A Review of Laser Ablation Propulsion

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Abstract. Laser Ablation Propulsion is a broad field with a wide range of applications. We review the 30-year history of laser ablation propulsion from the transition from earlier pure photon propulsion concepts of Oberth and Sänger through Kantrowitz's original laser ablation propulsion idea to the development of air-breathing "Lightcraft" and advanced spacecraft propulsion engines. The polymers POM and GAP have played an important rôle in experiments and liquid ablation fuels show great promise. Some applications use a laser system which is distant from the propelled object, for example, on another spacecraft, the Earth or a planet. Others use a laser that is part of the spacecraft propulsion system on the spacecraft. Propulsion is produced when an intense laser beam strikes a condensed matter surface and produces a vapor or plasma jet. The advantages of this idea are that exhaust velocity of the propulsion engine covers a broader range than is available from chemistry, that it can be varied to meet the instantaneous demands of the particular mission, and that practical realizations give lower mass and greater simplicity for a payload delivery system. We review the underlying theory, buttressed by extensive experimental data. The primary problem in laser space propulsion theory has been the absence of a way to predict thrust and specific impulse over the transition from the vapor to the plasma regimes. We briefly discuss a method for combining two new vapor regime treatments with plasma regime theory, giving a smooth transition from one regime to the other. We conclude with a section on future directions.

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INTRODUCTION:

What Laser Ablation Propulsion Offers

Laser Ablation Propulsion (LAP) is an electric propulsion concept with a thirty-five year history. In LAP, an intense laser beam [pulsed or continuous (CW)] strikes a condensed matter surface (solid or liquid) and produces a jet of vapor or plasma. Just as in a chemical rocket, thrust is produced by the resulting reaction force on the surface. Spacecraft and other objects can be propelled in this way. There are advantages for this technique compared to chemical and other electric propulsion schemes. LAP applications range from mW-level satellite thrusters, through kW-level

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systems for re-entering near-Earth space debris to MW and GW systems for direct launch to low Earth orbit. Table 1 indicates benefits of LAP.

TABLE 1. Laser Ablation Propulsion Performance Metrics
[L = Low; M = Moderate; H = High; VH = Very High]

Thrust to Mass ratio	Thrust	Thrust Density	Electrical Efficiency	Specific Impulse	Main Benefit	Main Limitations
H (15N/kg)	Scales linearly with laser power	H (8E5 N/m^2)	VH (>100%)	L to VH ($200<I_{sp}<3100$s)	VH electrical efficiency, I_{sp}	40-60% laser electrical efficiency; more than newton-level thrust not yet demonstrated

Thrust efficiency η_T can exceed 100% in spite of 50-60% electrical to optical conversion efficiency in the laser. This is because thrust efficiency

$$\eta_T = \eta_{eo}\,\eta_{AB} \tag{1}$$

is the product of the electrical-to-optical conversion and ablation efficiency

$$\eta_{AB} = \text{Exhaust power/Input electrical power}, \tag{2}$$

which can be as high as 230% with certain polymer ablating fuels because of the chemical energy contribution of these exothermic polymers [1].

How these Benefits are Achieved

Variable specific impulse,

$$I_{sp} = v_E/g_o \tag{3}$$

is achieved by adjusting laser intensity on target – by changing focal spot area and laser pulse duration – which causes exhaust velocity to vary across the range from chemical reactions (approximately, $I_{sp} \le 500$ seconds) to much higher values (3,500 – 6,000 seconds). This is because

$$I_{sp}=(2kT_i/m_i)^{0.5}/g_o \tag{4}$$

and 10,000K ion temperatures T_i can easily be created with a laser pulse. In short, I_{sp} is only a matter of intensity. Thrust can be varied independently of I_{sp} by changing the laser pulse repetition rate. Tens of ks specific impulse are possible using current laser technology, for example, I_{sp} = 8.3E4 s at T = 1E8K in inertially confined fusion [2] (although lasers required to do this are currently too massive to be practical for a space vehicle). Energy-use efficiency for a flight is strongly improved by "constant-momentum" exhaust velocity profiles [3]. which require variable I_{sp}, and this is extremely difficult to achieve with chemical jets. For ground-based laser applications, the thrust-to-weight ratio is much higher than in electric propulsion, because the power production source remains on the ground.

