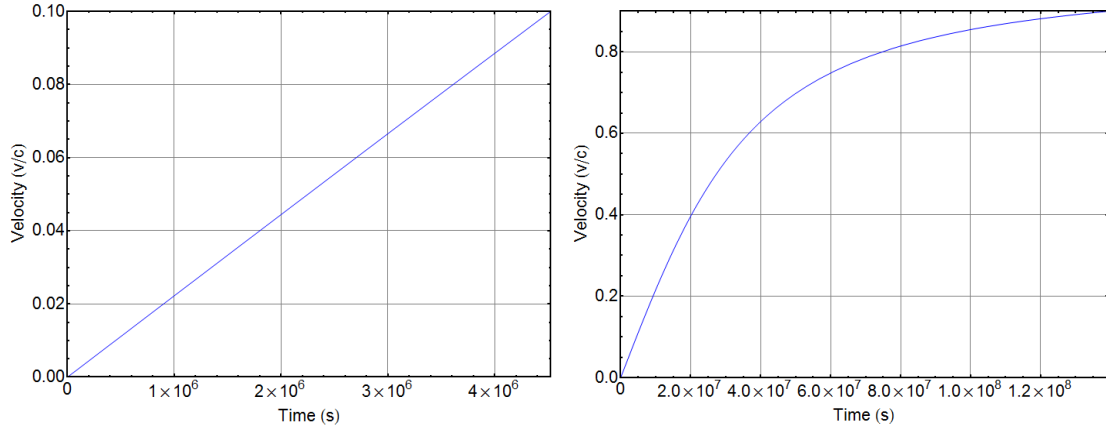

Figure 2. The left plot shows velocity versus time up to 10% c using the inverted equation for time (7), setting m_0 = 100kg, P_0 = 50GW, and $\varepsilon_r = 2$, and depicts the spacecraft traveling at non-relativistic velocities for the first 46 days. As the velocity increases, the spacecraft begins to display relativistic effects. At approximately 4 years, the velocity approaches its relativistic limit, c, shown in the right plot. This figure assumes a reflector size of sufficient diameter such that the spot size is always smaller than the reflector. At sufficiently large time, this becomes unrealistic for all known materials. These figures confirm that our equations obey the relativistic limit. For example, a time of 4.5×10^6s corresponds to a spot size (diameter) of 7.2×10^3 meters and a time of 10^8s corresponds to a spot diameter of 2.7×10^6m.

As a reality check, let us calculate how thick a reflector with diameter of 10^6m and mass of 100kg (as assumed in Fig. 2) must be. Given a density of 1g/cm^3 we have a thickness of 10^{-13}m, or 10^{-4}nm. While this is not possible with current technology (Section 2.4) it may one day be possible with nano-technology, we discuss this further in Section 2.4.

We can confirm the non-relativistic limit for $\beta << 1$

$$\ln\left|\frac{1+\beta}{1-\beta}\right| = \sum_{1}^{\infty}\frac{2}{2n-1}\beta^{2n-1} \rightarrow 2\beta, \beta << 1 \tag{8}$$

$$t \rightarrow \frac{m_0 c^2}{2P_0\varepsilon_r}(\beta+\beta) = \frac{m_0 vc}{P_0\varepsilon_r} = \frac{\rho}{F} \tag{9}$$

As expected, for heavy spacecraft (large m_0) the time to relativistic speed is longer. In the instance of a 10^4kg spacecraft the speed remains non-relativistic even after 190 months, as shown in Fig. 3.
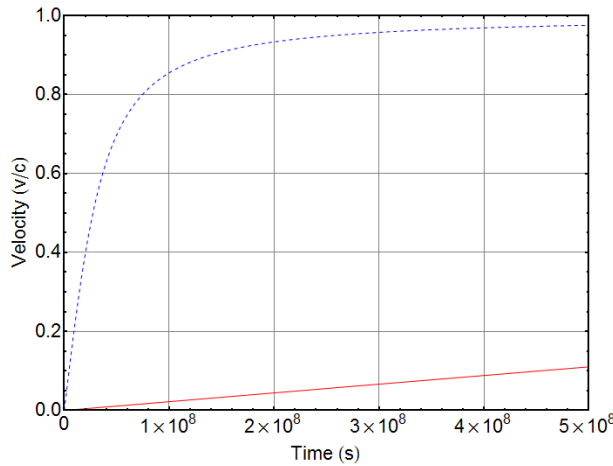

