Laser propulsion: a review

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We survey early proposals for laser propulsion. Propulsion theory and laboratory momentum coupling experiments demonstrate how it is possible to choose the target material so as to optimize payload efficiency, with a possible order-of-magnitude reduction in launch costs. American, German and Japanese experimental 'lightcraft' are described as well as the Orion programme to de-orbit space debris. We also discuss Marx's seminal paper on laser-driven, relativistic space propulsion and the ensuing controversy.

Introduction

A small but growing number of scientists and engineers believe that laser propulsion (LP) offers an order-of-magnitude reduction in the cost of launching spacecraft and also provides the best method of solving the space debris problem. The United States, Germany and Japan are conducting LP proof-of-principle experiments. Myrabo's well-publicized 'lightcraft' programme has extended laser propulsion to the world outside the laboratory[1] as have recently developed laser micro-thrusters.[2] Phipps *et al.*[3] have proposed the Orion project to 'de-orbit' space junk, while Japanese laboratories have initiated an ambitious LP programme based on their diode pumped solid-state lasers, to be flown on Antonov aircraft.[4]

In this first section, we review the somewhat utopian early proposals of Saenger,[5] Marx[6] and Forward.[7] This is followed by the more down-to-earth work of Moeckel[8,9] and Kantrowitz.[10] In the second section, we briefly survey the basics of laser propulsion theory[11,12] and describe some early laboratory experiments.[13–15] We then review more recent experimental work conducted in Germany[16] and Japan.[17] Myrabo's 'lightcraft' work occupies the fourth section as well as his plans and those of others to reach the primary objective: low Earth orbit (LEO). The potential to de-orbit the most dangerous space debris by LP as well as the new micro-thrusters for spacecraft attitude control are also covered here.

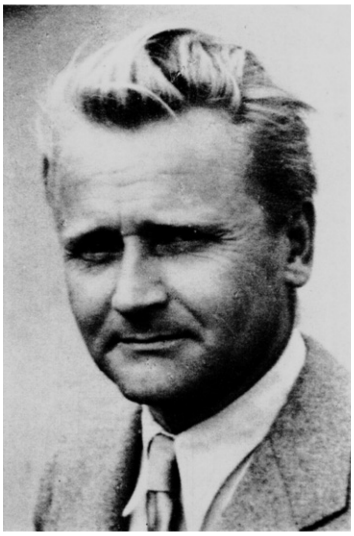

Fig. 1. Eugen Saenger, 1905–1964 (from ref. 35).

In the final section we return to the controversial question raised by the LP work of the late Professor Marx: is laser-propelled, interstellar travel (human or robotic) feasible even in the very long term?

Pioneers of laser propulsion

The very first proponent of photonic propulsion seems to have been Eugen Saenger (Fig. 1), the great German rocket scientist, whose early designs were scaled up by several orders of magnitude (Fig. 2). Saenger proposed photonic propulsion even before the invention of the laser. But his most famous scheme was an antimatter pumped laser designed to propel a spacecraft up to relativistic velocities. Recent German work on laser propulsion continues at Deutsche Luft und Raumfahrt Labor (DLR) in Stuttgart, the laboratory founded by Saenger.

A few years later, Georgii Marx (Fig. 3), the head of physics at Roland Eotvos University in Budapest, wrote a short but seminal paper in *Nature*[6] in which he derived the surprising conclusion (to which we return later) that, though the instantaneous and total efficiencies (Fig. 4) of laser energy transfer start at zero, they reach around 50% (67% and 42%, respectively) at half the speed of light and 100% at the speed of light itself.