High specific impulse allows for high payload fractions m/M. In self-contained laser propulsion engines, high-pressure or cryogenic fuel tanks, high-power gas-driven turbopumps, nozzle cooling systems and the like are replaced by relatively lightweight diode or diode-pumped fiber lasers. Because fiber lasers are efficient, distributed systems with large surface-to-volume ratio, cooling of the laser itself is not a difficult problem up to the kW-power, N-thrust level. For larger thrust, with technology available today, chemical rockets are still the best choice. But within this range, spacecraft with laser engines will be more agile. Vehicle specific mass of order 10N/kg has been demonstrated [4].

For flight within the atmosphere, polymer propellants cause insignificant pollution. The laser installation and power transmission unit for large systems on the ground constitute a considerable investment. However, since they are easily serviceable, they can be built more cheaply, without space qualification. Laser thrusters have demonstrated thrust density [5] of order 800 kN/m^2 because thrust is arising from a spot with area equal to that of the laser focus. This is important in comparison with the much larger throat area to thrust ratio of ion engines, for example.

In systems intended for direct launch to LEO using a launch frequency of about five per day, the cost/kg delivered to LEO is dramatically reduced from present costs to as little as $300/kg [6] for laser launch. Laser launching is inherently suited for high launch frequencies beyond what is practical for chemical systems. The cost reduction comes from spreading fixed equipment amortization and labor costs, the cost of ground-based electrical energy itself being only 3¢/MJ.

EARLY HISTORICAL BACKGROUND

The idea to send a beam of light to a distant location and use its energy or its momentum has been around since antiquity. Archimedes' mirrors reflecting sunlight and focusing it onto the Roman fleet of Commander Marcellus off the coast of Syracuse in 214 BC is the best-known example. The first seriously documented approaches to the application of directed light beams are found in the publications of astronautic visionaries of the 20th century. In 1923 - 24 the Russian pioneers Fridrikh Tsander [7], Konstantin Tsiolkovsky [8] and Hermann Oberth [9], mentioned the idea of propulsion by light pressure. The Russian work was virtually unknown to the West until the 1930's when rocket technology had developed through the efforts of Oberth in Germany and Goddard in the United States. Sänger proposed [10, 11] in 1953 the photon rocket for interstellar missions. Since the laser was not invented at that time, Sänger envisioned propulsion based on the continuum radiation of a hot plasma generated by a fission reactor placed at the focal point of a large reflector. Radiation pressure provided the necessary momentum. After the invention of the laser in 1960, Sänger modified the concept to feature a nuclear-pumped gas laser to provide the necessary radiation pressure. As an even more futuristic alternative, he considered a fusion reactor and a matter-antimatter annihilation reactor. Wolfgang Möckel wrote the basic equations for non-chemical propulsion in two seminal papers [12, 13]. He was first to realize that, whereas almost unlimited exhaust velocities are possible for laser propulsion, the highest exhaust velocity is not necessarily the best, since most of the momentum might go into the plume rather than the spacecraft.

Pure-photon pressure is minute: the "momentum coupling coefficient" for pure radiation reflecting off a polished surface is

$$C_{\mathrm{mh\nu}} = 2/c = 6.7 \text{ nN/W}, \tag{5}$$

and a 10-kW laser would produce a thrust of only 67μN. To get useful thrust, we need a very high power laser source, or enhancement by a secondary phenomenon, such as laser-induced surface ablation – the main subject of this paper.

The paradigm shift in laser propulsion technology occurred in 1972 when Arthur Kantrowitz[14] introduced and clearly formulated the idea of ablative laser propulsion: a high power laser beam focused onto the surface of a material can evaporate and even ionize part of that material, generating a specific impulse much higher than expected from classical chemical rockets. The coupling coefficient due to laser ablation of common materials can be 100N/MW to 10kN/MW, four to six orders of magnitude larger than the Eq. (5) value.

THEORY

The momentum coupling coefficient C_{m} is defined as the ratio of impulse density σ to the incident laser pulse fluence Φ (or pressure p to intensity I for a CW laser) where exhaust velocity $v_{\mathrm{E}} = \langle v_{\mathrm{x}} \rangle$ is the first moment of the velocity distribution $f(v_{\mathrm{x}})$ [15] along the thrust axis x.