Figure 3. Plot of velocity versus time for $m_0 = 10^2$kg (blue dashed line) and $m_0 = 10^4$kg (red solid line) with $P_0 = 50$GW and $\varepsilon_r = 2$. As expected the heavier mass is non-relativistic for a longer period of time. Be sure to note that 10^8s corresponds to an approximately 10^6m diameter spot size, an unrealistic sized reflector.

A 1,000 kg (assuming a 30m reflector) spacecraft propelled by DE-STAR 4 (70GW) reaches Mars in about 10 days. The 100 kg spacecraft discussed here reaches Mars in approximately 3 days. With constant illumination, the spacecraft undergoes rapid and prolonged acceleration followed by slow leveling off to constant velocity approaching the relativistic limit at approximately 5 light years distance from the Earth.
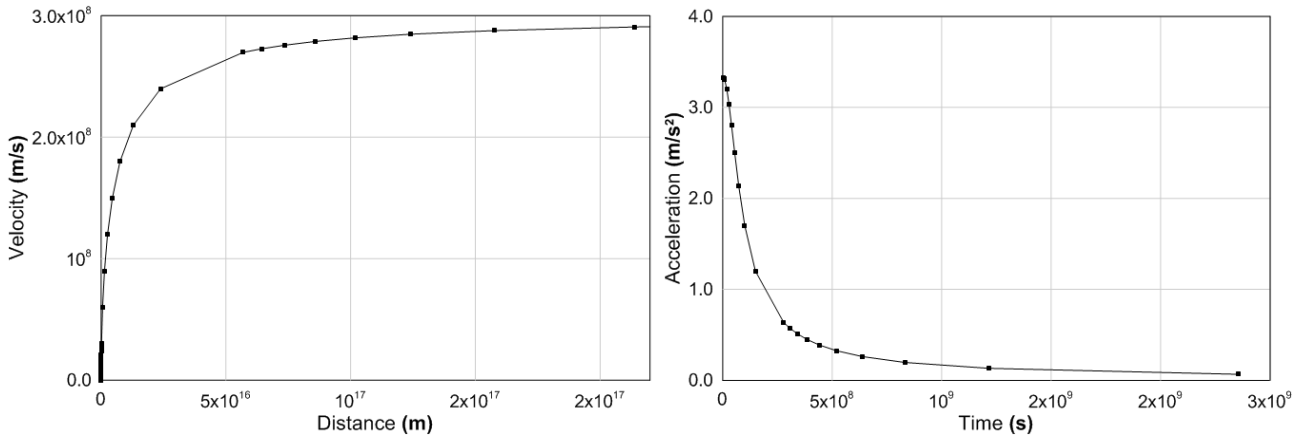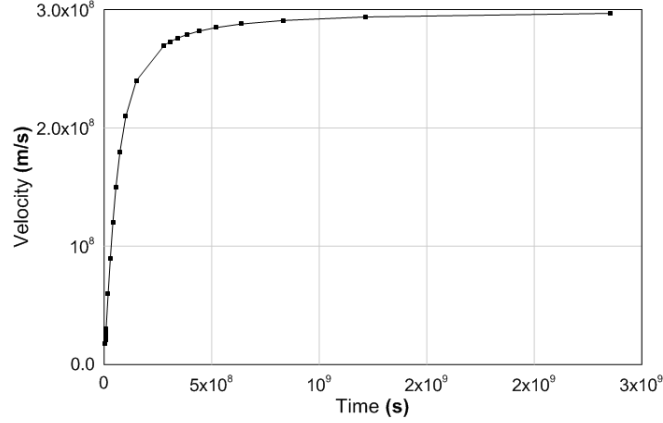
Figure 4. (a) Numerically solving for velocity and plotting it as a function of distance gives a sense of distance over which the spacecraft approaches it's relativistic limit. (b) Numerical solutions show rapid acceleration over the first six years followed by leveling off. Note that at the start, the acceleration is not much more than one third of Earth's gravity. (c) In roughly 6 years the spacecraft will travel approximately 300,000AU (~5ly). All of these plots assume Case I, where the reflector is always larger than the spot size. Both plots use $m_0 = 100$kg, $P_0 = 50$GW, and $\varepsilon_r = 2$.