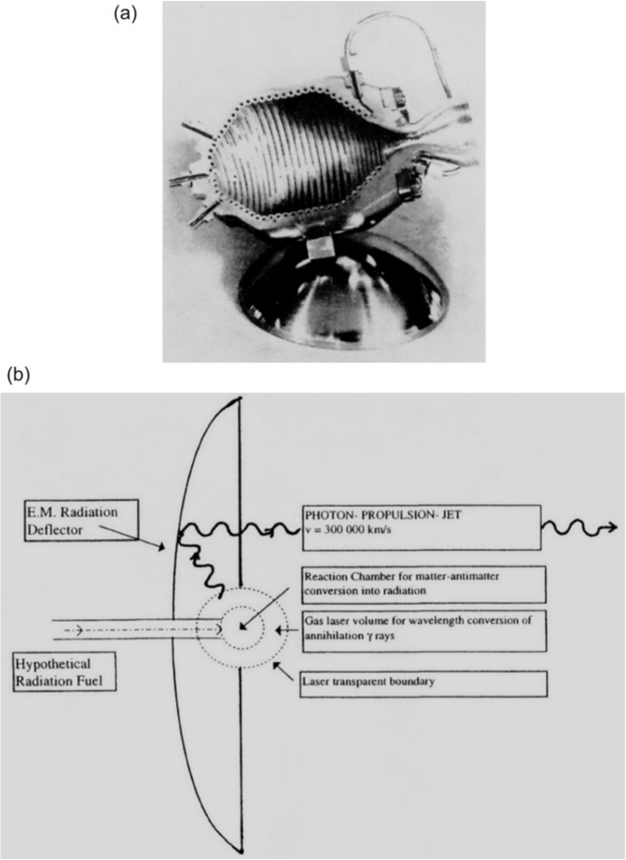

Fig. 2. (**a**) Hand-size liquid oxygen rocket (1933). (**b**) Laser propulsion scheme (1963): an antimatter pumped laser propels the spacecraft to relativistic velocities (from ref. 5).

In the early days of the laser, when energy and intensities were

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Fig. 3. Georgii Marx, 1927–2002.

Fig. 5. Arthur Kantrowitz, founder of the AVCO Everett laboratory (from ref. 3).

growing at a speed not very different from that of computer processing today, it was natural to assume that by the start of the third millennium, megajoule (MJ) lasers would be available for a multitude of nuclear (laser fusion), general industrial (material processing) and space uses. This gave Saenger and Marx's work a slightly utopian flavour. In a similar vein, the late Robert Forward proposed[18,19] creating solid antimatter (dubbed SANTIM) by decelerating antiproton and positron beams to generate anti-hydrogen atoms. A variety of lasers and particle traps would convert the anti-hydrogen atoms into solid anti-hydrogen molecules, which could then be used both for interstellar propulsion and for high-intensity information transmission from deep space.

Unlike Forward, Marx and Saenger, two other pioneers of laser propulsion were intimately concerned with the everyday applications of lasers and spacecraft. The first of these was Arthur Kantrowitz[10] (Fig. 5), who founded the AVCO Everett Research Laboratory in Boston, Massachusetts, where some of the leading technologies for high power/energy lasers were developed: gas dynamic, electrical discharge and chemical lasers were all taken from the laboratory to an industrial or military scale. One example, that of a 131-kW average power gas dynamic laser, is shown in Fig. 6. It seems appropriate in this context to quote Kantrowitz: 'wild ideas there are aplenty, some of which do not violate known physics. If we overcome the epidemic of fears so prominent today, there is much to look forward to … New technology for projecting energy to vehicles ascending to earth orbit would enable the large-scale expansion of mankind into space.' Kantrowitz did much to popularize laser propulsion by training laser technologists at AVCO and demonstrating the existence of suitable lasers.

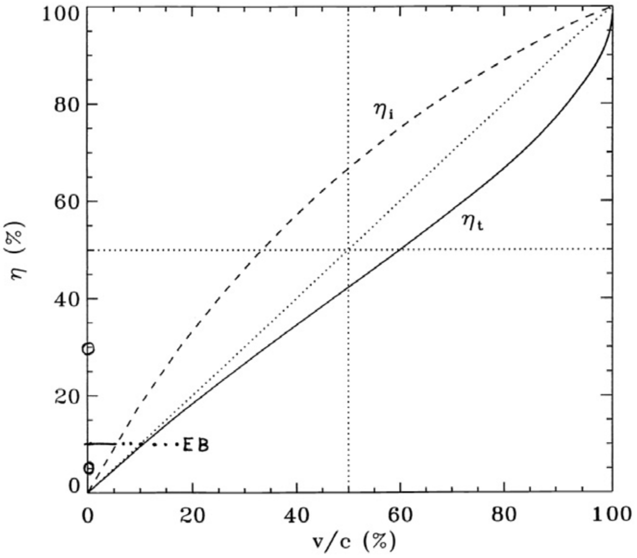

Fig. 4. Efficiency for pure photon propulsion versus velocity, where η_i and η_t are the instantaneous and total efficiencies, respectively. Typical propulsion efficiencies for laser ablation are marked on the vertical axis together with the Energy Bridge (EB) necessary to enter the photon propulsion regime (from ref. 6).

