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Prospective of Photon Propulsion for Interstellar Flight

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Abstract. Mastering photon propulsion is proposed to be the key to overcoming the limit of the current propulsion technology based on conventional rocketry and potentially opening a new space era. A perspective on photon propulsion is presented here to elucidate that interstellar manned roundtrip flight could be achievable in a century within a frame of exiting scientific principles, once the required existing technologies are further developed. It is shown that the developmental pathway towards the interstellar flight demands not only technological breakthroughs, but consistent long-term world-scale economic interest and investment. Such interest and investment will result from positive financial returns from routine interstellar commutes that can transport highly valuable commodities in a profitable manner. The Photonic Railway, a permanent energy-efficient transportation structure based on the Beamed-Laser Propulsion (BLP) by Forward and the Photonic Laser Thruster (PLT) by the author, is proposed to enable such routine interstellar commutes via Spacetrains. A four-phased evolutionary developmental pathway towards the Interstellar Photonic Railway is proposed. Each phase poses evolutionary, yet daunting, technological and financial challenges that need to be overcome within each time frame of 20 – 30 years, and is projected to generate multitudes of applications that would lead to sustainable reinvestment into its development. If successfully developed, the Photonic Railway would bring about a quantum leap in the human economic and social interests in space from explorations to terraforming, mining, colonization, and permanent habitation in exoplanets.

Keywords: photon propulsion, photon thruster, photon rocket, laser propulsion, laser thruster, Photonic Laser Thruster, PLT, Photonic Railway, Spacetrain, Beamed-Laser Propulsion, BLP, solar sail, lightsail, Space Solar Power, formation flying, space telescopes.
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INTRODUCTION

Photon propulsion has been widely discussed for decades as a next generation propulsion that can make interstellar flight possible, which requires the ability to propel spacecraft to speeds at least 10 % of the light speed, v~0.1c = 30,000 km/sec (Tsander, 1967). Photon propulsion has been considered to be one of the best available interstellar propulsion concepts, because it is founded on established physics and technologies (Forward, 1984). However, compared with its theoretical progress, its actual demonstration either in laboratory settings or space environment has progressed very slowly. It has been only very recent that a successful recycling photon thruster capable of amplifying thrust by orders of magnitude was demonstrated in a laboratory setting (Bae, 2007b, 2008), and that a successful space deployment of solar sail was achieved. (Takeuchi, 2011) With such successes along with recent impressive development of high power lasers and associated optics, which form necessary technological foundations for photon propulsion, therefore, the time has matured to take photon propulsion much more seriously.

One class of main traditional photon propulsion concepts utilizes photons generated by onboard photon generators, such as blackbodies or lasers, powered by solar or nuclear power. Regardless of the photon generator characteristics, a unified theory on such onboard photon propulsion can be used for providing insight on the perspective of photon propulsion. In this unified theory, it is assumed that the propulsion system has a single stage. Suppose the total mass of the photon rocket/spacecraft is M that includes fuels with a mass of αM with α<1. Let us assume that the fuel mass to propulsion-system energy conversion efficiency is γ, and the propulsion-system energy to photon energy conversion efficiency is δ that is much smaller than 1. Then the maximum total photon energy available for propulsion, E_{ph}, is given by

$$E_{ph} = \alpha\gamma\delta M c^2. \tag{1}$$

If the total photon flux can be directed at 100 % efficiency to generate thrust, the total photon thrust, T_{ph}, is given by

$$T_{ph} = \frac{E_{ph}}{c} = \alpha\gamma\delta M c. \tag{2}$$

The maximum attainable velocity, V_{max}, of the photon propulsion system for $V_{max} \ll c$, is given by

$$V_{max} \approx \frac{T_{ph}}{M} = \alpha\gamma\delta c. \tag{3}$$

For example, the approximate maximum velocities achievable by various onboard nuclear power photon propulsion systems are given in Table 1. The maximum velocity limits by two nuclear power concepts are orders of magnitude less than the required 0.1 c for interstellar travel.

Table 1 The maximum velocity obtainable by photon propulsion with onboard nuclear photon generators with exemplary parameters.

Energy Source	α	γ	δ	V_{max}/c
Fission	0.1	10^{-3}	0.5	5×10^{-5}
Fusion	0.1	4×10^{-3}	0.5	2×10^{-4}

Therefore, unless multistage nuclear photon propulsion engines are used, single-stage systems are unable to obtain the maximum velocity greater than 0.1 c, thus such photon propulsion systems are impractical for interstellar missions.

The above theoretical limits posed by photon propulsion with onboard photon generators can be overcome, if the photon generators and the spacecraft are physically separated. In this concept, the photons are beamed from the photon source to the spacecraft using lasers as in the Beamed-Laser Propulsion (BLP). In particular, Forward (1987a) worked on a wide range of interstellar propulsion concepts including photon propulsion and antimatter rocket propulsion, and emphatically summarized the potential of and technological challenges posed by photon propulsion for interstellar flight. (Forward, 1995)

> *Any sort of rocket, even an antimatter rocket, has marginal performance for interstellar missions. Only non-rocket propulsion offers any prospects for travel to even the nearest stars. The most promising concepts involve some sort of beamed-power propulsion. These non-rocket-propulsion systems keep the heavy parts of a vehicle (the expellant, the energy source, and the "engine" that puts the energy into the expellant) in the solar system. Because they are near the Sun, large amounts of mass are available, and we can maintain the energy source (usually the abundant sunlight) and the "engine" as the mission proceeds. The best technique seems to be beamed-laser-propulsion. Yet, beamed-laser propulsion is an inefficient way to put energy into a vehicle. At the start of the mission, most of the energy in the incident photons is still in the photons after they reflect from the sail. It is not until the vehicle velocity exceeds 0.5 c that the reflected photons are redshifted significantly, showing that much of the photon energy has gone into the vehicle. There must certainly be better and more energy-efficient methods to transport vehicles between the stars.*

In sum, Forward (1984) proposed for the first time BLP aiming at the goal of achieving roundtrip manned interstellar flight. However, according to the recent study by Millis (2010) the power and engineering requirements to implement the original BLP are projected to be only achievable beyond the year 2500. Considering the unprecedentedly large world-scale investment required for such interstellar flight, unless there is enormous potential financial return from such endeavors, the chance of sustaining continuous return investment in such programs is dismal. Furthermore, the duration of such development could expand well over a century, and in human history, there have been only a few projects, such as the Egyptian pyramids and the Chinese Great Wall, which continued over such a long duration. In modern times, such “century”-long projects are unlikely, thus, for interstellar BLP development, a multi-phased approach, in which each phase has its financial returns that can sustain the momentum and positive economic outlook of the program, seems to be more programmatic.

Here, for the sake of simplicity, BLP is used to represent a group of varying terminologies for photon propulsion using direct momentum transfer of laser generated photons, such as laser lightsail propulsion. An important theoretical understanding and development of BLP was obtained by Marx, (1966) Redding, (1967) and Simmons and McInnes (1993) who calculated that the energy conversion efficiency of photon propulsion is approximately proportional to v/c at low speeds (v<0.1c), thus is very small at very low speeds (v<<0.1c). However, once the spacecraft reaches higher speeds (v>0.1c), owing to the favorable Doppler-shift energy transfer, photon propulsion becomes much more energy efficient, thus there is a need to bridge this energy efficiency gap. Meyer et al. (1987) followed by Simmons and McInnes (1993) proposed that recycling photons between the spacecraft and the photon beaming source would be a solution to this issue. Possible applications of photon recycling using passive resonant optical cavities (lasers are located outside of the optical cavity), the Laser Elevator, in launching and propelling spacecraft at higher velocities with higher efficiencies than those available by exiting rocket engines, was first proposed and extensively studied by Meyer et al. (2002). They concluded that for missions requiring very fast transit times in the solar system or for interstellar fights, the recycling photon propulsion vehicles are much more energy efficient than that carry their own propellant, such as nuclear rockets.

However, the usage of such passive resonant optical cavities for recycling photon propulsion was questioned by the author, because they are extremely unstable against the motion of the cavity mirrors, thus unsuitable for propulsion. (Bae, 2006, 2007a) Therefore, the author proposed the use of active resonant optical cavities, in which the optical gain medium is located within the cavity, and named the thruster with such optical cavities as the Photonic Laser Thruster (PLT). (Bae, 2007a) The proof-of-concept PLT was demonstrated in laboratory environment by the author under the auspicious of NIAC/NASA, and its several spin-off space applications, including the usage in primary propulsion and satellite/spacecraft maneuvering were proposed and investigated. (Bae, 2007b, 2007c, 2008)

Recently, the author proposed a permanent energy efficient transport structure based on photon propulsion, the Photonic Railway, which aims enabling routine interstellar commutes via Spacetrains. (Bae, 2011) The Photonic Railway, if successful, would radically depart from the conventional spaceship concepts, in which a single spacecraft carries both an engine and a large quantity of fuel. Rather, the Photonic Railway would have permanent reusable space structures that propel Spacetrains, which would consist of mainly crew habitats, and navigation and crew safety equipment. The technological foundation of the Photonic Railway lies on a strategic combination of BLP by Forward and PLT, which is named here PLT-BLP. It is predicted that the development of PLT-BLP can be further expedited by incorporating the anticipated development in x-ray lasers and advanced material science and technologies, and the interstellar PLT-BLP is projected to be within reach in a century.

This paper reviews briefly the current status of BLP and general issues regarding photon propulsion. Then it presents technical issues and a brief history of PLT, and a summary of various applications of PLT including spacecraft maneuvering at earth orbits. Then a technical description of the Photonic Railway is presented, which is followed by its four-phased developmental pathway towards Interstellar Photonic Railway for routine manned interstellar commutes.