While it is not straightforward to analytically solve for $v(t)$, it is alternatively possible to use numeric methods to solve for distance and acceleration. We numerically solved for $d(t)$, $a(t)$, and $v(d)$, shown in Fig. 4.
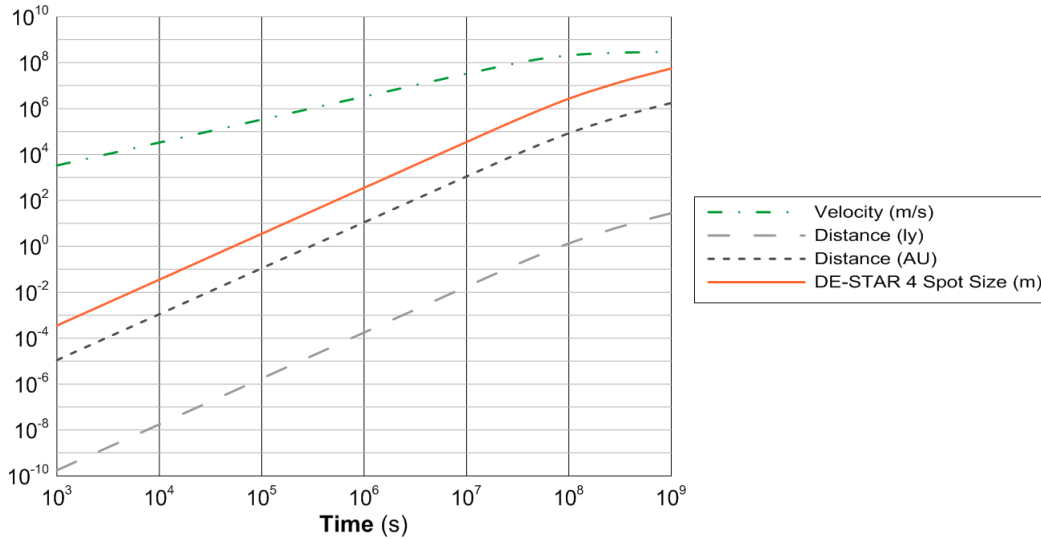

Figure 5. Plot of velocity, distance, and DE-STAR spot size (reflector size required) with respect to time. It is important to notice the size of the reflector that would be required in Fig. 2 in order to obtain 90% the speed of light. The y-axis corresponds to different units depending on which set of data you observe.

We must take into consideration the size of the reflector necessary at large distances. Assuming DE-STAR 4 is diffraction limited as seen in Fig. 5, we conclude that the reflector size required to reach 90% c (Fig. 3) is approximately 10^6m. As this is unrealistic, we must consider what happens when the spot size is larger than the reflector.

