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14. ABSTRACT

In this paper, we review the history of laser space propulsion from its earliest theoretical conceptions to modern practical applications. Applications begin with the "Lightcraft" flights of Myrabo and include practical thrusters for satellites now completing development as well as proposals for space debris removal and direct launch of payloads into orbit. We consider laser space propulsion in the most general sense, in which laser radiation is used to propel a vehicle in space. In this sense, the topic includes early proposals for pure photon propulsion, laser ablation propulsion, as well as propulsion using lasers to detonate a gas, expel a liquid, heat and expel a gas, or even to propagate power to a remote conventional electric thruster.

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LASER SPACE PROPULSION OVERVIEW (PREPRINT)

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Introduction

In this paper, we review the history of laser space propulsion from its earliest theoretical conceptions to modern practical applicatons. Applications begin with the "Lightcraft" flights of Myrabo and include practical thrusters for satellites now completing development as well as proposals for space debris removal and direct launch of payloads into orbit. We consider laser space propulsion in the most general sense, in which laser radiation is used to propel a vehicle in space. In this sense, the topic includes early proposals for pure photon propulsion, laser ablation propulsion, as well as propulsion using lasers to detonate a gas, expel a liquid, heat and expel a gas, or even to propagate power to a remote conventional electric thruster.

Terminology and Theory

To review this complex field, it is important to summarize its terminology.

The momentum coupling coefficient C_m is defined as the impulse δJ created by incident laser pulse energy W (or thrust F to power P for a continuous laser signal) where exhaust velocity $v_E = \langle v_x \rangle$ is the first moment of the velocity distribution $f(v_x)$ along the thrust axis x.

$$C_m = \delta J/W = \delta m v_E/W = F/P \tag{1}$$

Often, this distribution will be a "drift maxwellian" of the form[1]

$$f(v_x, v_y, v_z) = C_x C_y C_z \{\exp - \beta[(v_x - u)^2 + v_y^2 + v_z^2]\} \quad . \tag{2}$$

with significant Mach number $M = u/c_s$. Defining also specific ablation energy

$$Q^* = W/(\delta m v_E) \tag{3}$$

the relationship

$$v_E = C_m Q^*. \tag{4}$$

Offers a convenient way of determining exhaust velocity since both C_m and Q^* are easily measured. Specific impulse is related to exhaust velocity by

$$I_{sp} = v_E / g_o \tag{5}$$

and is a useful concept in rocketry since it is also the impulse created by unit *weight* of fuel,

$$I_{sp} = \delta J/(\delta m g_o), \tag{6}$$

with dimensions N-s/N or seconds.

Ablation efficiency

$$\eta_{AB} = W_E/W = \delta m \psi v_E^2/(2W) \tag{7}$$

is the efficiency with which laser pulse energy is converted into exhaust kinetic energy. It is related to the other parameters by

$$\eta_{AB} = \psi\, C_m v_E / 2 \quad , \tag{8}$$

where

$$\psi = \frac{\langle v_x^2 \rangle}{(\langle v_x \rangle)^2} = \left\{ \frac{u^2 + \frac{kT}{m_E}}{u^2} \right\} \quad . \tag{9}$$

We usually take $\psi = 1$ because it can be shown[1,2] that typical ablation plume shapes correspond to $\psi \leq 1.15$. This choice underestimates η_{AB}.

Eq. 8 can be restated to show that C_m and I_{sp} form a constant product controlled by the parameter η_{AB}:

$$C_m I_{sp} = 2\eta_{AB}/g_o. \quad (10)$$

From η_{AB} and η_{eo}, the efficiency with which electrical energy is converted to laser energy, thrust efficiency in laser ablation thrusters can be computed,

$$\eta_T = \eta_{eo}\,\eta_{AB} \quad (11)$$

The product is 0.204 when $\eta_{AB} = 1$. With laser repetition frequency f, laser average power P = fW and the rate of mass usage is

$$\dot{m} = \frac{P}{Q^*} \quad . \quad (12)$$

When considering C_m and I_{sp} as design variables, it must be kept in mind that the ablator lifetime decreases very rapidly with increasing C_m or decreasing I_{sp}. Where M is the original ablator mass, the lifetime is

$$\tau_{AB} = 2\eta_{AB}\,M/(PC_m{}^2) = g_o{}^2 M\,I_{sp}{}^2/(2\,P\,\eta_{AB}) \quad . \quad (13)$$