PHOTON PROPULSION PERSPECTIVES

Photon propulsion uses direct momentum transfer of photons to propel spacecraft and has been researched since the beginning of the 20th century. (Tsander, 1967) According to Special Relativity, the highest velocity of the rocket exhaust particle can have is the light velocity, $c = 3 \text{ x}10^8$ m/sec. Therefore, photons are the ultimate rocket fuel that will produce extremely high specific impulse, I_{sp}. The I_{sp} of photon propulsion can be derived from the following equations. The I_{sp} of a rocket engine is given by:

$$I_{sp} = \frac{F_T}{g\dot{M}}, \tag{4}$$

where F_T is the photon thrust, g is the gravity acceleration constant, and $\dot{M}$ is the mass flow rate. For photon propulsion, F_T of photon flux is given by:

$$F_T = \frac{Nh\nu}{c}, \tag{5}$$

where N is the photon number flux, h is the Plank constant, and ν is the photon frequency. To be simplistic, here we assume that all photons have a single frequency, ν. The mass flow of the photons is different from that of the non-relativistic fuel exhaust particles, because the photon does not have a rest mass. However, in the relativistic sense, the mass and energy are equivalent, and when the rocket emit photons, it loses small amount of mass through the energy loss. Thus, according to the mass-energy equivalence principle, $E = mc^2$, the equivalent mass flow $\dot{M}$ of photons is given by:

$$\dot{M} = \frac{Nh\nu}{c^2} \quad . \tag{6}$$

By combining Eqs. 5 and 6 with Eq. 4, one obtains:

$$I_{sp} = \frac{c}{g} = 3.06\times10^7\,\text{sec}\cdot \tag{7}$$

Although photons have the highest I_{sp}, the specific thrust, defined here as the thrust to power ratio of the rocket engine, of photon propulsion is many orders of magnitude smaller than conventional propulsion including electrical and beamed-energy propulsion. The specific thrust of the photon propulsion, F_s is given by:

$$F_s = \frac{F_T}{Nh\nu} = \frac{1}{c}\cdot \tag{8}$$

Fig. 1 shows the thrust to power ratio, which is defined as specific thrust here, of chemical rockets, electric thrusts that include Hall thrusters, and Pulsed Plasma Thrusters, in comparison with that of photon thrusters. The specific thrust of the photon thruster is several orders of magnitude smaller than that of conventional thruster, such as electrical thrusters, because it has the highest I_{sp}. The green line in Fig. 1 represents a universal $1/I_{sp}$ curve that shows the general behavior. The inefficiency in producing thrust at extremely high I_{sp}, is a universal tendency (the law of physics) in all thrusters, and it is not unique to the photon thruster. In other words, if conventional thrusters can be made to have I_{sp}~10^7 sec, theirs specific thrust would be similar to that of photon thrusters. Therefore, the thrust efficiency does not depend on whether the propellant is made of photons or other particles, such as protons, in achieving relativistic velocities. With 20,000 times photon thruster amplification, the specific thrust of PLT can be comparable with that of LOX thrusters and Lightcraft, but the I_{sp} of PLT would be orders of magnitude larger than that of the latter. (Bae, 2007a)

This equivalence of particle propellant and photon propellant at relativistic propellant exit velocities can be theoretically understood in the following manner. The relativistic momentum, p, of a propellant is given by

$$p = \sqrt{\frac{E^2}{c^2} - m_0^2c^2}\ . \tag{9}$$

where E is the kinetic energy of the propellant and m_0 is the rest mass of the propellant. E in turn is given by

$$E = \frac{m_0c^2}{\sqrt{1-\beta^2}}. \tag{10}$$

where β=v/c and v is the exit velocity of the propellant.

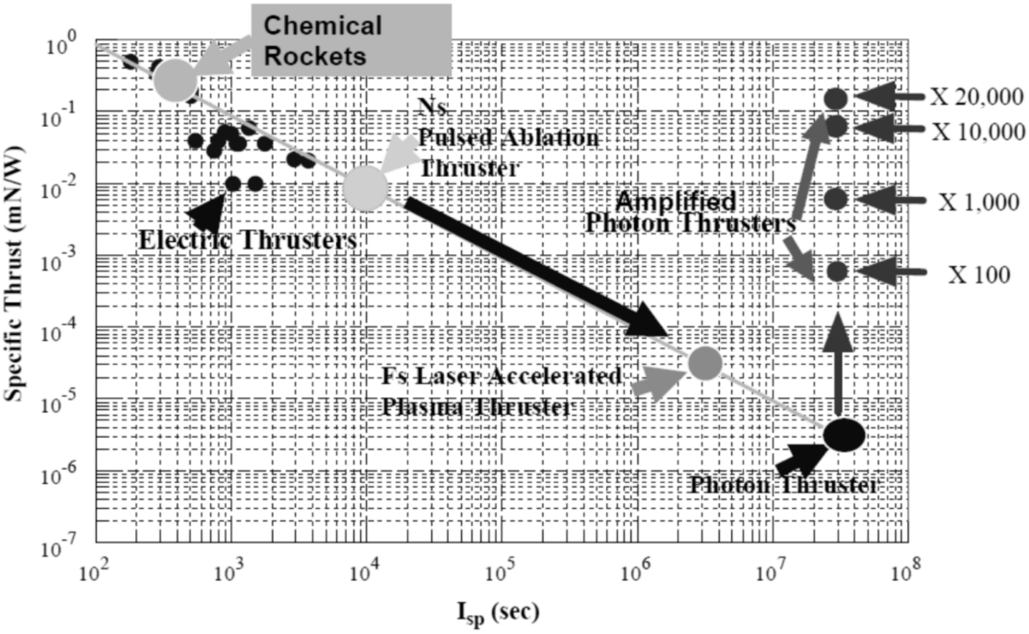

Figure 1. The overall specific thrust (thrust to power ratio) of representative propulsion systems. Without photon thrust amplification, the specific thrust of photon thrusters follows the classic trend: the higher I_{sp}, the lower the specific thrust. The trend can be explained by the universal specific thrust in Eq. 9. However, with photon thrust amplification by recycling greater than 1,000, the photon thruster can be comparable with other conventional thrusters.

The theoretical upper bound of specific thrust, the ratio of the relativistic momentum to the relativistic kinetic energy, F_{su}, now is given by

$$F_{su} = \frac{p}{E - m_0 c^2}. \tag{11}$$

By using Eqns. 9-10, Eq. 11 can be further simplified into

$$F_{su} = \left(\frac{1}{v}\right) \frac{\beta^2}{1 - \sqrt{1 - \beta^2}}. \tag{12}$$

Eq. 12 is a unified relativistic equation that can be applied whether the propellant is mass particles or photons. Thus, regardless of mass or photon propellant, F_{su} is proportional to 1/v modified by a factor $\frac{\beta^2}{1-\sqrt{1-\beta^2}}$, of which value is between 1 and 2. For non-relativistic cases with v<<c, β<<1, because $\sqrt{1-\beta^2} \approx 1 + \frac{\beta^2}{2}$ to the first order, thus

$$F_{su} \approx \frac{2}{v} = \frac{m_0 v}{\frac{1}{2} m_0 v^2}\ . \tag{13}$$

which recovers, the traditional non-relativistic specific thrust for mass particle propellant. The universal equation becomes in this case a non-relativistic specific thrust that is given by the ratio of the non-relativistic momentum and the non-relativistic kinetic energy. On the other hand, for v≈c, β≈1, then

$$F_{Su} \approx \frac{1}{c}. \tag{14}$$

which becomes that same as the specific thrust of the photon propellant given by Eq. 8. Thus, as the particle (non-photon) velocity approaches light velocity, its specific impulse approaches that of photons. This universal specific thrust equation thus points out that for the relativistic propulsion, particles and photons become nearly equivalent in the efficiency of generating thrust at a given propellant energy. The general trend is such that it becomes more and more technologically challenging with particles, such as protons and other ions, to generate relativistic particles. In addition, photon propulsion have other critical advantages over particle-based propulsion: the abilities of beaming and amplifying thrust with laser technologies as presented in the next section. Therefore, it makes much more sense to use photons for relativistic propulsion, and it is asserted here that photon propulsion, in particular PLT-BLP, is the next breakthrough propulsion needed for expanding the scope of human space activities from the near earth activities to routine interstellar commutes.

BEAMED-LASER PROPULSION (BLP)

It was shown here in the previous section that based on the energy conservation principle and the special theory of relativity there are fundamental maximum obtainable velocities by the photon propulsion with onboard photon generators, which are orders of magnitude smaller than 0.1c. Therefore, such photon propulsion is impractical for interstellar flight. BLP, thus is one of the best concepts for interstellar propulsion that is based on proven physics. However, BLP requires beaming of laser photons over astronomical distances, thus needs ultra-large lenses and mirrors, thus poses daunting technological and engineering challenges. Even with these daunting challenges, BLP seems to be the best available concept for interstellar travel because it uses known physics and known technologies. (Forward, 1984, 1995)

The first proposal of BLP over interstellar distances was published by Forward. (1962) A detailed theoretical analysis on BLP was presented by Marx, (1966) in which the use of hard x-rays in order to obtain the operational ranges needed for interstellar flight with ~ 1 km diameter laser beam and optics was first discussed. Marx's paper was followed by a paper by Redding (1967). Redding attempted to correct an error in Marx's equations for the extreme relativistic case and concluded in his paper with a reminder that there was still no way to decelerate the sailcraft at the target star system. Much later, Simmons and McInnes (1993) pointed out that the original calculation by Marx was right and reverted the conclusion by Redding (1967) .

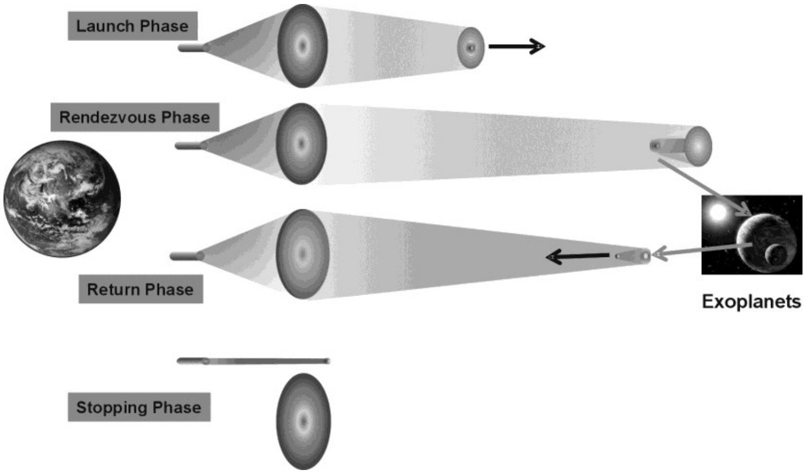

Figure 2. A four stage roundtrip interstellar flight based on BLP proposed by Forward (1984).

A method of interstellar rountrip travel employing BLP was first proposed and analyzed by Forward (1984). In this paper, Forward proposed to use an ultra-large scale solar pumped laser array to provide the required ultra-high laser power for BLP. Forward used 1 μm lasers for assessing the system requirement for a roundtrip travel to nearby stars. Fig. 2 illustrates the salient feature of Interstellar Roundtrip BLP by Forward (1984).