2.3 Case II: Spot Size Larger Than Reflector ($D_s > D$)

We consider the situation of a reflector size smaller than the laser spot size, that is $D_s > D$ as shown in Fig. 6. In the following we assume perfect reflection, that is $\varepsilon_r = 2$. Results are currently available for the non-relativistic case. The relativistic case must be considered and is ongoing research.
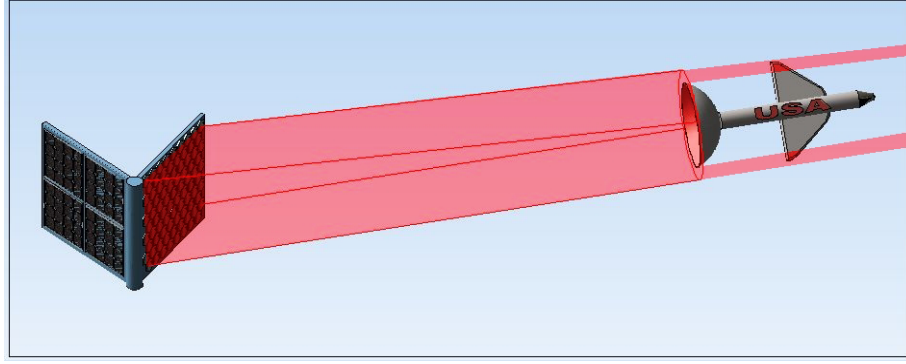
Figure 6. As the spacecraft distance from DE-STAR increases the laser spot size begins to spill over the area of the reflector resulting in loss of potential power input.
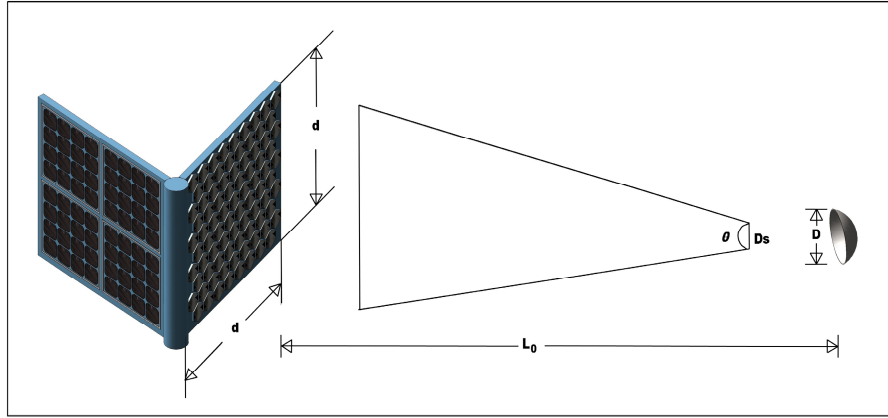

Figure 7. Diagram depicting relevant variables as discussed in Section 2.3. Note that image is not to scale.

In order to solve the non-relativistic case we must first define L_0 to be the distance at which $D_s = D$. Now let L be the distance to the reflector in meters. We solve for the kinetic energy from $L = 0 \to L_0$ $(D_s < D)$ (See Fig. 7.)

$$KE_1 = FL_0 \tag{10}$$

Given that $L_0 = \dfrac{dD}{2\lambda}$ and $F = \dfrac{P_0}{c}$ we rewrite our kinetic energy to a more reasonable form

$$KE_1 = \frac{P_0 dD}{c\lambda} \tag{12}$$

We can further solve for the kinetic energy from $L = L_0 \to \infty$,

$$KE_2 = \int_{L_0}^{\infty} FdL \tag{13}$$

for $D_s > D$ we know that the force is given by

$$F = \frac{2P_0}{c}\left(\frac{L_0}{L}\right)^2 \tag{14}$$

By using equations (13) and (14) we can then solve for our kinetic energy

$$KE_2 = \frac{P_0 d^2 D^2}{2c\lambda}\left(\frac{1}{L_0} - \frac{1}{L}\right) \tag{15}$$

We now want to find the total kinetic energy by adding (15) and (12).