$$C_{\mathrm{m}} = \sigma/I = \mu v_{\mathrm{E}}/\Phi = p/I \tag{6}$$

Defining specific ablation energy Q^* as the ratio of laser fluence to target areal mass density,

$$Q^* = \Phi/\mu \quad , \tag{7}$$

we have

$$v_{\mathrm{E}} = C_{\mathrm{m}} Q^* . \tag{8}$$

and ablation efficiency

$$\eta_{\mathrm{AB}} = \mu\psi v_{\mathrm{E}}^2/(2\Phi) = \psi\, C_{\mathrm{m}} v_{\mathrm{E}} / 2 \tag{9}$$

where [16]

$$\psi = \frac{\langle v_{\mathrm{x}}{}^2 \rangle}{(\langle v_{\mathrm{x}} \rangle)^2} = \left\{ \frac{u^2 + \frac{kT}{m_{\mathrm{E}}}}{u^2} \right\} \quad . \tag{7}$$

C_{m} and I_{sp} form a constant product

$$C_{\mathrm{m}}\, I_{\mathrm{sp}} = 2\eta_{\mathrm{AB}}/(\psi g_{\mathrm{o}}) \ . \tag{8}$$

Plasma Regime

At sufficient laser intensity, the ablation process progresses to the fully-formed plasma regime where the ionization fraction in the plasma regime is defined as

$$\eta_{\mathrm{i}} = n_{\mathrm{i}}/(n_{\mathrm{o}} + n_{\mathrm{i}}) \approx 1. \tag{9}$$

It was shown by Phipps, *et al.* [17] that the simple relationship

$$C_{\mathrm{mp}} = 5.83 \frac{\Psi^{9/16}}{A^{1/8}(I\lambda\sqrt{\tau})^{1/4}} \quad \text{dyn/W} \tag{10}$$

describes C_m to within a factor of two for surface absorbers in the plasma-dominated regime. There also resulted

$$I_{\mathrm{sp\,p}} = 1400 \frac{A^{1/8}}{\Psi^{9/16}}(I\lambda\sqrt{\tau})^{1/4} \quad \text{s} \tag{11}$$

for the plume specific impulse, where

$$\Psi = \frac{A}{2[Z^2(Z+1)]^{1/3}} \quad , \tag{12}$$

A is the average atomic mass number and $Z \geq 1$ is the average ionization state in the laser-produced plasma plume, which is, in turn, determined by applying Saha's equation [18],

$$\frac{n_e n_j}{n_{j-1}} = \frac{2u_j}{u_{j-1}}\left(\frac{2\pi A m_p k T_e}{h^2}\right)^{3/2} \exp(-W_{j,\,j-1}/kT_e) \quad , \tag{13}$$

and writing

$$Z = \frac{1}{n_i}\sum_{j=1}^{j\,\max}(j n_j) \geq 1 \quad , \tag{14}$$

under the obvious normalization constraint

$$\sum_{j=1}^{j\,\max}(n_j) = n_i \quad . \tag{15}$$

Parameters in the preceding relationships are: $W_{j,\,j-1}$, the ionization energy difference in eV between the (j-1)th and jth ionization states of the material; m_p, the proton mass; kT_e, the electron temperature in the plasma plume (eV); Planck's constant h; the neutral vapor density n_o; c, the speed of light; I the incident laser intensity (W cm^{-2}); the plume electron total number density n_e (cm^{-3}); u_j the quantum-mechanical partition functions of the jth state; and n_j, the number density of each of the ionized states.

Polymers in the Vapor Regime

The Sinko/Phipps vapor model [19] applies best to polymers, where tables of vapor pressure vs. temperature p(T) are difficult or impossible to obtain, but where the fluence for onset of ablation Φ_o is well known. Because Φ_o usually depends on wavelength and pulse duration, this approach is best applied to one combination of (λ, τ) at a time, but works very well. Where

$$\mu = (\rho/\alpha)\ln(C\Phi/\Phi_o) \tag{16}$$

is the ablated mass areal density and C is a constant combining energy losses such as reflectivity and exhaust energetic modes that do not contribute to propulsion, which is equal to the ablation efficiency, the ablation momentum areal density σ can be related to the laser parameters by energy conservation:

$$\sigma^2/2\mu = C\Phi - \Phi_o = \Phi_o\ (\xi\text{-}1), \tag{17}$$

(where $\xi = C\Phi/\Phi_o$). Based on Eq. (16 – 17), the momentum coupling coefficient and specific impulse can be obtained as

$$C_{mv} = \sigma/\Phi = \sqrt{\frac{2\rho C^2(\xi - 1)\ln\xi}{\alpha\Phi_o\xi^2}} \tag{18}$$