For a manned roundtrip to Epsilon Eridani, at 10.8 light-years, for example, the diameter of the lightsail would be 1,000 km, with the 1,000 km Fresnel transmission lens. The lightsail would be divided into three nested circular segments as shown in Fig. 2. The total vehicle mass would be 80,000 tons, including 3,000 tons for the crews, their habitat, and their exploration vehicles. The lightsail would be accelerated at 0.3 g by a 75,000 TW laser system. At this acceleration, the spacecraft would reach 0.5 c in 1.6 years. The expedition would take 20 years in Earth time and 17 years of crew time. At 0.4 light-years from the target star, the 320 km rendezvous part of the sail detaches from the lightsail center and turns to face the 1,000 km diameter ring sail. The laser light from the earth reflects from the ring sail. The reflected light decelerates the smaller rendezvous sail and brings it to a halt in the Epsilon Eridani system. The crew then explores the system for a few years using the lightsail as a solar sail. For return, the 100-km diameter return sail detaches from the center and turn to face the 320 km diameter ring sail that remains. Laser light beamed from the earth reflects from the ring sail onto the 100-km diameter return sail and accelerates it up to speed back toward the earth. As the return sail approaches the solar system 20 Earth-years later, it is brought to a halt by a final burst of the laser power. Crew members have been away 51 years (5 years exploring) and have aged 46 years. (Forward, 1984)

Other parallel researches on BLP were performed by many scientists and engineers, who used different terminologies, but fundamentally same concept as BLP. Briefly, Meyer et al. (1985) estimated delivering payloads of 10 kg to Mars in 10 days using BLP. Matloff, (1984) Forward, (1987) and Landis. (1999) explored the properties of efficient reflector materials for BLP. The structure engineering of sails and lenses needs high reflectivity mirrors and light, yet extremely rugged, support materials. Fink et al. (1998) proposed high reflectivity omnidirectional dielectric thin film reflectors. Recently, a new emerging technology to fabricate ultralarge adaptive space mirrors using the Photonic Muscle has been proposed and investigated by Ritter and his colleagues (2005). These technologies are predicted to form foundations for constructing the proposed Photonic Railway eventually. (Bae, 2011)

THE PHOTONIC LASER THRUSTER (PLT): A RECYCLING PHOTON THRUSTER

One of important factors in the rocketry is how efficient the energy transfer from the propellant energy to the spacecraft kinetic energy. This factor, as it was shown in the previous section, is governed by the fundamental law of physics: the energy is proportional to v^2 while the momentum and thrust to v, where v is the propellant velocity. Thus, regardless of propellants, the energy transfer efficiency, specific thrust, is always proportional to 1/v. In order to provide relativistic velocities, a propulsion system should have a relativistic v, and at such high v~c, the propellant based on particles, such as protons or electrons, and photons have similar specific thrust. Therefore, a crucial aspect of relativistic rocketry is how efficiently the propellant can be accelerated of expelled. Among propellants capable of delivering relativistic spacecraft velocities, photons are most promising, because their generation in high flux is much technologically simpler and lighter than that of particles. Another important reason for this is that photons can be recycled to amplify thrust using high reflectivity mirrors. The emerging high power high energy efficiency laser and high power optics technologies show great promise in the possibility of scaling up of recycling photon propulsion to propel interstellar spacecraft. This section considers the prospective of recycling photon propulsion, and details of Photonic Laser Thruster (PLT) that was demonstrated to amplify photon thrust by a factor of 3,000 by recycling photons (Bae, 2007b, 2008).

In his theoretical work, Marx (1966) derived for the first time the energy transfer efficiencies from the photon energy to the kinetic energy of the spacecraft of photon propulsion. For BLP, the instantaneous efficiency η_i and the total efficiency η_t, are given by: (Marx, 1966, Simmons, 1993)

$$\eta_i = \frac{2\beta}{1+\beta}, \tag{15}$$

$$\eta_t = 1 - \sqrt{\frac{1-\beta}{1+\beta}}, \tag{16}$$

where $\beta = v/c$. At low speeds, $\beta << 1$, $\eta_i \sim \beta$ and $\eta_t \sim \beta/2$, therefore, at non-relativistic velocities, BLP is highly inefficient. However, at relativistic velocities with $\beta \sim 1$, $\eta_i \sim 1$. Thus, photon propulsion is highly efficient at relativistic velocities.

One way of overcoming the low efficiency at low velocities in using photon propulsion is to use multistage approaches, in which at low spacecraft velocities, particle-based propulsion systems, such as electrical thrusters, are used. A detailed analysis of this multistage approach has been published by Kellet and his colleagues. (2008) Here, the effort is focused on making the propulsion system simple such that the spacecraft carries only minimal propellant for attitude control and maximal equipment for crew habitation and safety environment. One of the best ways to achieve such a goal is overcoming the inherent inefficiency in producing thrust of the photon thruster by amplifying the momentum transfer of photons by recycling photons between two high reflectance mirrors. The simplest recycling scheme is a Herriot cell with multi-bouncing laser beams between two high reflectance mirrors without forming a resonant optical cavity. This Herriot cell type approach was first proposed by Meyer (1986) followed by Simmons and McInnes, (1993) Their study was in depth analyzed by Mertzger and Landis (2001) recently. This approach requires highly focused laser beam spots on each mirror to avoid the beam interference that may induce optical resonance in the cavity.

Photon thrust amplification based on Herriot cells seems to be straightforward, however, the implementation of the concept turned out to be not. As the cavity length and the number of photon bouncing increase in Herriot cells, the focal spot diameter projected on mirrors increases, requiring extremely large mirrors to avoid the laser beam interferences (Bae, 2007a). Once the laser beam starts to interfere, the non-resonant cavity becomes a passive resonant cavity that is shown below to be impractical for photon propulsion amplification. In fact, the first experimental attempt on photon thrust amplification in a non-resonant Herriot-cell type optical cavity was performed by Grey et al. (2002) They could obtained amplified photon thrust of ~0.4 μN with a 300-W laser and a photon thrust amplification factor of ~2.6, which was much smaller than the anticipated amplification factor greater than 50 (Grey, 2002). The much lower-than-expected amplification factor obtained by Grey et al. (2002) revealed the above mentioned technical difficulties in the Herriot cell concept (Bae, 2007a).

Meyer et al. (2002) proposed to overcome the challenge posed by Herriot cell type photon amplification, and published elaborate calculations on the energy efficiency of recycling photons in a passive resonance optical cavity, in which a laser system is located outside of the optical cavity. The passive resonant optical cavity, Fabry-Perrot optical resonator, has been extensively used in high-sensitivity optical detection methods, such as the cavity ring down spectroscopy (Romanini, 1997). In the cavity ring down spectroscopy, typically laser pulses are injected through the first mirror and bounced between two mirrors as many as tens of thousand times. The current off-the-shelf technological limit of the system reported is obtained with super mirrors used for the cavity ring down spectroscopy with the reflectance of 0.99995 with the photon bounce number of 20,000 (Romanini, 1997). This experiment clearly demonstrated that thrust amplification in optical cavity by orders of magnitude is feasible.

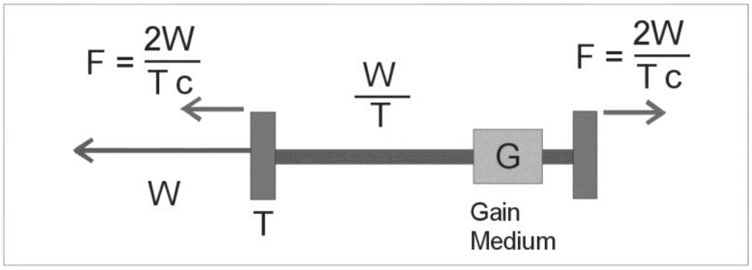

Figure 3. Schematic diagram of the Photonic Laser Thruster (PLT), which is based on the active resonant optical cavity approach to photon thrust amplification.

However, the passive resonant optical cavity for photon thrust amplification turned out to be unsuitable for propulsion applications, because it is highly sensitive to the small changes in the distance between the mirrors and mirror deterioration. This sensitivity was observed in the gravitational detection system (LIGO) with such high-Q passive optical cavities, in which even one nanometer perturbation in cavity length sets the system out of resonance and nulls the photon thrust (Sheard, 2004). In addition, the high-Q passive resonant optical cavity requires near single-frequency lasers to efficiently inject the laser through the input mirror. Typically such single-frequency lasers have poor power-to-photon conversion efficiency. Therefore, it was concluded that the passive resonant cavity photon thruster is unsuitable for photon thrust amplification (Bae, 2007a).

The author initially proposed PLT mainly to overcome the difficulties in injecting sufficient laser power in high-Q optical cavities for the usage of precision formation flying in which the mirrors of the optical cavity are in near static conditions (Bae, 2006). In PLT, a laser cavity is formed between two space platforms with the laser gain media located between them as illustrated in Fig. 3, in contrast to the previously proposed multiple reflection laser photon propulsion concepts that use passive optical cavities with the laser amplification located outside of optical cavity.

Under the auspice of NIAC/NASA, the author successfully demonstrated the proof-of-concept of a PLT (Bae, 2007b, 2007c). In this demonstration, a PLT was built from off-the-shelf optical components and a YAG gain medium, and the maximum amplified photon thrust achieved was 35 μN for a laser output of 1.7 W with the use of a HR mirror with a 0.99967 reflectance. This performance corresponds to an apparent photon thrust amplification factor of ~3,000. More importantly, in the experimental demonstration, the author accidentally discovered that the PLT cavity is highly stable against the mirror motion and misalignment unlike passive optical cavities. In fact, in the demonstration experiment by the author, the full resonance mode of the PLT was discovered to maintain even when one of the HR mirror was held, moved, and tilted by a hand to the author's surprise. In a more systematic experiment, the PLT cavity was systematically demonstrated to be highly stable against tilting, vibration and motion of mirrors. Subsequent theoretical analysis by the author showed that PLT can indeed be used for propulsion applications, and proposed Photonic Laser Propulsion (PLP), the propulsion with PLT (Bae, 2007a). The reason for the observed stability results from that in the active optical cavities for PLT and PLP the laser gain medium dynamically adapts to the changes in the cavity parameters, such as mirror motion, vibration and tilting, which does not exist in the passive optical cavities.