$$KE_{total} = \frac{2P_0}{c\lambda}L_0\left(2 - \frac{L}{L_0}\right) \tag{16}$$

which we can then solve for $v(L)$

$$v(L) = \sqrt{\frac{4P_0}{mc}L_0\left(2 - \frac{L_0}{L}\right)} \tag{17}$$

As this calculation does not take into account relativistic effects it will only be accurate for $v \ll c$. If we say that v_0 is the speed for which $L = L_0$, that is $v_0 = \sqrt{\frac{4P_0}{mc}L_0}$, then for any subsequent distance we can write

$$v(L) = v_0\sqrt{2 - \frac{L_0}{L}} \tag{18}$$

This is especially important, as we learn that approaching infinite distance our speed will essentially be $\sqrt{2}v_0$. Another point of interest is that the velocity is a function of $m^{-1/2}$, so for small mass the velocity will increase. Mass is proportional to one over the square of the diameter, hence speed will be proportional to $1/D^{1/2}$. Though it is counterintuitive, smaller reflectors (where the mass of the payload is insignificant compared to the reflector mass) go faster. Since $v = (2aL)^{1/2}$ where a is the acceleration and is inversely proportional to mass ($\propto 1/D^2$) and L is the distance over which the acceleration occurs, which is proportional to D, the product is proportional to $D^{-1/2}$. This raises the possibility of highly relativistic speeds for small reflectors and nano-spacecraft. The key technological advance would be a small reflector capable of handling extremely large fluxes.

2.4 Reflector

We have alluded to the importance of the reflector, which is arguably the most critical component. The extreme amount of power (70GW) contacting the surface requires near perfect reflection. Since our laser is extremely narrow-band, we can easily tune the reflector for lower energy loss. With dielectric coatings, 99.999% reflectivity efficiency has been achieved on glass, and with current technology, it appears to be possible to achieve 99.99+% on plastics. Problems begin to arise as the reflectivity decreases. Excess energy heats up the reflector, potentially damaging or destroying it. Table 1 depicts the temperature rise of a reflector of given reflectivity assuming 70GW power and only back-side emission, which lowers the temperature. Dual side emission would be better but is not assumed here to be conservative.

Table 1. Table depicts the temperature due to heat dissipation for three different reflectivities. It is assumed that there are only single side (back) emissions. These temperature elevations are practical for possible reflector materials.

Reflectivity	Heat Dissipation	Temperature
99.999%	800W/m^2	350K (76.85°C)
99.995%	4kW/m^2	520K (246.85°C)
99.99%	8kW/m^2	610K (336.85°C)

A thin film roll coat reflector is a possible option for large reflector design. A diameter of at least 30m is required at 1AU to match the DE-STAR 4 spot size[9]. In order to reduce the weight of our spacecraft, we also require a reflector that

is thin and lightweight. The current reflector design (Fig. 8) has 99.995% reflectivity, resulting in temperature elevation to approximately 500K. A film density of ~10g/m^2 leads to a reflector measuring 900m^2 (30m spot size) and 10μm thick, weighing only 9kg. This is realistic and satisfies our requirements. Given the distance of 1AU and DE-STAR 4 the diffraction limited spot size is 30m by 30m. With our initial power of 70GW this gives us 80MW/m^2 at 1AU.
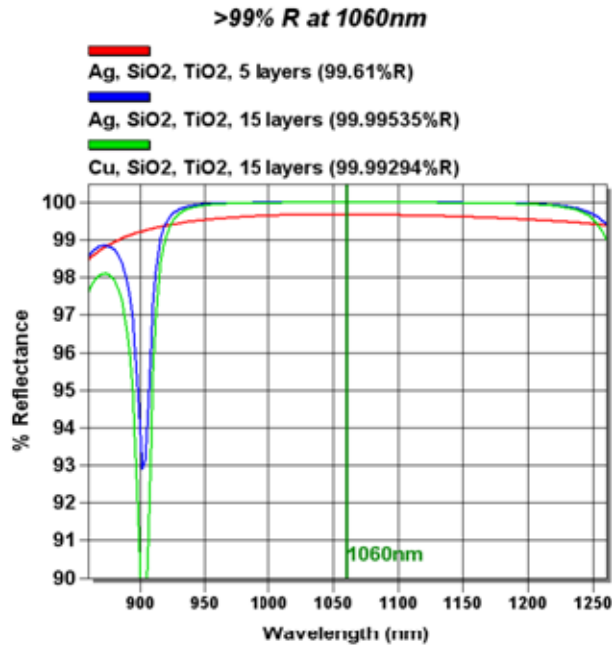