For this reason, increasing C_m to get more thrust via the relationship

$$F = PC_m \quad (14)$$

from a given laser entails a serious penalty for ablator lifetime, to the point where a mission cannot be accomplished because the ablator is used up. On the other hand, for planetary liftoff of mass M_o, the minimum value of $F = M_o g_o$ sets the required laser power P, or else the available power limits the liftoff mass.

Some useful theory applies to the case of laser ablation propulsion. When a pulsed laser beam strikes a solid-state surface above plasma threshold fluence, which is approximately equal to the fluence for optimum momentum generation[3],

$$\Phi_{opt} = 480\,\tau^{0.5}\ \mathrm{MJ/m^2}, \quad (15)$$

If the surface is a passive (i.e., non-exothermic) material, an expression derived from the relationship between plasma temperature and laser intensity[4]

$$I_{sp} = 442\ \frac{A^{1/8}}{\Psi^{9/16}}\,(I\,\lambda\,\sqrt{\tau})^{1/4} \quad (16)$$

allows us to estimate I_{sp}, where $\Psi = (A/2)[Z^2(Z+1)]^{1/3}$, A is the mean atomic mass number and Z the mean ionic charge in the laser-plasma plume. C_m is governed by the constant-product relation, Eq. 10.

If the surface is a volume absorber or exothermic, the theory is much more complex, but an estimate of C_m can be obtained from

$$C_m{}^2 = (2\rho t/\Phi)(T - \Phi_d/\Phi - \Phi_p/\Phi - \ln\xi/\xi)\ . \quad (17)$$

In Eq. 17, we require $(T - \Phi_d/\Phi - \ln\xi/\xi) \geq 0$, ρ and t are the target mass density and thickness, and Φ is the energy density at the interface where the laser beam is absorbed. This may be less than the incident laser fluence when the area of the interface is greater than the cross-sectional area of the incident laser beam. The fluence Φ_d is the energy density required to dissociate the material, Φ_{th} is the fluence at which thrust begins, $\Phi_p < \Phi$ is the portion of Φ invested in plasma and $\xi = \Phi/\Phi_{th}$. This relationship must be evaluated numerically because Φ_p is a function of Z and Φ, and Z is itself a function of Φ through the Saha equation[4]. Here, Eq. 10 can be used to determine I_{sp}. T is the transmission of any supporting layers which may be present in complex ablation fuel systems, normally near unity. An approximate version of Eq. 17 ignoring the plasma contribution was compared to experimental data near threshold in reference 5.

Advantages of Laser Space Propulsion

Laser space propulsion (LSP) offers a quantum shift in performance and versatility compared to present space technologies. There are four major reasons why this is so.

Lower Costs with Laser Launching

The way we now send things to space is very expensive. Present day costs of raising mass from the Earth's surface into low Earth orbit (LEO) with chemical rockets is more than $10,000/kg (Table 1). This cost, equivalent to the cost of gold, dominates all other considerations relating to spaceflight, limiting what we consider to be possible. But it need not be so.

Table 1. Present-day launch costs to Low Earth Orbit

Launch System	*Minimum Cost (k$/kg)*
Rockot	*10*
Shuttle	*12*
Athena 2	*12*
Taurus	*20*
ISS, commercial	*22*
Pegasus XL	*24*
Long March CZ-2C	*30*
Athena	*41*

Phipps and Michaelis[2], taking advantage of an innovative conceptual design for a high-power laser system appropriate for launching large payloads[6], showed that there is an optimum set of parameters for laser space propulsion which can reduce the cost of lifting mass to LEO nearly 100-fold from its current level. Fig. 1, based on the costs derived in that work, emphasizes that rapid launch is one of the main reasons for the reduced cost. When a curve for a launch frequency typical of the Shuttle is added to the original graph, it is seen that cost becomes greater than current costs (50k$/kg for 0.01/day vs. $400/kg for 5/day). Laser launching is uniquely adaptable to high launch frequency, while chemical rocket launches, even given extensive development, have never shown that capability because of the low mobility of the associated mechanical infrastructure. The financial cost is further reduced when comparing groundbased with spacebased laser concepts because power in space is much more expensive than power on the ground. This is due to the costs outlined in Table 1 and to the costs of establishing space-qualified reliability of parts.