Wolfgang Moeckel (Fig. 7) was chief of the Advanced Propulsion Division at NASA, the U.S. space agency, where he initiated research into electric, ion and plasma propulsion. In two seminal papers,[8,9] Moeckel laid down the basic equations for non-chemical propulsion. He was the first scientist to propagate the idea that, whereas almost unlimited exhaust velocities are possible for laser propulsion, the highest exhaust velocity is not necessarily the best. Most of the energy might go into the plume rather than the spacecraft. We return to this topic in the next section. Many of Moeckel's ideas have been vindicated by recent space missions: the Deep Space I comet rendezvous mission (1998–2001) and, most recently, the ion-driven SMART-1 mission to the Moon.

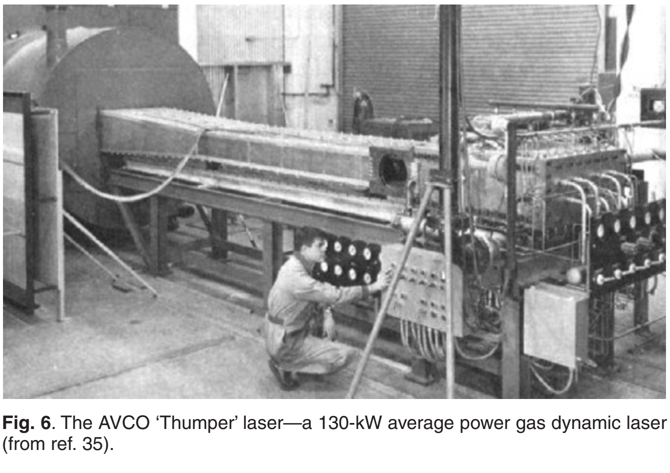

Fig. 6. The AVCO 'Thumper' laser—a 130-kW average power gas dynamic laser (from ref. 35).

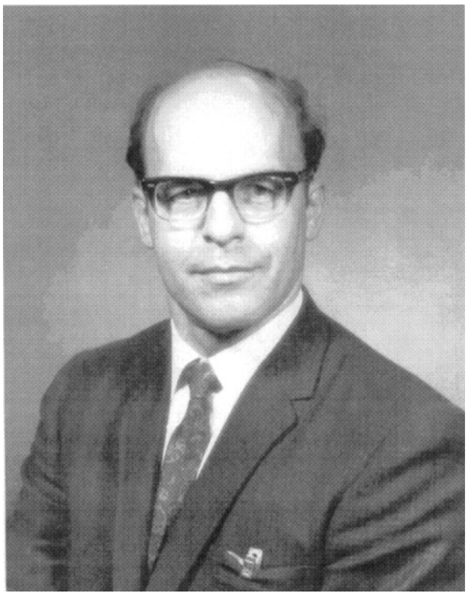

Fig. 7. Wolfgang Moeckel (from ref. 36).

Laser propulsion theory

The concept of laser propulsion rests on some elementary theory as well as on some basic and early experimental results. Our treatment of the theory follows that of C.R. Phipps and one of us.[11]

The cost in joules of laser light for launching a kilogram of material into low Earth orbit, is derived from the well-known 'Rocket Equation' for payload ratio:

$$\zeta = \frac{M}{m} = \exp\left[(\upsilon_F + gt_F)/\upsilon_E\right], \tag{1}$$

where M is the initial mass (launch pad mass) and m is that which reaches LEO, υ_E and υ_F are the exhaust and final velocities, respectively, g is the gravitational acceleration and t_F is the time to orbit in seconds. Since $\upsilon_F \approx 8$ km/s near LEO, and υ_E for various chemical fuels lies between 2 and 4 km/s this becomes quite prohibitive for chemical propulsion: for the NASA space shuttle we have $\zeta = 30$, which is why for a combined shuttle and payload mass of 27 tons, lift-off mass is 850 tons for the shuttle and fuel tank alone, not including the 600-ton solid booster rockets.

Parameters found in many LP papers are the specific impulse, defined as $I_{sp} = \upsilon_E/g$ in seconds; the momentum coupling constant C_m expressed either in dynes-seconds/joule or sometimes in μN/W; the specific ablation energy Q^* in joules per gram: $Q^* = \Phi/\dot{m}$ where Φ is the laser power in watts.