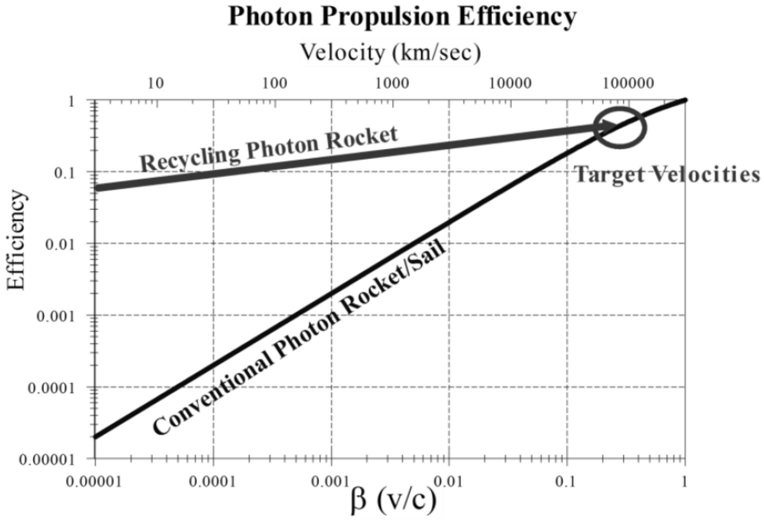

Figure 4. Energy transfer efficiency from the photon energy to the spacecraft kinetic energy as a function of β=v/c.

Fig. 4 schematically shows the energy transfer efficiency from the photon energy to the spacecraft kinetic energy as a function of β=v/c in BLP. Fundamentally, photons transfer their energy to the spacecraft by redshifting due to Doppler shift upon reflection, thus the higher the spacecraft speed is, the higher the efficiency is. It is interesting to note that at speeds near c nearly 100 % of light energy is converted to the spacecraft kinetic energy, as if the spacecraft acts like a black hole in the moving direction. The lower solid curve in Fig. 4 represents the efficiency of conventional photon rocket and sail with photon recycling. The upper solid line represents schematically an example the efficiency of recycling photon rocket, PLT. At low β, the PLT can have a very high thrust amplification factor (in this example, ~3,000), however, it is expected that as β approaches 1, the PLT amplification factor should asymptotically converge to 1. Theoretical details on this behavior will be published elsewhere.

In PLT, the photon thrust, F_T, produced by a laser beam on each mirror is given by:

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$$F_T = \frac{2}{c}\frac{W}{T}, \tag{17}$$

where W is the extracavity laser power through the mirror, and T is the cavity loss factor. More realistically, because PLT has the gain medium in the laser cavity, the circulating power in the cavity, W/T, can be estimated by (Siegman, 1986)

$$\frac{W}{T} \approx \frac{G}{T'} \frac{I_{sat}}{2} A \tag{18}$$

where G is the unsaturated round-trip gain factor, I_{sat} is the saturation intensity of the gain medium, A is the effective lasing area in the gain medium, and T' is given by:

$$T' = T + a + s \tag{19}$$

where ***a*** is the roundtrip absorption coefficient and ***s*** is the roundtrip scattering coefficient. To have a high W/T, PLT should have high G and I_{sat}, but low T'.

Examples of the maximum theoretical thrust as a function of the cross sectional area correlating with various laser powers with I_{sat} ~ 1.4 kW/cm^2, G~1, T'~0.001, are summarized in Table 2. The PLT system for this estimation is based on Nd:YAG crystal. The actual achievable thrust also depends on other parameters, such as thermal management capability. Another important question is how large the cross sectional area of gain media can be constructed. With the use of the recently developed slab gain medium design, achieving the cross sectional area of 100 cm^2 is within reach with the current-state-of-the-art high power solid state lasers. However, the gain medium with greater than 100 m^2, is technologically extremely challenging. One approach to overcome the thermal management problem is to combine lasers beams from a number of small gain media on a grating employing the spectral beam combining technique. (Daneu, 2000) Another approach is to use gas laser technologies, as in the Air Borne Laser (ABL). One interesting approach alternative to diode pumped lasers, which may be highly important to PLT development, is solar pumped lasers, (Landis, 1992, Tsidulko, 1992) as was first envisioned by Forward (1984).

TABLE 2. The Maximum Theoretical Thrusts of the Photon Thruster based on Nd:YAG with I_{sat} ~ 1.4 kW/cm^2, G~1, and T'~0.001. The actual achievable thrust also depends on other parameters, such as thermal management capability. The large cross sectional area of gain media can be achievable either with a single crystal or by multiplexing numbers of smaller gain media.

Power Required in Intracavity Due to Loss	Minimum Cross Sectional Area of Gain Medium (Nd:YAG)	Maximum Intracavity Power	Maximum Theoretical Thrust
1 k W	1.43 cm^2	1 MW	6.7 mN
1 MW	1,430 cm^2	1 GW	6.7 N
1 GW	143 m^2	1 TW	6.7 kN
1 TW	143,000 m^2	1,000 TW	6.7 MN

One of the factors that limit the maximum obtainable velocity of the accelerating mirror and its accommodating spacecraft is limited by the Doppler shift of the bouncing photons. Doppler shift effect on the active resonant cavity behavior is an extremely complicated issue, which is beyond the scope of the current paper. Eventually, this aspect should be studied with computer optical simulation. Optical gain in the laser cavity can only occur for a finite range of optical frequencies. The gain bandwidth is basically the width of this frequency range. For example, the gain bandwidth of the YAG laser system with the laser wavelength in the order of 1,000 nm is in the order of 0.6 nm, (Yariv, 1975) which is ~ 0.06 % of the wavelength. For an order of magnitude estimation, we assume that PLT utilizing the YAG laser system will be limited by the gain bandwidth to the first order, then, theoretical maximum spacecraft velocity is ~1.8 x 10^5 m/sec (180 km/sec) that is 0.06 % of the light velocity, c=3x10^8 m/sec. To overcome this redshift limitation, PLT, at high operation velocities, should employ wide bandwidth lasers.

Traditionally, the intracavity laser arrangement required for PLT operation had been operated in relatively short cavities less than 10 m long. Therefore, there has been a concern that the action distance of PLT may not be more than tens of meters. However, recently, Bohn (2008) of the German Aerospace Center (DLR) reported that the German company Rheinmetall Defense demonstrated a 1-km long laser resonator similar to the PLT optical resonator in 1994-1995 with the use of a telescopic arrangement in the optical cavity, and that such long laser resonators can be scalable to 100 km with the usage of optics in the diameter of 70 cm. (Bohn, 2008) These successful demonstrations promise that PLT can be operated beyond distances in the order of 100 km. Further studies should be performed whether PLT can be used for interstellar scales, but so far there is no show stopper on this issue.

One of key technological issues in implementing PLT is in the intracavity laser beam aiming, aligning, and tracking, which will be addressed more in depth in the discussion section. With the rapid advancement in laser weapons, the aiming, alignment, and tracking of laser beams on rapidly moving uncooperative targets over the distance greater than 100 km have become technologically feasible. Although the technical details of such aiming, alignment, and tracking system is grossly classified, the nut-shell of the technology is available in open literatures. Especially, the technology developed for ABL will play crucial role in PLT systems. Based on open literature, in ABL, the aiming, alignment, and tracking of the main laser rely on the scattered beam of the beacon laser (also diode pumped lasers at power level of a few kW). Similar to this, a small laser (power level of a few watts) in the mission vehicle can be used as a beacon laser. It seems that the aiming, aligning, and tracking system can be scaled to interstellar distances.

THE PHOTONIC RAILWAY: A PERMENENT SPACE COMMUTE STRUCTURE

In this section, we consider how the roundtrip manned interstellar flight based on Forward (1984) BLP can be made within reach in a century with projected power production capabilities and technologies. It is proposed here to achieve such a progress, BLP should be combined with PLT and short-wave length lasers. Fig. 5 shows an example of an hypothetical projection of the required power for PLT-BLP as a function of year. The projected total world power production at 1.9 % yearly growth rate in TW (10^{12} W) as a function of year, which has recently analyzed by Millis (2010) in depth, is plotted as the upper thick black line. The 10 % of the total world power production as a function of year is plotted as the lower thick gray line. Assuming an equivalent power of the total world power production (probably in a form of space solar power) can be dedicated to the ambitious interstellar flight, and assuming that the BLP laser has an energy conversion efficiency of 10%, the originally estimated power consumption by the Forward roundtrip interstellar flight would require about 80,000 TW (Forward, 1984), which is projected to be achievable well beyond the year 2500 as shown in Fig. 5. In this example, it is estimated that the incorporation of PLT into BLP would cut down the power requirement of BLP by a factor of 10 – 100 and that the incorporation of short wavelength laser by a factor of 10-100.

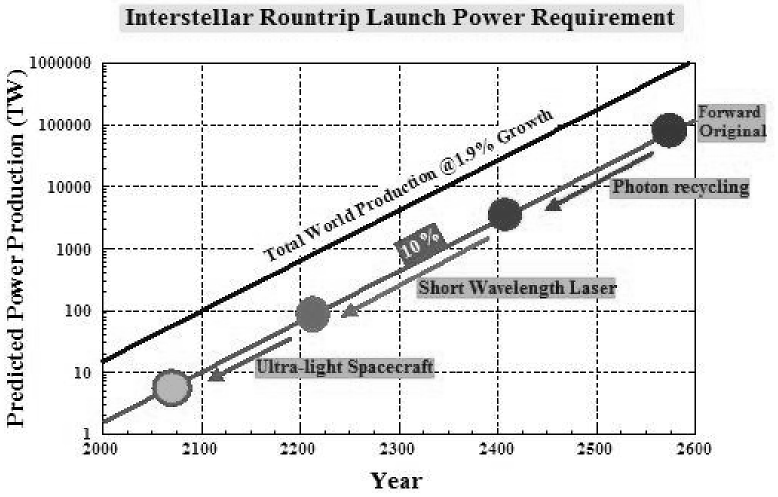

Figure 5. A projection of the required power for PLT-BLP as a function of year based on the world power production projection by Millis (2010).

In this case the total required photon power for BLP can be reduced by a factor of 100 – 10,000. In an optimal case with a reduction factor of 10,000, these two technological developments will be sufficient to make the PLT-BLP within reach by the year 2100. However, in less optimal case as shown in Fig. 5, suppose that PLT factor reduction is only 30 and the short wavelength laser 30, then an additional power reduction by a factor of 10 is required. Such power reduction can be achieved by spacecraft weight reduction with the rapidly developing material technologies, such as carbon nanotube materials, (Zhang, 2005) and physiological technologies, such as minimal long-duration survival closed systems for crews in the future.