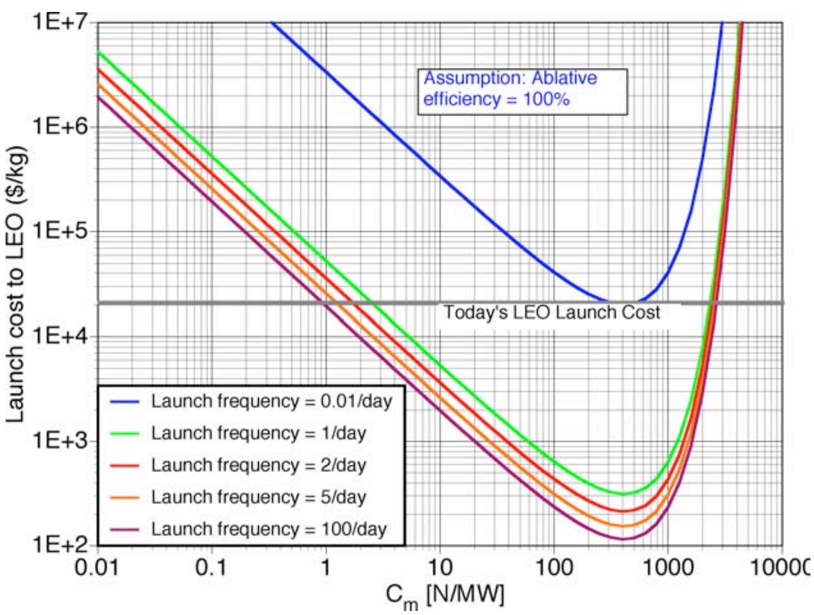

Figure 1. Cost of laser launching payloads to LEO using a repetitive-pulse laser. Calculations are based on η_{AB} = 100%. A 0.01/day launch frequency plot (similar to Shuttle launch frequency) emphasizes the importance of high launch rate in reducing cost.

Lower Dead Mass

A second immediate advantage of LSP is reduced dead mass while raising payload mass into low planetary orbit (LPO). This benefit derives from not having to raise turbines, pumps, tanks, exhaust nozzles, etc. along with the payload.

Adjustable Exhaust Velocity

A third advantage is being able to adjust exhaust velocity to the optimum value for each mission and, where needed, to achieve exhaust velocities well beyond what is possible with chemistry due to higher temperatures in laser-produced plasma. The maximum specific impulse of ordinary chemical rockets is about 500s, limited by the temperatures available in chemical reactions. For example, the heat of formation for hydrogen-oxygen combustion, one of the hottest chemical reactions, is 57.8 kcal/mole[7]. This translates to a reaction temperature of 2.91E4K, for which the most probable thermal velocity $(2kT/m_E)^{0.5}$ = 5.17 km/s, giving I_{sp} = 527 s. In contrast, I_{sp} up to 7600s has been measured[2] laser produced aluminum plasmas driven by an ordinary 20ns KrF laser. This I_{sp} corresponds to T = 9.1E6 K (780 eV). In more recent work,[8] a ns-pulse laser thruster using a few mJ per pulse produced a sustained I_{sp} =3200 seconds. In both cases, I_{sp} was determined from mass loss of the ablative target according to Eq. 6.

The energy cost C in Fig. 1 was derived for flight in vacuum according to[9]

$$C = \frac{W}{m} = \left[\frac{(1-m/M)}{(m/M)}\right] Q^* = \frac{v_E}{C_m}\left[\exp\left(\frac{v_{LEO}+g_o t_{LEO}}{v_E}\right) - 1\right] \quad , \tag{18}$$

where m/M is the ratio of mass delivered to orbit to initial mass at launch. For putting mass into LEO, this cost minimizes at about 100MJ/kg. The energy cost can, in turn, be related to dollar cost (Fig. 1) using algorithms given in reference 2. The dependence on launch frequency in Figure 1 occurs because the costs of personnel and facility amortization, which depend linearly on time, easily outweigh the cost of consumables and energy on the ground when launches are infrequent.