One writes:

$$C_m Q^* = \upsilon_E\,. \tag{2}$$

Another essential parameter is the ablation efficiency:

$$\eta = \frac{1}{2}\dot{m}\upsilon_E^{\,2}/\Phi\,. \tag{3}$$

The ratio of exhaust kinetic power and laser power, η, can be close to unity, in which case one sees that, since

$$C_m = \dot{m}\upsilon_E/\Phi = \dot{m}\upsilon_E \Big/ \frac{1}{2}\dot{m}\upsilon_E^{\,2} = 2/\upsilon_E\,, \tag{4}$$

C_m varies inversely with exhaust velocity υ_E. This is approximately true even when $\eta \neq 1$ and gives one a rough estimate for typical C_m values. For example, if as in many space applications υ_E = 10 km/s, then C_m is around 200 μN/W. Most important, though, is the statement: 'High C_m corresponds to low υ_E and vice versa'. One writes for constant υ_E: $C_m Q^* = \upsilon_E$, and therefore

$$\eta = \frac{1}{2}\dot{m}\upsilon_E^{\,2}/\left(\dot{m}Q^*\right) = \frac{1}{2}C_m^{\,2}Q^*,$$

giving

$$\zeta = \exp\left[\frac{\upsilon_F}{C_m Q^*}\left(1+\frac{gt_F}{\upsilon_F}\right)\right] = \exp\left[\frac{C_m\upsilon_F}{2\eta}\left(1+\frac{gt_F}{\upsilon_F}\right)\right]. \tag{5}$$

To solve for t_F, one first rewrites $Q^* = \Phi/\dot{m}$ in integral form and finds the transcendental equation representing the solution space:

$$\int_M^m dm = -\int_0^{t_F}\frac{\Phi(t)}{Q^*}dt\,. \tag{6}$$

In the case of a pulsed laser, the laser power integrated over a time t_F simply returns the total delivered energy over that time period, or $E_T = Eft_F$, where E is the energy per laser pulse, f is the laser repetition rate and ft_F is the total number of pulses delivered to the target over the time t_F.

Solving Equation (6) leads to:

$$M - m = \frac{Eft_F}{Q^*}$$

$$\Rightarrow 1 - \frac{m}{M} = \frac{Eft_F}{MQ^*}\,.$$

And so

$$t_F = \frac{MQ^*}{Ef}\left(1-\frac{1}{\zeta}\right). \tag{7}$$

This also implies that for large values of ζ, $t_F \approx MQ^*/Ef$. The cost C in laser joules/gram of payload into orbit can be calculated from Equation (6), giving:

$$C = \frac{E_T}{m} = Q^*(\zeta - 1)\,. \tag{8}$$

From years of experience designing and building large lasers, Phipps transforms the expressions for C as a function of m into one for the cost of launching a mass of about a pound (equivalent to roughly half a kilogram) of spacecraft in 1994 U.S. dollars, which is plotted in Figs 8a and 8b:

$$C = Q^*\left(F + \frac{B}{f}\right)(\zeta - 1), \tag{9}$$

where F is a financial term that depends on laser type, size, facility amortization and costs, f is the launch frequency, and B depends on laser consumables, materials and so on. This graph predicts well over an order of magnitude reduction in costs for LP over conventional launch methods. At optimum C_m we were able to predict launch costs as low as \$200/kg. Note how sensitive the cost is to the optimum momentum coupling being achieved. If the momentum coupling is too high (low υ_E), most of the energy goes into heating too large a mass of fuel: region D. For the reverse case (region A), too much of the laser energy ends up as fuel kinetic energy (high υ_E). Below a C_m threshold, the spacecraft no longer rises. At threshold C_m (when the upward acceleration matches g), it hovers and just above it takes an eternity to reach LEO.

If one prefers to think in terms of the exhaust velocity and final velocity, one writes as did Moeckel:

$$\begin{aligned} C &= Q^*\left(\exp\left[(\upsilon_F + gt_F)/\upsilon_E\right] - 1\right) \\ &= \frac{\upsilon_E^2}{2}\left(\exp\left[(\upsilon_F + gt_F)/\upsilon_E\right] - 1\right), \end{aligned} \tag{10}$$