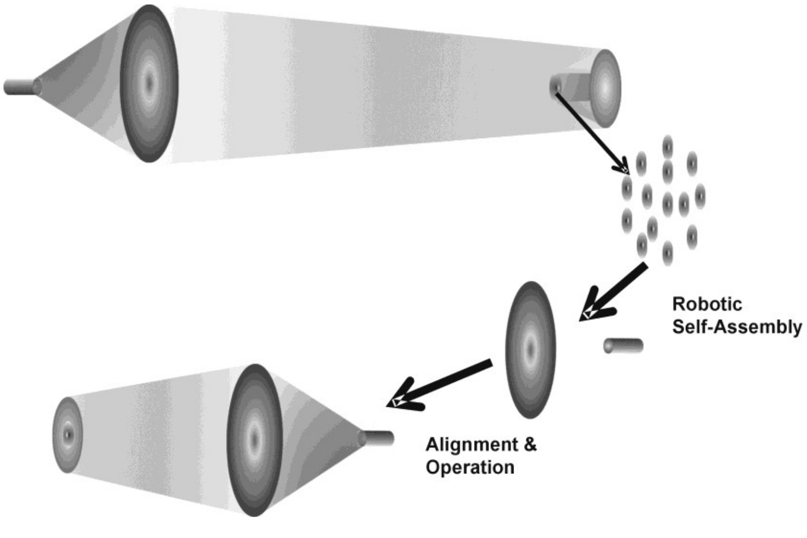

Figure 6. Construction of Photonic Railway with PLT-BLP.

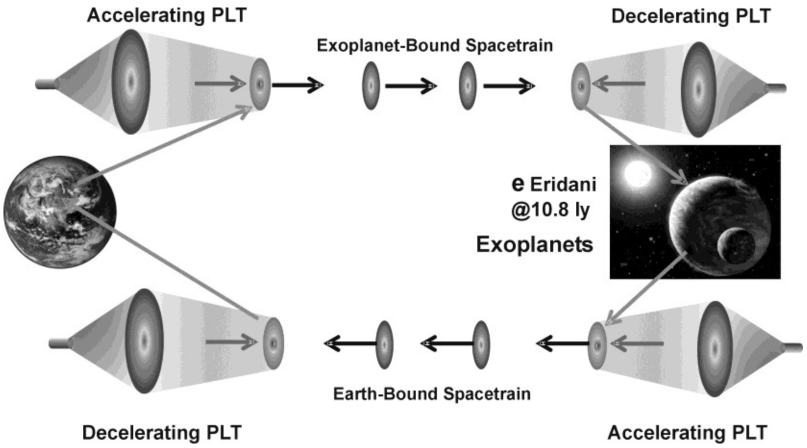

Figure 7. A Photonic Railway consists of four PLTs: two for acceleration and two for deceleration. The Spacetrain will have small thrusters for attitude control and most of the onboard spacecraft resource will be dedicated to crew comfort and safety.

Once PLT-BLP is implemented, the initial exploration flight would be performed, which will be followed by construction of the Photonic Railway as shown in Fig. 6. In this figure, a multitude of structural parts for constructing a large lens system and laser system will be transported from the Earth. In this case, the PLT-BLP system in the earth will be used for delivering the necessary components by both propelling and slowing down them. Once the components start to arrive at the vicinity of the exoplanet, they will be assembled and made to operate fully automatically by probably a sophisticated self-directing robotic system projected to be available by the end of the 21st century. Once the PLT system at the exoplanet becomes fully functional, it can be used for stopping the exoplanet-bound Spacetrain and for propelling the earth-bound Spacetrain. Fig. 7 illustrates a Photonic Railway consists of four PLTs: two for acceleration and two for deceleration. One important factor is that the Photonic Railway PLT needs to operate much shorter distance than the distance between the earth and the exoplanet. Typically, depending on the Spacetrain acceleration condition (the optimal case would be 1 g acceleration for maximum crew comfort), the system operation distance would be at least a factor of 3.2 shorter than the flight distance. Because of this, the Photonic Railway optical system can be at least a factor of 10 smaller in size than the PLT-BLP optical system.

DEVELOPMENTAL PATHWAY OF THE PHOTONIC RAILWAY TOWARDS INTERSTELLAR COMMUTES

In the previous sections, it was shown that photon propulsion has a premise to revolutionize future human endeavors in space, beyond that can be achieved with conventional rocketry. It is proposed here that the Photonic Railway, a permanent transport structure based on photon propulsion, has a potential to enable routine interstellar commutes via Spacetrains. The Photonic Railway, as the transcontinental railway systems did, is projected to inspire sustainable economic interest and return investment, and to potentially achieve the goal: rountrip manned interstellar flight potentially within a century (Bae, 2011). In this section, a four-phased developmental pathway of the Photonic Railway toward interstellar manned roundtrip is proposed: 1) Development of PLTs for satellite and NEO maneuvering, 2) Interlunar Photonic Railway, 3) Interplanetary Photonic Railway, and 4) Interstellar Photonic Railway. It is projected that these developmental phases will result in systematic evolutionary applications, such as satellite formation flying, NEO mitigation, lunar mining, and Space Solar Power, which is projected to generate sufficient sustainable economic interest and return investment to the development pathway.

Phase I: Satellite and NEO Maneuvering with PLT

The first phase in the developmental pathway towards interstellar manned roundtrip flight is maturing PLT technologies and systematic scaling up of its power/thrust and operation distance capabilities. PLT can provide the unprecedented capabilities in maneuvering spacecraft in near earth orbits, thus PLT is predicted to meet the needs of the next generation of space industry by enabling a wide range of innovative space applications near the earth. Examples of such unprecedented capabilities include propellantless operation, thrust and power beaming, and ultra-precision spacecraft maneuvering, (Bae, 2006, 2007c, Norman 2010). In this phase, which is predicted to evolve over the 5 – 30 year time frame, PLT would be capable of providing thrusts in the range of 1 mN – 1 kN, which requires the operation power of 100 W – 100 MW. The solar panel based space power currently can provide electrical powers up to 100 kW, therefore, the PLT capable of providing thrusts up to 1 N can be readily implemented in the near future. Further scaling up of PLT with 1 kN thrust will require a large solar power system capable of providing power up to 100 MW, of which development and implementation may depend on the space solar power or space nuclear power development in the future.

In Phase I, the operation distance of PLT is projected to be up to 100,000 km, which can cover a wide range of spacecraft maneuvering at LEO, MEO, and GEO. For example, once the spacecraft is in orbit, a 1 ton vehicle will take about 2.3 hours to cover 100,000 km via a 100 MW PLT with a thrust amplification factor of 1,000 for flying by. The diffraction limited size of the beaming mirror/lens should be on the order of 100 m and the spacecraft mirror diameter 2.44 m. The maximum thrust of such a system would be on the order of 1 kN. For rendezvous missions, such a spacecraft will take about 5 hours including deceleration time to traverse 100,000 km.

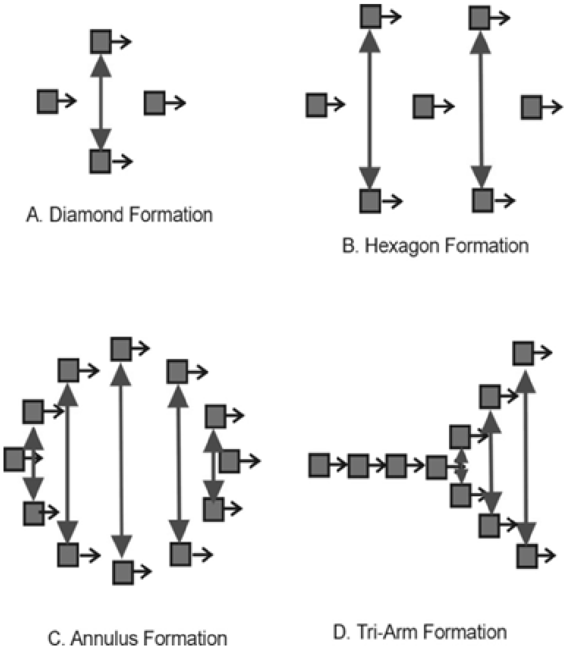
A. Diamond Formation
B. Hexagon Formation
C. Annulus Formation
D. Tri-Arm Formation

Figure 8. Examples of satellite formation using PLT pushing-out force and counterbalancing “virtual tug” generated by gravity gradient (Bae, 2007c, Norman, 2010).

As PLT is successfully implemented in space and systematically scaled up, its economic interest is predicted to grow exponentially. In addition, PLT is predicted to reduce the use of toxic chemicals and minimizes the pollution in near earth space environment, which is becoming a growing concern as the number of space activities rapidly increase. Spacecraft formation flying is vital to the construction of next generation satellites with fractionated components and space solar power facilities for power beaming the harnessed solar power in space to the earth. Numerous commercial and defense applications of the formation flying technologies are projected to be potentially enabled by PLT, which include large space telescopes at GEO for real-time "Google" map and large low-cost space radars. Precision formation flying with PLT will play a vital role in constructing large scale space structures in GEO by significantly reducing the orbit raising cost from LEO. Examples of such space structures, which would need this technology, would be space solar power beaming facilities, large space radars, large surveillance optical satellite structure, space stations and space habitats. These applications will provide sustainable development of the Phase I PLTs.

The nanometer precision formation flying of satellite using a combination of PLTs and tether, the Photon Tether Formation Flight (PTFF), was proposed and investigated in detail by the author (Bae, 2006). In an another approach, a group of spacecraft exploit relative positions and velocities so that differential gravity provides a force opposite that of the photon thrust from PLT in a way similar to what a tether might provide (Bae, 2007c, Norman, 2009). In such a scheme with two orbiting platforms, their positions to the center of the mass can be controlled by adjusting the two balancing forces: 1) the **photon thrust** from PLT, 2) the counterbalancing "**virtual tug**" that is generated by relative-orbital perturbation to create a capability for maneuvering spacecraft in earth orbit without using propellant and tethers. Fig. 8 illustrates examples of satellite formation using PLT pushing-out force and counterbalancing "virtual tug" generated by gravity gradient (Bae, 2007c, Norman 2009).

A more general motions are possible in the case of a PLT system without tethers than that with tethers (Bae, 2006), where the relative displacements are very limited. The PLT maneuvering system, however, could accomplish control of out-of-plane motions as shown in Fig. 8, thus would represent a breakthrough technology (Bae, 2007c, Norman, 2009). In addition, its propellantless performance prevents contamination, and saves considerable mass. PLT force acting in the along-track direction has the long-term effect of speeding up and slowing the pair of satellites between which it acts, which can be used for propellantless rendezvous of satellites. (Norman, 2009, Peck, 2010)

In addition, PLT can be used for second-party propellantless stationkeeping. A specific example of stationkeeping is north/south orbit maintenance for a GEO spacecraft as illustrated in Fig. 9. (Norman, 2009, Peck, 2010) Here, it is envisioned that at least one satellite in a low-inclination elliptical orbit (similar to GTO) with an apogee at GEO and an orbital period that is a simple fraction of 24 hours, e.g. e=0.309, a=32,200 km, which has a period of 2/3 day. This faster, chief satellite repeatedly is in a position to apply ΔV to the target from either below or above (but not both) to tilt the orbital angular-momentum vector in one direction. For example, ten total minute's thrust at 100 mN is comparable to the stationkeeping ΔV imparted by biprop on GEO communications satellites once every couple of weeks. Here, the orbits synchronize every three days. So, the pulses may be more frequent and therefore the stationkeeping more finely resolved in the case of the PLT spacecraft. Such ΔV would represent inclination-change capability in one direction and with one sign. To achieve PLT-based stationkeeping in both planes and with both signs, four chief satellites would be required. With these chief satellites in identical orbits with different arguments of perigee, they can also stationkeep one another to some extent (Peck, 2010).