Present energy costs are about 0.03USD/MJ at retail on the ground. Accordingly, at 100MJ/kg, it ought not cost a great deal more than $\$3/\eta$ per kg to reach LEO, where η is the product of all efficiencies intervening between the wall plug and the kinetic energy of the laser-ablation rocket exhaust. That this cost can be as little as 300USD/kg makes sense even if η is as small as 1%.

Fig. 1 also shows that cost is a sensitive function of C_m, with a relatively sharp minimum which depends on the assumed η_{AB} and time to LEO, t_{LEO}. This is because, for C_m below the optimum, more expensive laser power is needed to lift the same weight, while for C_m above the optimum, I_{sp} is smaller, and less payload mass is delivered to orbit per unit of laser energy. The optimum in Fig. 1 is what would be calculated from Möckel's optimization of the rocket equation in vacuum[10]:

$$v_{E(opt)} = g_o I_{sp(opt)} = 0.6275\,(\Delta v + g_o \Delta t)\,. \tag{19}$$

Where $\Delta v = v_{LEO}$ = 7.73 km/s, $\Delta t = t_{LEO}$ = 400s and $g_o t_{LEO} \sim 4$ km/s, Eq. (19) gives $v_{E\,(opt)}$ = 7.36km/s and Eq. (3) gives $C_m = 270\ \eta_{AB}$ N/MW = 109N/MW. Detailed careful analytics and detailed flight simulations which include atmospheric effects[9] for a launch of a notional 1-m diameter cone-shaped flyer from 30km initial altitude gave a similar value

$$C_{m(opt)} = 2\eta_{AB}/v_{E(opt)} = 280\ \eta_{AB}\ \text{N/MW} \tag{20}$$

for the same conditions.

C_m and I_{sp} can be adjusted both by selecting appropriate target materials and by changing laser intensity or pulsewidth, or both, and, because lasers are electrical devices, the most important parts of this adjustment can be done essentially instantly.

Getting the flight vehicle to 30km initial altitude can be done with high performance aircraft, a railgun or other ground launch system [Figure 2], or an airbreathing or other type of rocket. Airbreathing laser-propelled flyers will be discussed in the next section.

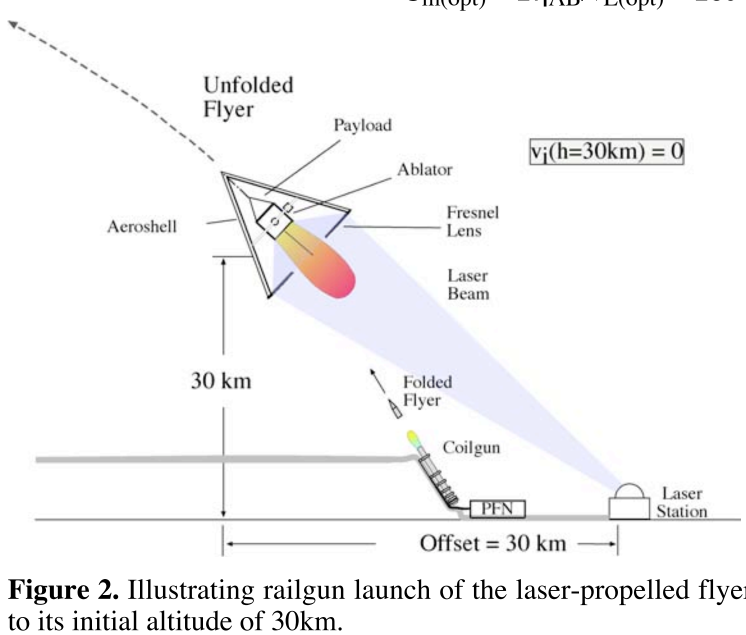

Figure 2. Illustrating railgun launch of the laser-propelled flyer to its initial altitude of 30km.