$$I_{spv} = \sqrt{\frac{2\alpha\Phi_o(\xi - 1)}{\rho g_o^2 \ln\xi}} \tag{12}$$

Elemental Materials in the Vapor Regime

For some elemental materials, tables of vapor pressure vs. temperature $p(T)$ exist, e.g., the Los Alamos SESAME tables [20]. For such materials, by working backwards from hydrodynamic variables based on wavelength-independent material parameters to the incident intensity I which must exist to balance these variables, we showed in [21] that the expressions

$$I = \frac{pv}{a}\left(\frac{\gamma}{\gamma-1}\right)\left[1 + \frac{q}{C_pT} + \frac{\gamma-1}{2} + \frac{\sigma\varepsilon}{a}T^4\right] + B(\tau) \tag{13}$$

with
$$B(\tau) = \frac{1}{a}\left[\phi(T,x_h) + \frac{x_h\,\rho_s C_v(T-T_o)}{\tau}\right] \tag{14}$$

can be used to generate a numerical solution which relates ablation pressure p and vapor velocity v to I over the range corresponding to our $p(T)$ data, and we can compute the vapor regime coupling coefficient (for elemental materials such as aluminum) as

$$C_{mv} = p/I \quad . \tag{15}$$

Vapor specific impulse is
$$I_{sp\,v} = v/g_o \quad . \tag{16}$$

These relationships are wavelength-independent, except for the variation of a with λ.

Combined Models

Having results for the two physical extremes of vapor and plasma, we make a smooth transition between the models using the approach of [19], writing for the combined coupling coefficient,

$$C_m = p/I = [(1-\eta_i)p_v + \eta_i p_p]/I = (1-\eta_i) C_{mv} + \eta_i C_{mp} \quad (17)$$

where the ionization fraction η_i [(Eq. (9)] is determined during the process indicated in Eqs. (13-15). Specific impulse can be combined in the same way. The success of these approaches for a typical polymer (polyoxymethylene) and a typical elemental material (aluminum) are discussed in more detail in [22].

APPLICATIONS

In a paper of this length, it is not possible to make a complete review of laser ablation applications. For this, the reader is referred to [1].

Flights in Air

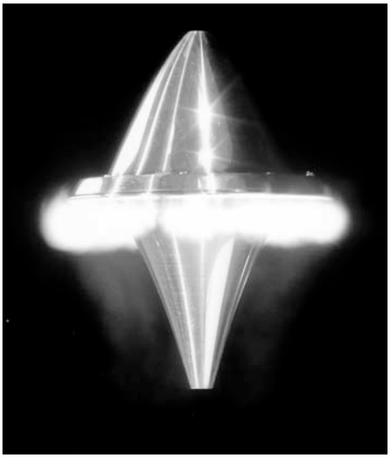

FIGURE 1. Lightcraft vehicle at launch.

The first free flight of a 1997 laser rocket design by Myrabo (Figure 1) resulted in a record flight height of 72 m at the White Sands Missile Range in 2000 [23-24]. It was driven by the 10kW repetitively pulsed "PLVTS" CO_2 laser. These experiments demonstrated the viability of this beam-riding pulsejet vehicle concept. Key contributions to Lightcraft research are: 1) experimental and numerical investigations by Mead, Jr., *et al.*[25]; 2) theoretical studies on laser energy conversion by Larson, *et al.* [26], and 3) laser propulsion launch trajectory simulations by Knecht, *et al.*[27]. The goal of this work is to launch a laser propulsion vehicle into suborbital flight (e.g., vertical sounding rocket trajectory).

The ASLPE engine (Figure 2) has been demonstrated by Rezunkov, *et al.* to generate 2N thrust and C_m = 270N/MW in wire-guided flights in the laboratory driven by a 6kW repetitively pulsed CO_2 laser.

FIGURE 2. The ASLPE engine.

Space Engines

The Laser Plasma Thruster (LPT)

The LPT (Figure 3) [29] was developed for microsatellite positioning and pointing. High power, bare-facet, 920nm diode lasers were used in this ms-pulse LPT, with a fuel tape composed of polymerized GAP film applied to a kapton backing. At its present state of development, it gives 10mN thrust with 20W electrical input, but, with liquid fuels, the design is extensible to units developing 6N thrust in ms-pulse mode for agile spacecraft propulsion [30].

FIGURE 3. The Photonic Associates Laser Plasma Thruster; operating in a high vacuum space test chamber (right)

By varying laser intensity, such a device can span the range $120 < I_{sp} < 3660$ s. $I_{sp} = 3.6$ks was measured in a ns-pulse LPT with gold targets [31, 32].