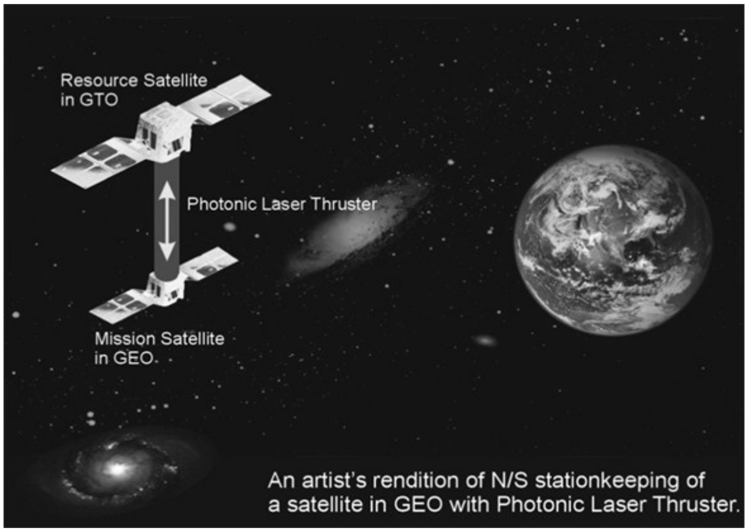

Figure 9. PLT stationkeeping for north/south orbit maintenance for a GEO spacecraft (Peck, 2010).

PLT can be used for second-party propellantless orbit-drag compensation. This PLT application will greatly reduce propellant requirement. Here, two spacecraft in very similar orbits with low inter-vehicle velocity are used for making the mission much more economical and reliable (Peck, 2010). For example, a large resource space vehicle carries no payload of military value and conventional propellant, while relatively small multiple-mission vehicles carry a specific payload of interest but minimum conventional propellant. The replacement of the resource vehicle can be very faster and more economical than replacing the more important mission vehicles. This situation is similar to that of in-air refueling of fighter jets. PLT technology can be used for imparting ΔV to mission vehicles for making up orbit drag by a resource vehicle to extend its mission duration in the same way as a refueling tanker. Of course, the orbital energy of the resource vehicle is ultimately lost to the mission vehicles through energy exchange. To the extent that the mission vehicles are less readily replaced than the resource vehicle, this trade favors a PLT architecture in which orbital energy is beamed to the mission vehicles, allowing such a space system to persist in a LEO orbit (Peck 2010). In a similar way, it is projected that PLT in combination with BLP can be used for mitigating or mining NEO or NEA.

Phase II: the Interlunar Photonic Railway

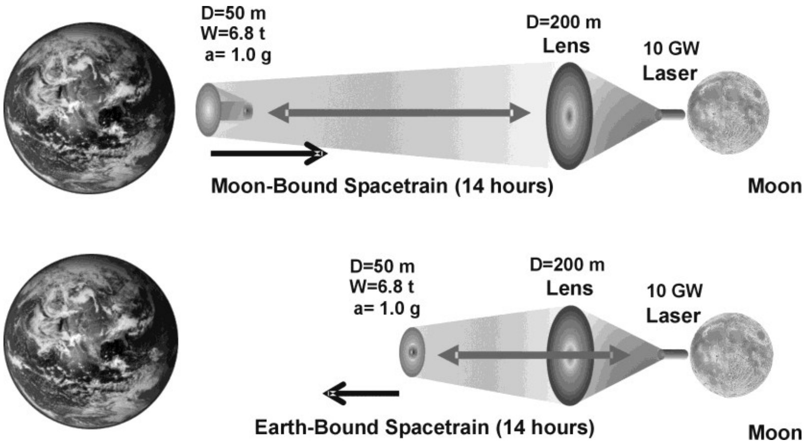

Figure 10. An Interlunar Photonic Railway consists of one PLT-BLP system located on the moon.

The first stepping stone technologies for PLT technologies are for near earth operation. A wide range of financially profitable near earth activities as described in the previous section are predicted to jumpstart full-scale PLT development. After Phase I PLT technologies and applications are fully developed and implemented, further scaling up of the PLT thrust and operation distance can enable maneuvering spacecraft and objects over the lunar distance of 384,500 km. In this phase, which is predicted to evolve over the 30 – 50 year time frame, PLT would be capable of providing thrusts in the range of 1 - 100 kN, which requires the operation power of 100 MW – 10 GW. The operation distance of PLT is projected to be up to 1,000,000 km, which can cover a wide range of spacecraft maneuvering over lunar-scale distances. The diffraction limited size of the beaming lens should be on the order of 200 m and the spacecraft mirror diameter 50 m. The sizes the lens and mirror will decrease proportionally as the laser wavelength decreases. For example, a 100 time reduction in the laser wavelength will result in the lens diameter 20 m and the mirror diameter 5 m.

The Interlunar Photonic Railway with PLTs is predicted to meet the needs of the future generation of space industry market by enabling a wide range of innovative space applications involving the moon as a second step towards interstellar manned roundtrip commutes. For example, a 10 GW PLT with a thrust multiplication factor of 1,000, will generate a thrust of 66.7 kN, which can accelerate 6.8 ton Spacetrain at 1.0 g, a comfortable cruising acceleration as illustrated in Fig. 10. In this example, the Photonic Railway consists of one PLT-BLP system, that handles both Moon- bound and Earth-bound Spacetrains. However, if the orbit issues are mitigated, a Photonic Railway system with four PLTs can be constructed similar to the one shown in Fig. 7: two PLTs for Moon-bound Spacetrains and two for Earth-bound Spacetrains. At this acceleration, lunar flyby will take about 6.8 hours, and for landing on moon about 14 hours. If PLT-BLP could be built on one of the earth orbits, such as GEO, and then used for transporting materials and robots for constructing PLTs either one of the earth-moon Lagrange points or directly on the moon to structure the Interlunar Photonic Railway as illustrated in Fig. 10. In this example, only one PLT-BLP system located on the moon is used. For the earth-bound Spacetrain from the moon, the lightsail would be divided into two nested circular segments as shown in Fig. 10. The total vehicle mass would be, for example, 6.8 tons, including 3 tons for the crews, their habitat, and their exploration vehicles. The lightsail would be accelerated at 1 g by a 10 GW laser system. Near the half way to the earth after about 7 hours later, the 10 m spacecraft with a built-in mirror detaches from the lightsail center and turns to face the 50 m diameter ring sail. The laser light from the moon reflects from the ring sail. The reflected light decelerates the spacecraft and inserts it into a near earth orbit. The total flight time would be 14 hours. For the moon-bound Spacetrain, in an earth orbit the 10 m diameter spacecraft with a built-in mirror detaches from the 50-m diameter lightsail center and accelerates from the face of the ring sail. The laser light from the moon reflects from the ring sail. As the return spacecraft approaches the moon 7 hours later, it is decelerated to a halt on the moon surface or inserted into a near lunar orbit by the laser light from the moon. The detailed orbit dynamics of the Spacetrain and Interlunar Photonic Railway is well over the scope of the present paper, and it will be presented elsewhere.

The proposed Spacetrain can be built with very light materials using advanced materials and structures, which are predicted to be developed in Phase II time frame, and thus will have a large comfortable crew environment with small and light attitude control thrusters and electronics. Some of the applications of Interlunar Photonic Railway and Spacetrain include lunar mining and permanent lunar habitation. The moon is atmosphere free and has much less gravity (1/6 of the earth gravity), therefore, it would be highly ideal place to form space launch station to other planets and stars. Therefore, it seems that the Interlunar Photonic Railway will be an important stepping stone towards Interstellar Photonic Railway, which is described in detail in the following sections.

Phase III: the Interplanetary Photonic Railway

After Phase II technologies and applications for Interlunar Photonic Railway are fully developed and implemented, further scaling up of the PLT thrust and operation distance will enable maneuvering and propelling the spacecraft and objects over interplanetary distances. The Phase III is predicted to evolve over the 50 – 70 year time frame, PLT will be capable of providing thrusts in the range of 100 kN - 10 MN, which will require the operation power of 10 GW – 1 TW. By this time frame, it is projected that high-power short wavelength laser will be fully developed for the required PLT power level. The operation distance of PLT is projected to be up to 10 billion km, the Earth-Pluto distance. One of the important milestone of this phase is the construction of Earth-Mars Photonic Railway. With the Earth-Mars distance of 225 million km, the diffraction limit sets the beaming lens diameter 2.5 km, and the spacecraft mirror diameter 220 m with 1 μm lasers. For the Earth-Pluto Photonic Railway with a distance of 7.3 billion km, the diffraction limit sets the beaming lens diameter 35 km, and the spacecraft mirror diameter 500 m with 1 μm lasers. A 1,000 times reduction in wavelength will reduce both the lens and mirror diameters by a factor of 32 respectively, and the lens and mirror diameters required for Earth-Pluto Railway will be 1 km and 16 m, respectively.

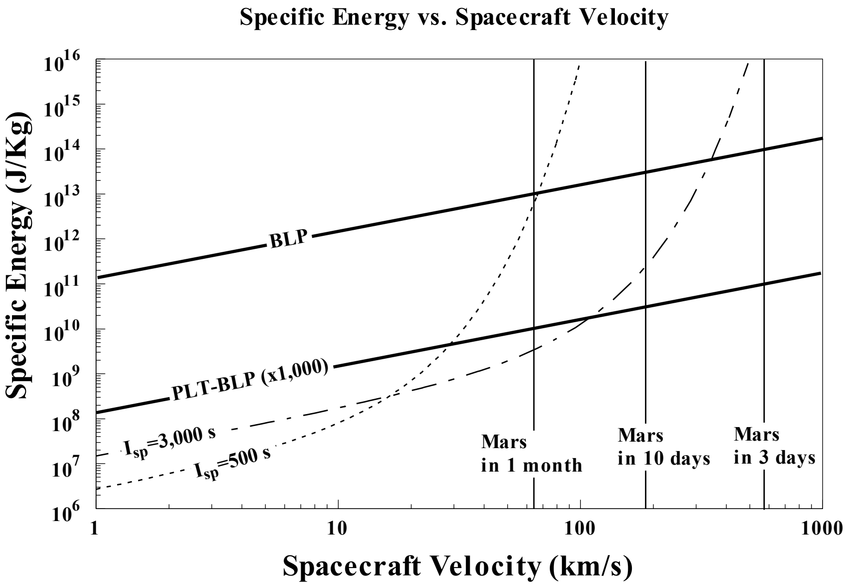

Figure 11. Specific energy as a function of spacecraft velocity relevant to Mars missions. The flight time to Mars is for flyby missions, and rendezvous missions would take more than twice longer.