Enabling Otherwise Impossible Missions

A fourth advantage results from considering the previous three together in practical designs, which can yield situations in which LSP can do what no other existing thruster hardware can do. A recent "Broad Area Announcement" set the following graduate-level aerospace engineering problem[11]. A 180-kg spacecraft has 1kW prime power. You are allowed to design an engine whose total mass including fuel is 80kg. Its baseline orbit is at 500km altitude. The spacecraft must be able to complete any of the following four missions on demand:

- Rephase the orbit 180 degrees in 12 hours
- Raise the spacecraft from to 1500km in two days, then return to baseline in 30 days
- Crank the orbital plane 15 degrees in 90 days
- Drop the spacecraft to 300km, fight ram pressure for a year with only 50W prime power, then return to baseline in 30 days.

The criteria were deliberately chosen to be impossible to meet with currently fielded thruster technology. However, a laser-ablation propulsion engine using a set of diode-pumped glass fiber amplifiers with a total of 350-W optical power can accomplish all the tasks, according to our unpublished calculations.

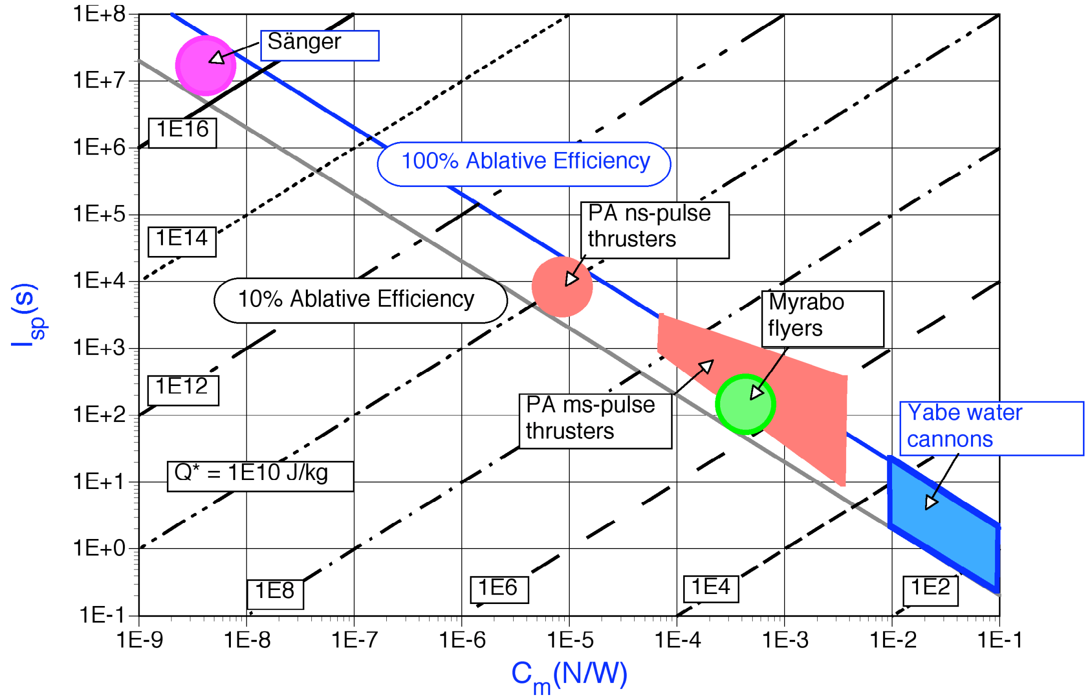

Figure 3. In a plot of I_{sp} vs. C_m, constant products corresponding to 100% and 10% ablation efficiency are shown for reference. Most concepts fall within these boundaries although, because the definition of η_{AB} considers only optical, not chemical energy, it is possible to have η_{AB} = 300% with chemical augmentation in Photonic Associates' ms-pulse laser thrusters.

Ablation fuel would be a high-viscosity, very low vapor pressure liquid version of those which will be discussed under the section on laser ablation thrusters below.