Laser In-tube Accelerator (LITA)

In-tube propulsion is a method to enhance propulsion performance by utilizing the confinement of propellant in a launch tube so that the pressure behind the projectile or vehicle is increased [33, 34]. This concept is the basis of gun technologies and is also seen in rocket technology as the ram accelerator. Several versions have been developed. Figure 4 shows the version which operates in vacuum, developing 1.5 kN/MW with polyoxymethylene solid propellant. Other versions developed up to 4kN/MW in a tube filled with argon, krypton or xenon, and used the ambient gas for propulsion.

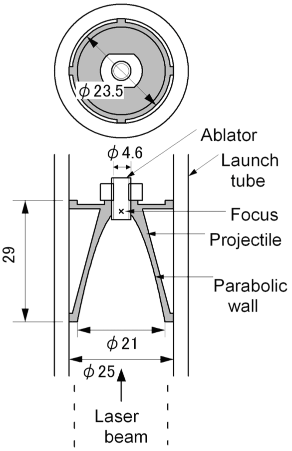

FIGURE 4. LITA using onboard ablator (V-LITA).

PROPELLANTS

The LPT required specially designed ablatants (laser ablation propellants) that exceeded the capabilities of common commercial polymers. The key requirements were very low thermal conductivity (because of the ms-duration laser pulses employed in that device) and maximum exothermic energy content, to give maximum thrust to power ratio. Various commercially available and specially designed polymers were tested [36-39]. Three polymers (GAP, PVN and PVC) with two different absorbers (carbon nanoparticles and an infrared-dye (IR) [Epolite 2057)] were studied as fuel for the laser plasma thruster. GAP and PVN are energetic polymers with a high decomposition enthalpy of –3829 J/g (PVN) and –2053 J/g (GAP).

Liquid fuels are very attractive because they are more easily stored and dispensed. The problem is that liquids splash, preferentially converting incident laser energy to low velocity droplets. There are two approaches which have been used to mitigate this problem. One way to eliminate splashing is to increase the viscosity of the liquid fuel. Shadowgraphy measurements in GAP [40], as well as I_{sp} measurements in partially polymerized GAP [41], both demonstrated that this will work, and can give I_{sp} as high as 680s. There is no physical reason that I_{sp} cannot be as large in viscous liquids as in solids. A second approach to mitigating splashing is in novel propellant geometries such as thin films or 1-dimensional streams [42].

ADVANCED CONCEPTS

kW Liquid-fueled Laser-plasma Engine

A kW-level laser plasma engine has been proposed [30]. This would use a liquid fuel delivery system, and low-mass, 100W diode-pumped fiber lasers to illuminate the fuel. The design uses the same principles employed in laser welding and cutting to avoid target blowback to the illumination optics. Gas flow through an illumination head in which the mean free path for a backscattered particle is less than the distance to the optics solves the problem. In space, the flow required to provide the required 1.0Pa pressure through the 600μm orifice of the delivery channel is only 30 grams per year of operation. This engine assumes achievement of 3,660s I_{sp} on liquids, via the viscous fluids approach. Stable viscosity can be achieved by dissolving polymerized GAP in ionic liquids, which have vanishing vapor pressure and are already used in electric propulsion engines for spacecraft.

ORION

Laser space debris removal uses a high-intensity pulsed laser beam to ablate (not pulverize) a fraction of the debris itself in an orientation such that the debris is slowed sufficiently to re-enter the atmosphere and burn up. This system is discussed in detail in [22].

The way we send things to space from Earth is expensive, energy-inefficient and polluting. Present day costs of raising mass from the Earth's surface into low Earth orbit (LEO) with chemical rockets is about \$20,000/kg. This cost, equivalent to the cost of gold, dominates all other considerations relating to spaceflight, limiting what we consider to be possible. Phipps and Michaelis [6], using an innovative design for a high-power laser system appropriate for launching large payloads [43], 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 [Figure 5]. Cost becomes \$300/kg for five launches per day. At \$300/kg, a spin around the Earth comes within a factor of three of the cost of a flight on the Concorde when it was still flying, adjusted for inflation.