Let us compare the energy need to speed spacecraft for conventional rockets and that for PLT-BLP, in terms of specific energy (J/kg) that is the energy required for propelling a unit mass to a given velocity. The founding physics of this issue for non-relativistic cases was obtained by Meyer et al. (2002). The specific energy of rockets, E_R is given by (Meyer, 2002)

$$E_R = \frac{1}{2} m_f u^2 \left(e^{\frac{\Delta v}{u}} - 1\right) \qquad (20)$$

Where m_f is the mass of the payload, u is the velocity of the rocket engine jet, which is $u = gI_{sp}$, and Δv is the spacecraft velocity. For PLT-BLP, the specific energy, E_P is given by

$$E_P = \frac{1}{2M} m_f \Delta v c \tag{21}$$

where M is the thrust amplification factor of PLT. Fig. 11 shows examples of the specific energy, E_p, (J/kg) as a function of the spacecraft velocity (km/s) relevant to Mars Photonic Railway. Two curves represent the specific energies for rockets with I_{sp} = 500 s and 3,000 s respectively. The upper straight solid line represent the specific energy for BLP and the lower straight solid line for PLT-BLP with M=1,000. BPL without thrust amplification becomes more energy efficient than rockets with I_{sp}=500 s, if the travel time needs to be shorter than 1 month. BPL without thrust amplification becomes more energy efficient than rockets with I_{sp}=3,000 s, if the travel time needs to be shorter than a week. On the other hand, PLT-BPL with a thrust amplification factor of 1,000 becomes more energy efficient than rockets with I_{sp}=500 s, if the travel time needs to be shorter than 2 month. BPL without thrust amplification becomes more energy efficient than rockets with I_{sp}=3,000 s, if the travel time needs to be shorter than two weeks. Eventually, when the flight time needs to be 3 days, for example, both BLP and PLT-BLP are much more energy efficient than rockets with I_{sp}=3,000 s. This estimate shown in Fig. 11 clearly demonstrates Photonic Railway based on PLT-BLP is potentially one of the most energy efficient ways to commute to planets in the solar system.

With the required Phase III technologies within reach, PLT-BLP can be built on one of the Earth orbits, such as GEO, and then used for constructing PLTs either one of the Lagrange points of a planet of interest to structure an Interplanetary Photonic Railway. For Mars, the solar power is still strong, thus solar pumped PLT can be operated near Mars without too much disadvantages. However, planets farther away from the sun, such as the Pluto, the solar pumping may not be efficient because of the reduced solar power at such a distance, therefore, the Photonic Railway would have two PLT-BLP systems near the Earth. The detailed orbit dynamics of the Spacetrain and Interplanetary Photonic Railway is well over the scope of the present paper, and will be presented elsewhere. The Interplanetary Photonic Railway PLT is predicted to meet the needs of the future space industry market by enabling a wide range of innovative space applications involving planets and asteroids. Some of the applications include mining and permanent habitation on other planets and asteroids. For example, once the Earth-Mars Photonic Railway is fully operated, it will play a vital role in terraforming and colonizing Mars. Once the permanent habitation on a planet is established, the planet can be used as a space station to go to other planets or exoplanets.

Phase IV: the Interstellar Photonic Railway

The Phase IV aims at the ultimate goal of human space exploration: manned roundtrip interstellar flight in one human generation. Once Phase III PLT-BLP technologies and applications are fully developed and implemented, further scaling up of the PLT thrust and operation distance will enable maneuvering and propelling the spacecraft and objects over interstellar distances. In this phase, which is predicted to evolve over the 70 – 100 year time frame, PLT-BLP is projected to be capable of providing thrusts greater than 10 MN, which requires the operation power of 1 - 100 TW. The operation distance of PLT-BLP is projected to be up to 100 trillion km, which can cover a wide range of spacecraft maneuvering over earth-nearby-star distance. For the Earth-ε-Eridani BLP with an operation distance of 10.8 ly (~100 trillion km), the diffraction limit sets the beaming lens diameter 1,000 km, and the spacecraft mirror diameter 252 km with 1 μm lasers as mentioned before in the previous sections (Forward, 1984).

Table 2 presents a comparison between the parameters for the original BLP by Forward (1984) and a hypothetical PLT-BLP with a thrust amplification factor of 100 and a 1 keV x-ray laser, which is projected to be available by the time frame of the Phase 4. The incorporation of the 1 keV x-ray laser relaxes the diffraction limit by a factor of 1,000. Millis (2010) conservatively predicts that by the year 2100 the total world power production would be ~100 TW assuming 1.9 % average annual growth. Assuming that the same power is available for interstellar mission in a form of probably solar power and that the efficiency of the PLT from the energy to photon power conversion is about 12 %, the required 12 TW of photon power before amplification is projected to be met by the year 2100.

Once this is achieved, PLT-BLP can be built on one of the solar system planets or satellites, such as the Pluto, and then used for constructing PLTs either one of the Lagrange points of an exo-planet of interest to structure the

Interstellar Photonic Railway. The detailed orbit dynamics of the Spacetrain and Interstellar Photonic Railway is well over the scope of the present paper, and it will be presented elsewhere. It is difficult to assess what would be a financial interest or value of interstellar roundtrip flight at that time, however, by the time of Phase IV, the rapidly growing space industries and science are predicted to discover advanced resources that can be harvested from exoplanets and hopefully the demand of such resources would inspire interstellar roundtrip flight. If such financial rewards are present, the Interstellar Photonic Railway is predicted to meet the needs of the far-future space industry market by further enabling a wide range of innovative space applications involving exoplanets and other space objects beyond the solar system. Some of the applications would probably include exoplanet mining and permanent exoplanet habitation.

Table 3. Comparison between parameters for the original BLP by Forward (1984) and a hypothetical PLT-BLP with a thrust amplification factor of 100 and a 1 keV x-ray laser.

	Original BLP Parameters By Forward (1984) Lens Diameter (1,000 km)			**Interstellar Photonic Railway with PLTs Photon Recycling (x100) + Short Wavelength (x1,000) Lens Diameter (32 km)**		
Phase	**Laser Power**	**Spacecraft Weight**	**Sail Diameter**	**Laser Power**	**Spacecraft Weight**	**Mirror Diameter**
Launch	75,000 TW	78,500 t	1000 km	10 TW	800 t	0.4 km
Rendezvous	17,000 TW	7,850 t	320 km	10 TW	800 t	0.4 km
Return	17,000 TW	3,000 t	100 km	10 TW	800 t	0.4 km
Stopping	430 TW	785 t	100 km	10 TW	800 t	0.4 km

DISCUSSIONS

Foretelling the development of technologies that are needed for the Photonic Railways over next 100 years is extremely challenging. Here based on extrapolation of the existing science and technology, it was predicted that PLT in conjunction with BLP would potentially revolutionize the way in which space missions and travels are executed. However, numerous daunting technological challenges exist in pursuing the development of the Photonic Railway. The present paper addresses some of critical issues, however, many other potential technological challenges are anticipated and the scope of these challenges covers an extremely wide range of science and engineering. For example, one of the fundamental challenges in applying PLT for the interstellar missions lies in the use of the astronomically long resonant optical cavities. A major technological difficulty exists in such a system: alignment of the optics. The precision in the unit of radian in selected missions are shown in Table 4.

In terms of available aiming accuracy of lasers, for example, typical ABL operation requires the operation distance on the order of 1,000 km and the target irradiation size of 10 cm (10^{-4} km). The reflected laser signal return from the moon requires the operation distance $4\text{x}10^{6}$ km and the reflection mirror size on the order of 1 m (10^{-3} km), which requires the aiming accuracy of $2.5\text{x}10^{-10}$ rad. Such an operation requires the angular aiming accuracy on the order of 10^{-10} rad. Therefore, the existing aiming accuracy can meet the accuracy required for missions up to the interplanetary mission.

Table 4. The precision in angular alignment required for exemplary missions.

Destination	Typical Distance (km)	Typical Spacecraft Mirror Diameter (km)	Angular Aiming Precision (Rad)
Near Earth	10^5	10^{-3}	10^{-8}
Moon	$4x10^6$	$4x10^{-2}$	10^{-8}
Mars	$2x10^8$	$2x10^{-1}$	10^{-9}
Pluto	$7x10^9$	1	$1.5x10^{-10}$
ε Eridani	10^{14}	1	$<10^{-14}$

Very recent researches on the space telescope metrology propose systems that can achieve the angular aiming accuracy on the order of 10^{-12} rad. However, the aiming accuracy required for interstellar missions is more than 2 - 4 orders magnitude smaller than the currently used ones, and by the time the present propulsion system is applied for interstellar missions, which is 70 – 100 years from now, such a technology is predicted to be available.

Another important issue is in the feedback mechanism required for maintaining such high relative angular accuracy. For interstellar missions, the feedback signals in the PLT optical cavities would take years to arrive at the sensors for adjusting the aim. Thus, by the time the angular adjustment is performed to offset the misalignment, the spacecraft mirror/sail would be in an unpredictable angular and spatial position. Therefore, the angular aiming accuracy for interstellar mission will require to ability to sustain absolute angular accuracy without relying on feedback mechanisms. These topics are for future studies.

CONCULSIONS

The main objective of the present paper is to show that the interstellar manned roundtrip flight could be achievable with a century within a frame of exiting scientific principles, once the required existing technologies are further developed. The perspective on photon propulsion presented here results in a conclusion that mastering photon propulsion that uses photon momentum directly is the key to overcoming the limit of the current propulsion technology based on conventional rocketry and potentially opening a new space era (Bae, 2007a, 2011). A universal equation that can be applied for both particle and photon propulsion was developed to explain the general behavior of the specific thrust as a function of I_{sp}, which is a measure of how efficient a thruster is in generating thrust at a given propellant kinetic energy. The universal equation clearly shows that at relativistic I_{sp}, there is no distinction between photons and particles as propellants. The chief advantage of photon propulsion stems from its capability in separating the energy source from the spacecraft as in Beamed Laser propulsion (BLP), which can avoid the exponentially increasing fuel mass as a function of I_{sp}. BPL further permits the reusable power beaming structures that are similar to railway structures, and the minimal weight of spacecraft. Thus, for the missions requiring high I_{sp}, photon propulsion was shown to be far superior to conventional propulsion based on particles. The emerging science and technologies, such as high power lasers, solar sails, precision optics, ultra-light large scale space optics and telescopes, and detailed information of solar system planets, NEO, and exoplanets, now provide a fertile ground for a full-scale development of photon propulsion in space.