The main points of this section are:

- Laser launching can ultimately be relatively inexpensive with several launches per day, a ticket to LEO costing $50,000 or less per passenger
- Cost is a sensitive function of C_m
- $C_{m(opt)}$ is around 100 N/MW for fast flights from 30km initial altitude with η_{AB}=40%.
- Practical laser propulsion engines based on fiber lasers are possible in the near term.

Taxonomy of Laser Space Propulsion

We will summarize the many variants of laser space propulsion (LSP) which have been proposed in this section. Figure 3 puts some of these LSP concepts[8,12-15] in perspective, over a nine-order-of-magnitude range of I_{sp}. We will discuss these and other concepts in more detail in what follows.

Pure Photon Propulsion

The earliest reference to space propulsion using photons is in a paper by Eugen Sänger[15], written before the demonstration of the laser, and perhaps before Charles Townes thought of the concept. In the paper, it is shown how one can circumnavigate the universe in 20 years using pure photon propulsion. This and related papers by Marx[16] and Möckel[17] in succeeding decades considered only rockets driven by transmission, reflection or absorption of photons. Even assuming total reflection, the momentum coupling coefficient C_m that can be obtained in this way is only 2/c = 6.7E-9 N/W, while specific impulse I_{sp} is as large as it can be, 3.1E7 seconds. However, this means that, as an example, to accelerate a 1-tonne object at 1 Earth gravity, 1.5 TW of optical power is required. Möckel did not shrink from this, envisioning a 1TW, 1-km diameter x-ray laser beam with 1Å wavelength impinging on a 1-km diameter sail to propel a spacecraft to α-Centauri in 10 years. At the present time, space propulsion by light is only remotely practical in the context of photon sails, in which the optical input is light emitted by the sun or another bright incoherent source, rather than by a laser[18], and in Bae's concept for intracavity photon thrusters for highly precise positioning of nanosatellites[19].

Propulsion by Laser Ablation

Kantrowitz[20] suggested the first practical approach to laser space propulsion (LSP), in which a laser is used to heat a solid propellant surface to generate a vapor or plasma jet which provides the thrust. The propellant may be inert, or exothermic. The laser may be remote, i.e., a ground-based beam projected by a beam director of suitable aperture, or it may be onboard the spacecraft. The concept is more practical than photon propulsion because it involves practical lasers: C_m's that are four to as much as eight orders of magnitude larger permit using lasers with optical power of watts to several kW, rather than several GW, to do useful tasks. These will almost invariably be repetitively pulsed rather than CW lasers to allow achievement of high I_{sp} when necessary, to broaden the range in which the values of I_{sp} and C_m may be adjusted, and to facilitate clearing exhaust from the optical path between pulses.

The ms-pulse Laser Plasma Thruster[12,21,22] (msLPT) is a good example of recent practical applications, and may be the first realization of LSP to actually fly in space [Table 2, Figure 4]. It is also the first realization of chemically-augmented electric propulsion. Among microthrusters, it excels in specific mass (0.05 kg/kW), thrust density (4,000 N/m^2) and total thrust efficiency (195% is obviously a result that no other technology can match). This surprising value for thrust efficiency arises because η_{eo} (see Eq. 11) can be 65% for the latest generation of diode lasers, and η_{AB} values up to 300% have been measured with the exothermic polymer ablation fuels.

A substantial literature[23-26] exists concerning the physical chemistry and the correlation of thrust with material, plasma and shockwave properties of the exothermic polymers which were developed specifically for the microthruster laser ablation fuel application.

The developmental ns-pulse thruster (nsLPT)[8] has achieved I_{sp} = 3660s with C_m = 56μN/W and η_{AB} = 100%.

These two units will be combined in a single device using low-mass diode-pumped glass fiber laser amplifiers to operate in either long- or short-pulse regimes at will. Adequate fiber lasers have been demonstrated[27].

Another, so far less practical, concept for using laser ablation space propulsion is the ORION system design[28,29] for removing LEO space debris in the 1- to 10-cm size range using a 20-kW average power groundbased laser and 6-m diameter beam director.

This concept is matched by a spacebased system design for accomplishing the same task[30,31]. Further work is required to determine which approach to debris removal would be less costly and more efficient.