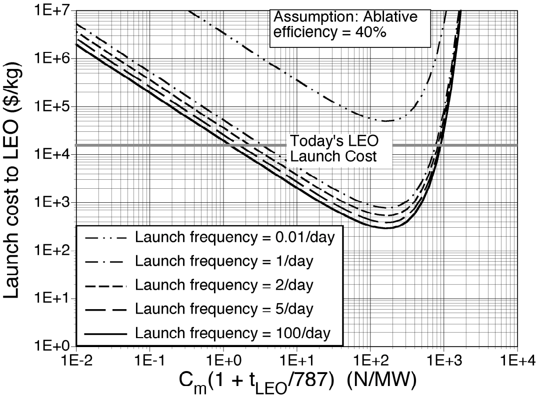

FIGURE 5. Unit cost of laser launching a large payload to LEO using a repetitive-pulse laser and η_{AB} = 40%.

PROMISE FOR THE FUTURE

In this section, we give our estimates for the times to realize practical application of laser ablation propulsion.

One to Two Years

The first practical space application of LAP is already built, tested and awaiting a flight: the Laser Plasma Thruster. This could occur within 1-2 years. The first application to have a large effect on the Earth's space environment will be the ORION system for clearing space debris. This application is important because debris is still being added to the near-Earth environment, and we can approach an instability in which long-term access to space is denied and present assets are threatened by fratricidal collisions among the debris. Several agencies are considering funding an ORION demonstration in the near future.

Two to Ten Years

The Lightcraft is the first laser-powered device to fly in the atmosphere and, with material modifications, could possibly endure a flight through the atmosphere and into LEO. Depending on funding, practical realization of the Lightcraft could take 2-10 years, because it is still orders of magnitude away from the required operating range, and performance over that range remains to be proven. Alternatively, an airbreathing

Lightcraft could act as the first stage of a laser-propelled flyer with a second stage optimized for spaceflight.

Five to Ten Years

Within 5 years, it is easily possible to build MW-class, repetitively pulsed lasers and launch vehicles which can take ~5kg payloads to LEO, for assembly of larger objects there. Also within a 5 year timeframe are laser orbital transfer vehicles (LEO to GEO), and efficient vehicles powered by an orbiting mother ship for Mars sample return. In the 5-10-year timeframe, laser-electromagnetic hybrid devices may take over interplanetary missions because I_{sp} greater than 6,000s has already been demonstrated. KW-level newton-thrust liquid-fueled engines can revitalize satellite propulsion with instantaneously variable I_{sp}, and complement Hall thrusters because of their ability to generate large C_m at low I_{sp}, matching a Hall thruster deficit. They can also compete with ion thrusters for outer planet research and beyond. Engine design concepts such as the ASLPE may well play a role.

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REFERENCES

1. C. Phipps, M. Birkan, W. Bohn, H.-A. Eckel, H. Horisawa, T. Lippert, M. Michaelis, Y. Rezunkov, A. Sasoh, W. Schall, S. Scharring and J. Sinko, "Laser Ablation Propulsion," *J. Propulsion and Power*, to appear (2010)
2. E. Moses, "Multi-megajoule NIF: ushering in a new era in high energy density science," *High-Power Laser Ablation VII*, Proceedings of SPIE **7005**, pp. 0F1-0F11 (2008)
3. C. W. Larson, F. B. Mead, Jr. And S. D. Knecht, "Benefit of constant momentum propulsion for large Δv Missions – applications in laser propulsion," paper AIAA 2004-0649, 42d Aerospace Sciences Meeting, Reno, 5-8 January 2004
4. F. B. Mead Jr., L. Myrabo and D. Messitt, "Flight experiments and evolutionary development of a laser propelled, trans-atmospheric vehicle," *High-Power Laser Ablation I*, Proceedings of SPIE **3343,** 560-563 (1998)
5. Yu. Rezunkov, A. Safronov, A. Ageichik, M. Egorov, V. Stepanov, V. Rachuk, V. Guterman, A. Ivanov, S. Rebrov and A. Golikov, "Performance characteristics of laser propulsion engine operating both in CW and repetitively-pulsed modes," Proceedings of the Fourth International Symposium on Beamed Energy Propulsion, Nara, Japan, *AIP Conference Proceedings* **830**, 3-13 (2006)
6. C. Phipps and M. Michaelis, "LISP: Laser impulse space propulsion," *Laser and Particle Beams,* **12** (1), 23-54 (1994)
7. F. Tsander, "Flight to other planets," (1924) in Ye. Moshkin, *Development of Russian Rocket Technology*, Mashinostroyeniye Press, Moscow (1973) (in Russian)
8. K. Tsiolkovsky, "Plan of Space Exploration". 1926 (in Russian), available in English in "Exploration of the Universe with Reaction Machines: Exploring the Unknown," NASA History Series. NASA SP 4407, Washington, D.C. (1995)
9. H. Oberth, "Die Rakete zu den Planetenräumen", (The Rocket to the Planet Spaces) Oldenbourg Verlag, München (1923)
10. E. Sänger, "Zur Theorie der Photonenraketen," Probleme der Weltraumforschung (IV. Internationaler Astronautischer Kongress, Zürich 1953; S. 32, Biel-Bienne: Laubscher (1955)
11. E. Sänger, "Flight Mechanics of Photon Rockets," *Aero Digest*, pp. 68-73 (1956)