Figure 8. Graph of the percent reflectance for a thin film roll reflector. The green line of 1060nm corresponds to DE-STAR's laser wavelength. (Source: figure and data from Surface Optics - private communications (2013)).

In the future it may be possible to use nano-technology to produce ultra thin reflectors. Assuming that we have a 1nm thick graphene reflector that is optimized for our laser, the mass will decrease by 10^{4}m leading to a 100 times increase in velocity. However, graphene reflectors are not yet developed and not yet able to be tuned to our laser.

Table 2. The mass of a reflector with density 1g/cm^3 is shown for various thicknesses (t) and diameters (D) assuming a square reflector shape.

	D=1m	D=10m	D=10^{2}m	D=10^{3}m	D=10^{4}m	D=10^{5}m	D=10^{6}m
t=1nm	10^{-6}kg	10^{-4}kg	10^{-2}kg	10^{0}kg	10^{2}kg	10^{4}kg	10^{6}kg
t=10nm	10^{-5}kg	10^{-3}kg	10^{-1}kg	10^{1}kg	10^{3}kg	10^{5}kg	10^{7}kg
t=10^{2}nm	10^{-4}kg	10^{-2}kg	10^{0}kg	10^{2}kg	10^{4}kg	10^{6}kg	10^{8}kg
t=10^{3}nm	10^{-3}kg	10^{-1}kg	10^{1}kg	10^{3}kg	10^{5}kg	10^{7}kg	10^{9}kg
t=10^{4}nm	10^{-2}kg	10^{0}kg	10^{2}kg	10^{4}kg	10^{6}kg	10^{8}kg	10^{10}kg

2.5 Realistic Example

Let us consider a realistic example. Suppose we have a DE-STAR 4 photon drive outputting an average of 70GW (470N). Let our spacecraft have a 30m reflector and 9kg weight as depicted in Section 2.4. Allowing for a 91kg structure and payload, our total spacecraft weight is 100kg. Under these conditions, it would take the spacecraft approximately 3 days to reach Mars, and it would be traveling 0.4% the speed of light and about 0.6% c at the end of the solar system. If we wanted to simply propel the reflector with minimal payload (say 1kg additional payload plus the 9kg reflector) the speeds would increase by 10$^{1/2}$ (approximately 3.2) or 1.4% c at 1 AU and 2% c at the edge of the solar system. For a small CubeSat like payload this is an interesting option.