Propulsion by Laser Gas Detonation

Table 2. msLPT performance

Parameter	*Value*
Thrust	*0.1 – 10 mN*
C_m	*3 mN/W*
I_{sp}	*200 s*
Ablation Efficiency η_{AB}	*300%*
Thrust Efficiency η_T	*195%*
Minimum Impulse	*1* μN-s
Volume	*670 cm*^{3}
Mass	*0.5 kg*
Electrical Power	*20 W (max)*
Lifetime Impulse	*50 N-s*
Fuel Capacity	*44 g*
Type of Laser	*JDSU 6396 diode*
Ablation Fuel	*Glycidyl azide polymer*

In 1982, Myrabo[32,33] proposed an air-breathing laser-propelled flyer (Figure 5) which, at least in the atmosphere, would require no ablation fuel other than ambient air. The first ground and flight tests of this vehicle were reported in 1998, in which active tracking and beam control were demonstrated to 122m on a horizontal wire. Two years later[34,35], spin-stabilized flight powered by a repetitively-pulsed 10kW CO_2 laser was reported, reaching an altitude of 71 m. In this device, a reflective biparabolic afterbody concentrates light in the rim of the flyer, producing air breakdown and detonation which, in turn, produces thrust. It is proposed that, outside the atmosphere, the device would use solid ablatants. Where measurements exist, data gives moderate I_{sp}<1000s (Figure 3). C_m ranges from about 250μN/W for air to 900μN/W for solid propellant in air.

Bohn and coworkers[36,37] tested an alternate monoparabolic configuration, obtaining slightly larger values of C_m. He also flew the monoparabolic flyer to an altitude of 6m in the laboratory. Simulations were done which showed that a 1MW laser could deliver 10kg to LEO using a fuel mass of about 1kg if C_m = 1mN/W. Mori, et al. also studied this configuration, obtaining similar results.[38]

Rezunkov[39] has used a gasdynamic laser in a wireguided flight to propel a craft with a novel re-entrant reflector design and a solid delrin rod for ablation fuel, achieving C_m = 125 μN/W with Isp = 530 and η_{AB} = 33%. The mass of the craft was 92g.

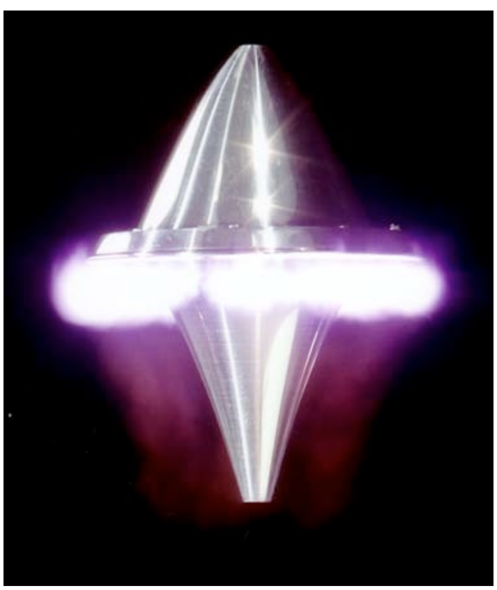

Figure 5. The Myrabo "Lightcraft." Diameter is about 10 cm and mass 20-50g.

Figure 4. The msLPT is about to undergo final acceptance tests. Six diode lasers drive a special ablation fuel tape behind the output ports. These are fired in matched pairs to maintain a fixed center of thrust. A ns-pulse version is being developed.

Sasoh[40] has used a 500W repetitive-pulse CO_2 laser to fly a different re-entrant reflector design propelled, like the Bohn device, by detonation of ambient gas (Ar, Kr and Xe), up a lucite tube in the laboratory, achieving $C_m = 300\mu N/W$ with Xe.