12. W. Möckel, “Comparison of advanced propulsion concepts for deep space exploration,” *J. Spacecraft and Rockets*, **9**, 863-868 (1972)
13. W. Möckel, “Optimum exhaust velocity for laser driven rockets,” *J. Spacecraft and Rockets*, **12** 700-701 (1975)
14. A. Kantrowitz, “Propulsion to Orbit by Ground-Based Lasers,” *Astronautics and Aeronautics* **10** (5), 74-76 (1972)
15. C. R. Phipps and J. R. Luke, “Laser Space Propulsion,” *Laser Ablation and its Applications*, Chap.16, Springer, 407-434 (2007)
16. C. R. Phipps, J. P. Reilly and J. W. Campbell, “Optimum Parameters for Laser-launching Objects into Low Earth Orbit”, *J. Laser and Particle Beams*, **18**, 661-695 (2000)
17. C. R. Phipps, Jr., T. P. Turner, R. F. Harrison, G. W. York, W. Z. Osborne, G. K. Anderson, X. F. Corlis, L. C. Haynes, H. S. Steele, K. C. Spicochi and T. R. King, "Impulse Coupling to Targets in Vacuum by KrF, HF and CO_2 Lasers" , *J. Appl. Phys.,* **64**, 1083 (1988)
18. M. Saha, “Ionization in the solar chromosphere,” *Phil. Mag.* **40**, 472 (1920)
19. J. Sinko and C. Phipps, “Modeling CO_2 laser ablation impulse of polymers in vapor and plasma regimes,” *Appl. Phys. Lett.,* **95**, 131105-1 to 131105-3 (2009)
20. The SESAME equation-of-state database is maintained by group T-1 at Los Alamos National Laboratory (sesame@lanl.gov); see S.P. Lyon and J.D. Johnson, "SESAME: The Los Alamos National Laboratory Equation of State Database," LANL Report No. LA-UR-92-3407 (1992) for additional information.
21. C. Phipps, “An Alternate Treatment of the Vapor-Plasma Transition,” *Int. J. Aerospace Innovations* **1**(1) to appear (2010)
22. C. Phipps and J. Sinko, “Applying New Laser Interaction Models to the ORION Problem,” paper HPLA010_77, this conference.
23. L. N. Myrabo, D. G. Messitt, F. B. Mead Jr., “Ground and flight tests of a laser propelled vehicle,” paper AIAA 98-1001, 36th AIAA Aerospace Science Meeting & Exhibit, 12-15 January 1998, Reno, NV (1998)
24. L. N. Myrabo, “World Record Flights of Beam-Riding Rocket Lightcraft: Demonstration of ‘Disruptive’ Propulsion Technology,” paper AIAA 2001-3798, 37th AIAA/ASME/ SAE/ASEE Joint Propulsion Conference, 8-11 July 2001, Salt Lake City, UT (2001)
25. F. Mead Jr., C. Larson and S. Knecht, “An Overview of the Experimental 50-cm Laser Ramjet (X-50LR) Program,” *4th International Symposium on Beamed Energy Propulsion (ISBEP)*, AIP Conference Proceedings **830**, 534-552 (2005).
26. C. Larson, F. Mead Jr. and W. Kalliomaa, “Energy Conversion in Laser Propulsion III,” ,” *1st International Symposium on Beamed Energy Propulsion (ISBEP), AIP Conference Proceedings* **664**, 170-181 (2002)
27. S. Knecht, F. Mead Jr., M. Micci and C. Larson, “Trajectory Simulations, Qualitative Analyses and Parametric Studies of A Laser-Launched Micro-Satellite Using OTIS,” *4th International Symposium on Beamed Energy Propulsion (ISBEP), AIP Conference Proceedings* **830**, 522-533, (2005)
28. A. A. Ageichik, M. S. Egorov, S. V. Ostapenko, Y. A. Rezunkov, A. L. Safronov, V. V. Stepanov, “Model Test of the Aerospace Laser Propulsion Engine,” *Beamed Energy Propulsion, Third International Symposium on Beamed Energy Propulsion*, eds. V. A. Pakhomov and L. N. Myrabo, AIP Conference Proceedings **766,** 183-194 (2005)
29. C. R. Phipps, J. R. Luke, W. Helgeson and R. Johnson, “Performance Test Results for the Laser-Powered Microthruster,” Proceedings of the Fourth International Symposium on Beamed Energy Propulsion, Nara, Japan, ed. A. V. Pakhomov, *AIP Conference Proceedings* **830**, 224-234 (2006). Figure 3 is used with permission of the American Institute of Physics, copyright 2007.
30. C. Phipps, J. Luke and W. Helgeson, “Laser-powered, multi-newton thrust space engine with variable specific impulse,” *High-Power Laser Ablation VII, Proceedings of SPIE* **7005**, 1X1-1X-8 (2008)
31. C. R. Phipps, J. R. Luke and W. D. Helgeson, “3ks Specific Impulse with a ns-pulse Laser Microthruster,” paper IEPC 319, Proceedings of the 29th Internatioal Electric Propulsion Conference, Princeton, New Jersey (2005) [published on CD ROM]
32. C. R. Phipps, J. R. Luke, W. Helgeson and R. Johnson, “A ns-Pulse Laser Microthruster,” *Fourth International Symposium on Beamed Energy Propulsion, Nara, Japan, AIP Conference Proceedings* **830**, 235-246 (2006).
33. A. Sasoh, S. Suzuki, M. Shimono and K. Sawada, “Moderate-Acceleration Launch Using Repetitive-Pulse Laser Ablation in a Tube” *Journal of Propulsion and Power*, **24**, No. 5, 1144-1146 (2008)
34. A. Sasoh, S. Suzuki and A. Matsuda, “Wall-Propelled, In-Tube Propulsion with Repetitive-Pulse Laser Ablation,” *Journal of Propulsion and Power*, accepted for publication (2009)
35. H. Horisawa, M. Kawakami and I. Kimura, “Laser-assisted pulsed plasma thruster for space propulsion applications,” *Applied Physics A* **81**, 303-310 (2005)
36. T. Lippert, C. David, M. Hauer, C. Phipps, A. Wokaun, “Tailor-Made Polymers for Laser Applications,” *The Review of Laser Engineering* **29**, 734 (2001)