3. PRACTICALITY

While we have attempted a realistic approach to this rather futuristic topic, consideration of its practicality is desired. Foremost, DE-STAR is designed primarily as an asteroid impact defense system. It is, however, important to note that as a standoff system, DE-STAR is available on a continuous basis not only for ongoing planetary defense but also for alternate topics under study. While other methods for destroying or deflecting asteroids have been proposed (kinetic impactors, nuclear weapons, etc.), these systems are "stand-on" methods. That is, each is available for a single mission and as such, would have a risk of failing. For true planetary defense, numerous backup systems would need to be on standby, ready for immediate deployment[10]. Additionally, unlike DE-STAR, the cost of other approaches can not be distributed amongst multiple uses, thus mitigating the cost. DE-STAR is in a state of constant readiness. In the case we make here, DE-STAR is able to co-operate as a planetary defense system and a source for photons to drive relativistic travel.
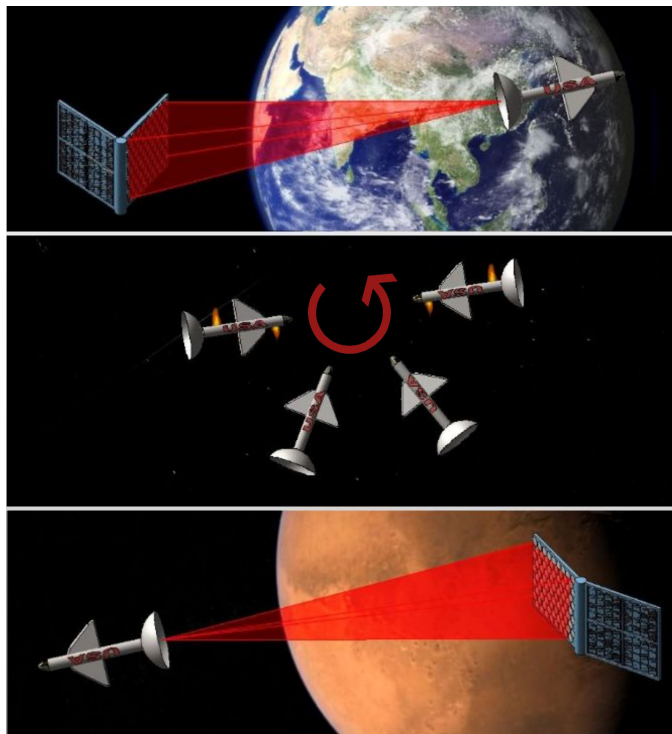

Figure 9. By stationing a second DE-STAR photon drive at the mission destination, a spacecraft can be decelerated under controlled conditions. This deceleration is achieved by a "ping-pong" method where the spacecraft rotates and first one DE-STAR and then the second provide opposing forces to the reflector.

Of importance in the design concept we have put forth here, is the detachment of the photon drive from the spacecraft. The elimination of onboard spacecraft engines other than the light duty ones necessary for steering creates meaningful advantages in terms of weight. These advantages translate directly to increased capability for acceleration and deceleration. Other uses include unmanned flyby missions to distant objects. In cases of short distance travel, such as a manned mission to Mars for instance, two DE-STAR systems are employed, one orbiting the Earth and one stationed at the destination. The two photon drives are used to "ping-pong" the spacecraft between them thus achieving controlled deceleration as shown in Fig. 9.

4. ONGOING WORK

DE-STAR is a continuing research project. The relativistic case when the laser spot size is larger than the size of the reflector requires further thought (Section 2.3). Additionally, reflector science is an area of rapid development, which warrants further discussion. The field of nano-technology will likely increase our ability for drastically thinner and larger reflectors enabling $D_s < D$ at larger distances. Other projects include interstellar communications, asteroid deflection, and asteroid spectroscopy.

4.1 Future Possibilities

We have restricted the analysis to the size of DE-STAR needed for planetary defense but a far future society may master building even larger DE-STAR systems than a DE-STAR 4. In the non-relativistic limit the speed to the point L_0 of the beam no longer filling the reflector is

$$v_0 = \sqrt{\frac{4P_0}{mc}L_0} \tag{19}$$

Note that the power P_0 scales as the d^2 where d is the array size and the distance to beam filling L_0 scales as d (divergence angle scales as $1/d$) and thus the speed to L_0 scales as $d^{3/2}$ for a given reflector size. Hence a scale up to a DE-STAR 5 or 6 would increase the speed by $10^{3/2} \sim 32$ and $100^{3/2} \sim 1000$ respectively. These are clearly large factors to consider. We can barely imagine building a DE-STAR 4 let alone a class 5 or 6 but a future society might be able to and this would enable large-scale relativistic travel. In the relativistic limit from Eq. 6 we can compute the time to a given speed is given by

$$t = \frac{m_0 c^2}{2P_0 \varepsilon_r}\left(\frac{\beta}{1-\beta^2} + \frac{1}{2}\ln\left|\frac{1+\beta}{1-\beta}\right|\right) \tag{20}$$

Thus the time to a speed scales as $1/P_0$ or d^{-2}. Hence a DE-STAR 5 or 6 would shorten the time to a given speed by a factor of 10^2 and 10^4 respectively or alternatively allow mass increases of the same factor. These are clearly dramatic changes.