It was proposed here that the permanent energy-efficient interstellar transportation structure, the Photonic Railway, similar to transcontinental railway systems, is necessary to attract sustainable economic interest and reinvestment over a century to the development pathway (Bae, 2011). The technological foundation of the Photonic Railway lies on BLP, which was originally proposed and extensively studied by Forward (1984, 1995), and PLT, of which proof-of-concept was recently demonstrated by the author (Bae, 2006, 2007a-c, 2008, 2011). The combined photon propulsion, PLT-BLP is projected to further advance its development by incorporating the anticipated x-ray laser and advanced material science and technologies so that its power and engineering requirements for interstellar manned roundtrip flight can be achievable probably within a century by reducing its size and power requirement by orders of magnitude. Once the PLT-BLP is implemented, it is proposed to be used to construct a more permanent and energy-efficient transportation structure: the Photonic Railway that is mainly composed of PLTs. Such a structure would allow the interstellar commute in comfortable and safe, yet light Spacetrain that is mainly composed of crew habitation, safety environment, and navigation systems.

A four-phased evolutionary developmental pathway of the Photonic Railway towards interstellar manned roundtrip travel is described: 1) Development of PLTs for satellites and NEO manipulation, 2) Interlunar Photonic Railway, 3) Interplanetary Photonic Railway, and 4) Interstellar Photonic Railway. It is projected that these developmental phases will result in systematic evolutionary applications, such as satellite formation flying, NEO mining/mitigation, and Space Solar Power, which will provide sufficient sustainable economic interest and return investment to self-sustain the development pathway. Once fully developed, the Photonic Railway would expand the horizon of the human economic and social interests in space from space exploration to space mining, colonization, and permanent habitation.

NOMENCLATURE

A = effective lasing area of a gain medium
A_F = thrust amplification factor of PLT
$\boldsymbol{a}$ = roundtrip absorption coefficient
α = ratio of fuel mass to the total spacecraft mass
β = ratio of propellant velocity to light speed in vacuum
c = light speed in vacuum (m/s)
γ = conversion efficiency of fuel mass to propulsion energy
δ = conversion efficiency of propulsion energy to photon energy for propulsion
Δv = spacecraft velocity
E = kinetic energy of propellant (J)
E_{ph} = total photon energy available for propulsion (J)
E_R = specific energy of rockets (J/kg)
F_{su} = specific thrust (m/s)
F_T = photon thrust (N)
g = gravity acceleration constant (m/s^2)
η_i = instantaneous photon energy to spacecraft kinetic energy conversion efficiency
η_t = total photon energy to spacecraft kinetic energy conversion efficiency
h = Plank constant (kgm^2/s)
I_{sat} = saturation intensity of gain medium (W/cm^2)
I_{sp} = specific impulse (s)
M = total mass of spacecraft including fuel mass (kg)
m_f = mass of the payload (kg)
m_0 = rest mass of particle propellant (kg)
$\dot{M}$ = mass flow rate (kg/s)
N = photon number flux (s^{-1})
ν = photon frequency (s^{-1})
p = relativistic momentum (kgm/s)
$\boldsymbol{s}$ = roundtrip scattering coefficient
T = cavity loss factor
T_{ph} = total photon thrust (N)
T' = effective cavity loss factor including absorption and scattering effects
u = velocity of the rocket engine jet (m/s)
v = exit velocity of propellant
V_{max} = maximum attainable spacecraft velocity (m/s)
W = extracavity laser power (W)

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REFERENCES

Bae, Y. K., “A Contamination-Free Ultrahigh Precision Formation Flying Method for Micro-, Nano, and Pico-Satellites with Nanometer Accuracy”, *Space Technology and Applications International Forum*, ed. M.S. El-Genk, AIP Conf. Proc. AP813, 2006, pp.1213-1223.

Bae, Y. K., ”Photonic Laser Propulsion (PLP): Photon Propulsion Using an Active Resonant Optical Cavity”, AIAA 2007-6131-818, *Space 2007 Conference Proceedings*, 2007a.

Bae, Y. K., “Photonic Laser Thruster (PLT): Experimental Prototype Development and Demonstration”, AIAA 2007-6156-318, *Space 2007 Conference Proceedings*, 2007b.

Bae, Y. K., “Photon Tether Formation Flight for Distributed and Fractionated Architectures”, AIAA 2007-6084-275, *Space 2007 Conference Proceedings*, 2007c.

Bae, Y. K., “Photonic Laser Propulsion: Proof-of-Concept Demonstration”, *AIAA Journal of Spacecraft and Rockets*, **45**, pp 153-155, 2008.

Bae, Y. K., “The Photonic Railway: A Sustainable Developmental Pathway towards Interstellar Flight,” to be published in the 100 Year Starship Public Symposium Proceedings, 2011.

Bohn, W. L., “Novel Aspect of Laser Propulsion”, *High-Power Laser Ablation VII*, ed. Claude R. Phipps, *Proc. of SPIE*, **7005**, 2008, pp. 70051C.

Daneu V. *et al.*, “Spectral beam combining of a broad-stripe diode laser array in an external cavity”, Opt. Lett., 25, 2000, pp. 405-407.

Fink, Y. et al., “A Dielectric Omnidirectional Reflector”, *Science*, **282**, 1998, pp. 1679–1682.

Forward, R. L. "Pluto—The Gateway to the Stars”, *Missiles and Rockets,* **10**, 1962, pp. 26-28.

Forward, R. L., “Roundtrip Interstellar Travel Using Laser-Pushed Lightsails”, *Journal of Spacecraft and Rockets*, **21**, 1984, pp. 187–195.

Forward, R. L, “Advanced Space Propulsion Study,” AFRL Final Report, F04611-86-C-0039. 1987a.

Forward, R. L., “Laser Weapon Target Practice with Gee-Whiz Targets”, *Proceedings SDIO/DARPA Workshop on Laser Propulsion*, Vol. 2, ed. J. T. Kare, CONF-860778, Lawrence Livermore National Lab., Livermore, CA, 1987, pp. 41–44.

Forward, R. L., “Advanced Propulsion Systems”, in *Space Propulsion Analysis and Design*, ed. R. W. Humble, G. N. Henry, and W. J. Larson, McGraw-Hill Co., New York, 1995, pp 631,

Gray, P. A. et al., “Photon Flux Amplification for Enhancing Photonic Laser Propulsive Forces”, *AIAA 33 rd. Plasmadynamics and Lasers Conference*, Maui Hawaii, 2002.

Kellett, B. J. et al, “Space Polypropulsion”, in *High-Power Laser Ablation VII, Proc. of SPIE 7005*, 70052W, 2008.

Landis, G. A., "New Approaches for a Solar-Pumped GaAs Laser”, *Optics Communications,* **92**, pp 261-265, 1992.

Landis, G. A., “Advanced Solar- and Laser-Pushed Lightsail Concepts”, *Final Rept. for NASA Inst. for Advanced Concepts*, Ohio Aerospace Inst., Brook Park, OH, 1999.

Marx, G., “Interstellar vehicle propelled by terrestrial laser beam”, *Nature,* **211**, 1966, pp. 22–23.

Matloff, G. L., “Interstellar Solar Sailing: Consideration of Real and Projected Sail Material”, *JBIS*, **37**, 1984, pp. 135–141.

Metzger, R. A. and Landis, G., "Multi-Bounce Laser-Based Sails”, *STAIF Conference on Space Exploration Technology*, Albuquerque NM, AIP Conference Proceedings, **552**, 2001, pp. 397-402.

Meyer, T. R. et al., “Rapid Delivery of Small Payloads to Mars”, *The Case for Mars II*, Vol. 62, Science and Technology Series, Univelt, Inc., San Diego, CA, 1985, pp. 419–431.

Meyer, T. R. et al., “The Laser Elevator: Momentum Transfer Using an Optical Resonator”, 38th IAF Conference, Brighton, UK, October 11-17, 1987.

Meyer, T. R., “Laser Elevator: Momentum Transfer Using an Optical Resonator”, Journal of Spacecraft and Rockets, **39**, 2002, pp. 258-266.

Millis, M. G., “Energy, Incessant Obsolescence, and the First Interstellar Missions”, *61st International Astronautical Congress*, IAC-10-D4.2.7, Prague, CZ, 2010.

Norman, M. C. and Peck, M. A., “Orbit Maneuvers Through Inter-Satellite Forcing”, *AIAA Conference Proceedings,* 2009**,** 2009-6097.

Peck, M. A., private communications, 2010.

Redding. J. L., “Interstellar vehicle propelled by terrestrial laser beam”, *Nature,* **213**, 1967, pp. 588–589.

Ritter, J. et al., “Photonic Muscles: Optically Controlled Active Optics”, Proc. SPIE 5894, 2006, pp. 589419.

Romanini, D. et al., “CW Cavity Ring Down Spectroscopy”, *Chem. Phy. Lett.,* **264**, 1997, pp. 316-322.

Sheard, B. S. et al., “Observation and Characterization of an Optical Spring”, *Phys. Rev. A*, 69, 2004, pp. 051801(R).

Siegman, A. E. “*Lasers”*, University science Books, Sausalito, California, 1986.

Simmons, J. F. L. and McInnes, C. R., “Was Marx right? Or how efficient are laser driven interstellar spacecraft?”, *Am. J. Phys*., **61**, 1993, pp. 205–207.

Takeuich, H. et al, “VLBI Tracking of the Solar Sail Mission IKAROS,” URSI 30th Symposium Proceedings, pp. 1-4, 2011.

Tsander, K., “From a Scientific Heritage”, NASA TTF-541, 1967 (quoting a 1924 report from Tsander).

Tsidulko, I. M., "Semiconductor Laser Pumped by Solar Radiation," *Soviet Journal of Quantum Electronics,* **22**, 1992, pp. 463-466.

Yariv, A., “*Quantum Electronics*”, John Wiley & Sons, New York, 1975.

Zhang, M. *et al.*. "Strong, Transparent, Multifunctional, Carbon Nanotube Sheets”, *Science,* **309**, 2005, pp. 1215–1219.