37. T. Lippert, C. David, M. Hauer, A. Wokaun, J. Robert, O. Nuyken, C. Phipps, “Polymers for UV and Near-IR irradiation,” *J. Photochem. Photobiol. A Chem.* **145**, 87 (2001)
38. T. Lippert, C. David, M. Hauer, T. Masubuchi, H. Masuhara, O. Nuyken, C. Phipps, J. Robert, T. Tada, K. Tomita, A. Wokaun, “Novel applications for laser ablation of photopolymers,” *Appl. Surf. Sci.* **186**, 14 (2002)
39. Lippert, M. Hauer, C. Phipps, A. Wokaun, “Fundamentals and applications of polymers designed for laser ablation,” *Appl. Phys. A* **77**, 259 (2003)
40. R. Fardel, L. Urech, T. Lippert, C. R. Phipps, J. M. Fitz-Gerald, A. Wokaun, “Laser ablation of energetic polymer solutions: effect of viscosity and fluence on the splashing behavior*,” Appl. Phys. A*, **94**, 667 (2009)
41. C. Phipps and J. Luke, “Feasibility of a 5-millinewton laser minithruster,” Final report Contract NNC07QA25P (2007) available from NASA Glenn Research Center, 21000 Brookpark Road, Cleveland OH 44135
42. J. E. Sinko, Nilesh B. Dhote, and A. V. Pakhomov, “Laser Propulsion with Liquid Propellants Part I: An Overview”, *Fifth International Symposium on Beamed Energy Propulsion, 12-15 November 2007, Kailua-Kona, HI, USA, AIP Proceedings* **997**, 195-208 (2008).
43. C. Phipps, “Conceptual Design of a 170-MJ Hydrogen Fluoride Laser for Fusion,” *Laser and Particle Beams,* **7**, 835 (1989)