5. CONCLUSION

We propose a method of relativistic travel utilizing a stationary photon drive. Utilization of DE-STAR, propels a 100kg spacecraft with a 30m reflector to obtain 0.4% c at the edge of the solar system and with continued illumination 0.6% c. If we maintain a fully illuminated reflector (900m diameter at 30AU) we would have a speed of 2% c at the edge of the solar system and 3% ($2^{1/2}$ times 2%) with continued partial illumination for large distances. In order to calculate the travel velocity of the spacecraft, two cases must be considered; the laser spot smaller than the reflector on the spacecraft and then again, once the size of the laser beam spills over the reflector diameter. We provide a solution for $t(v)$ in the case of DE-STAR spot size smaller than the reflector, and subsequently numerically solve for acceleration and distance along with $v(d)$. We then address the non-relativistic case as the spot size becomes larger than the reflector. Work is ongoing for the relativistic portion of this case. We find that our solutions are reasonable and approach the proper limits. The reflector diameter is of significant importance, as larger reflectors allow us to propel our spacecraft for longer distances. Though it should be noted that lighter reflectors allow for faster velocities. A thin film roll reflector with 99.995% reflectance has been designed and is currently possible to construct. The design is of sufficient quality to operate within projected heat buildup constraints. The reflector weight is sufficiently small (9kg for 30m by 30m) to allow the addition of a reasonable payload and meets our propulsion projections. We conclude, upon further discussion of practicality constraints, the feasibility of our proposed method of relativistic travel if DE-STAR is indeed a launched system.

REFERENCES

[1] Bussard, R., "Concepts for Future Nuclear Rocket Propulsion," Journal of Jet Propulsion 28, 223-227 (1958).
[2] Bond, A., and Martin, A. R., "Project Daedalus - Final Report," Journal of the British Interplanetary Society Supplement, 5-7 (1978).
[3] Beals, K. A., Beaulieu, M., Dembia, F. J., Kerstiens, J., Kramer, D. L., West, J. R., and Zito, J. A., "Project Longshot: An Unmanned Probe to Alpha Centauri," US Naval Academy, NASA-CR-184718, (1988).
[4] Forward, R. L., "Antiproton annihilation propulsion," Journal of Propulsion and Power 1, 370-374 (1985).
[5] Schmidt, G., "Propulsion research and technology at NASA Marshall Flight Center," 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, DOI:10.2514/6.1998-3230, (1998).
[6] Marx, G., "Interstellar vehicle propelled by terrestrial laser beam," Nature 211, 22-23 (1966).

[7] Forward, R. L., "Roundtrip interstellar travel using laser-pushed lightsails," Journal of Spacecraft and Rockets 21, 187-195 (1984).

[8] Bae, Y. K., "Prospective of photon propulsion for interstellar flight," Physics Procedia 38, 253-279 (2012).

[9] Lubin, P. M., Hughes, G. B., Bible, J., Bublitz, J., Arriola, J., Motta, C., Suen, J., Johansson, I., Wu, J., Milich, A., Oleson, M., and Pryor, M., "Directed Energy Planetary Defense," Proc. of SPIE, Optics & Photonics (2013).

[10] Hughes, G. B., Lubin, P. M., Bible, J., Bublitz, J., Arriola, J., Motta, C., Suen, J., Johannson, I., Riley, J., Sarvian, N., Wu, J., Milich, A., and Pryor, M., "DE-STAR: Phased Array Laser Technology for Planetary Defense and Other Scientific Purposes," Proc. of SPIE, Optics & Photonics (2013).