Propulsion by Laser Expulsion of Liquids

In 2002, Yabe and coworkers proposed[14,41] laser-powered microairplane which could be used, e.g., for collecting climate data or observing volcanic eruptions. The model tested in the laboratory generated extreme values of C_m by using the shock generated by a laser-irradiated absorber at the back of a container of liquid water to drive liquid water from the container. Measured C_m's ranged from 0.24 to 5mN/W, while simulations gave values up to 70mN/W near threshold intensity. Although these are the largest momentum coupling coefficients ever observed, it should be noted that the corresponding I_{sp} is on the order of 10 (Figure 3). This means that, by Eq. 13, ablator lifetime will be at least ten thousand times less than that of a device with $I_{sp} = 1000$. If, for example, M=100kg, P = 100W, $I_{sp} = 10$ and $\eta_{AB}=1$ Eq. 13 gives $\tau_{AB} = 4800$s. However, for the short flight times envisioned in the climate data application, this should not be a problem.

Laser-Electric Hybrids

Horisawa[42] has built and tested a hybrid laser-electric thruster in which a laser-ablation plasma is additionally accelerated by an electric field. Mechanically, this device resembles a pulsed plasma thruster[43] (PPT), and achieves thrust efficiency near 10% (similar to that of the PPT[43]) together with specific impulse up to 2500s, which is considerably better than the ≈1000s produced by conventional PPT's.[44] C_m for the laser-electric hybrid was about 7μN/W.

Laser Heat Exchangers

Kare has suggested a laser driven spaceflight concept called the HX thruster[45,46] which is essentially a laser-heated boiler. In simulations, with an exhaust temperature of 1000C, the thruster achieves $I_{sp} = 600$s. In Kare's design, the heat exchanger by itself achieves very high specific power (1MW/kg). The concept requires two lasers, for launch and mid-range acceleration. Water injection is used at low altitude to increase thrust for the system, which uses a hydrogen exhaust above the atmosphere. Laser power of 100MW is assumed. With M = 5400kg liftoff mass, m = 180kg is delivered to LEO, giving a ratio m/M = 0.033.

Rather[47] has proposed a similar concept, in which a Shuttle hydrogen tank with mass 30,000kg could be propelled to geostationary orbit (GEO) in 45 days using a 10MW laser to heat 4,000kg hydrogen sufficiently to achieve $I_{sp} = 1500$s. He proposes that these tanks could then be used to build, e.g., a manned GEO station, or a LEO-GEO shuttle.

Perspective and Conclusions

We have reviewed the theory and several proposed applications in the field of laser space propulsion. Except for one pure photon propulsion concept[19], these share the idea of using a laser to create thrust, or augment the creation of thrust by heating a target to cause the ejection of mass. Most exciting in the near term is the possibility of accomplishing near-Earth missions that are impossible with conventional thrusters in laser-powered macrothrusters which take advantage of extremely lightweight diode-pumped glass fiber lasers onboard the spacecraft to provide thrust with variable I_{sp} and unmatched thrust efficiency deriving from exothermic laser ablation fuels. Another interesting near-term application is powering small climate sampling craft with very simple water expulsion engines for short flights using a groundbased laser. Also interesting for the near term is using pure photon propulsion to provide the very small impulse bits needed to position nanosatellites with nm precision.

In the medium term (say, the next decade), propelling some kind of lightcraft from the Earth's surface to a proof-of-concept altitude such as 10km would be of great interest for the future development of this technology. However, considerable infrastructure has to be in place for this to occur, including laser guidestars, tracking and illuminating lasers, a repetitively-pulsed thrust laser with at least 100kW average power, and a large beam director equipped with adaptive optics. Many of these items already exist in various places, or it is well understood how to build them. The expensive part will be to integrate such a system in one location and make it work. If additional elements such as railguns are required in the concept, this only adds to the difficulty. However, the problem here is funding, not technical unknowns.

Also in the medium term, it would be relatively easier than Earth-launch to launch samples into low Mars orbit from Mars surface, to be collected for Mars Sample Return (MSR). The low density of the Martian atmosphere would make surface launch energetically similar to launch beginning 20km above Earth's surface as regards atmospheric drag and, of course, Mars' gravitational field is considerably weaker.

Beyond the medium term (say, fifteen years), it will be possible to routinely laser-launch 10-20kg nanosatellites, or parts of a larger space vehicle, into LEO. Lifting space vehicle components off the planet and launching completed space vehicles into interplanetary trajectories at very low cost will profoundly alter our relationship to space. Whether and to what extent this possibility is pursued depends on the priority decisions of our scientific and engineering programs.

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