for which the optimized solution is

$$\upsilon_E = 0.63(\upsilon_F + gt_F)\,. \tag{11}$$

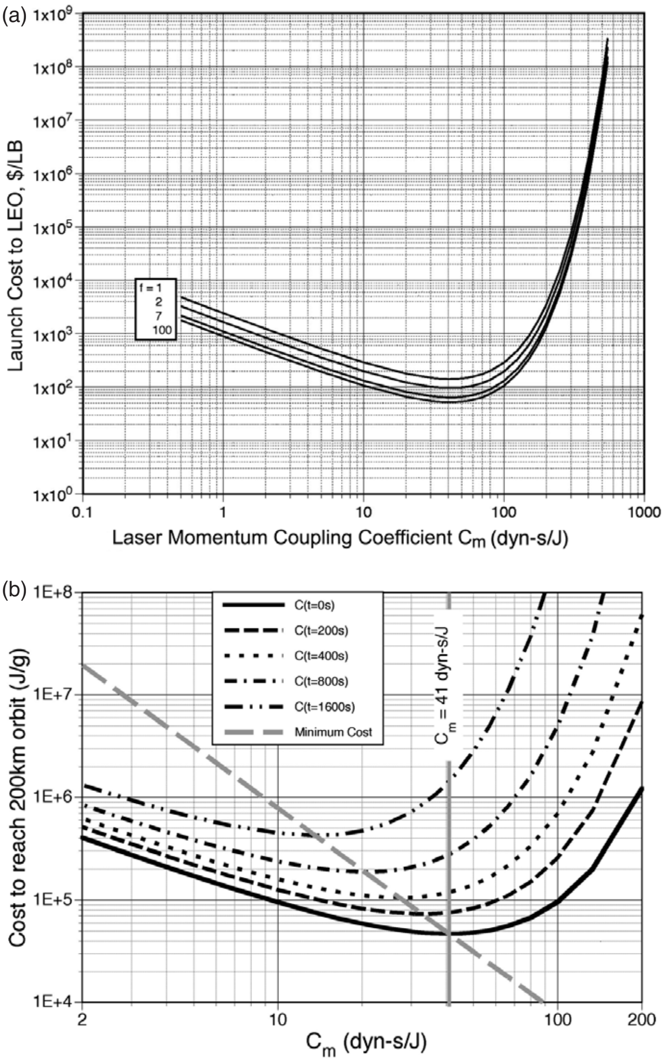

Fig. 8. The Phipps equations (from ref. 11): (**a**) Cost of launching one pound of mass in terms of 1994 U.S.$. (**b**) Energy cost in joules per gram delivered to a 200-km altitude orbit, for various flight times.

Likewise one finds that

$$C_m = 4.44\eta / (\upsilon_F + gt_F)\,. \qquad (12)$$

More recent work[12] includes more sophisticated computations, incorporating aerodynamic drag on a test 'flyer' and the option of programming the laser power: 'The cost can be as little as \$100/kg … even if η is as small as 3%'. They also consider the realities of adaptive optics and conclude that, starting from a 30-km-high balloon platform launch, a satellite of mass 3–6 kg could be launched with a 1-MW laser. The 6-kg spacecraft would take time t_F ~700 s versus 270 s for the 3-kg spacecraft and needs to be laser-tracked for 1300 km rather than 470 km. One of the authors of this study (J.W. Campbell) is at NASA's Marshall Space-flight Center, which gives this work the benefit of experience with practical space-laser systems.

Experimental programmes

Early days

Early experiments (some of which were classified at the time) confirmed the feasibility of laser propulsion. In 1972 at the UK Atomic Energy Authority (UKAEA), Rumsby, Burgess and one of us[13] were among the first to propel small targets in a vacuum to high velocities and to measure the coupling as a function of laser wavelength and target material. To give the reader a flavour of this type of early experiment, we indicate its broad outlines. One target was a 25-μm-thick molybdenum foil, not an easy thing to manufacture and to suspend on two silica fibres inside a vacuum chamber. These 1970s experiments gave birth to a complex range of 'target fabrication laboratories' for laser fusion and target irradiation experiments. The propulsion beams, from either a 25-MW, 45-ns, pulsed TEA CO_2 laser (made in our laboratory) or from a commercial 500-MW, 18-ns ruby, were focused onto the foil so as to illuminate it uniformly. Momentum coupling was measured by taking shadowgrams of the moving foil with a third laser: a 40-MW, 20-ns ruby. Figure 9a illustrates the complex set of lasers as well as the vacuum chamber and the target holder. Figure 9b shows the shadowgrams of the flying foil 24 μs after irradiation and in its initial stationary position for reference. Some of the foils were laser propelled close to one-tenth the lunar escape velocity in a single laser shot and adhered strongly on impact to the metal of the vacuum chamber. Others were spun up to 5 million revolutions per minute by deliberately illuminating only one side of the foil. More recent experiments at the U.S. Naval Research Laboratory and other military and civilian laboratories have propelled targets up to small fractions of the speed of light (*c*/1000): an important feature of these experiments is that the foils do not disintegrate.

Probably even more important from a practical LP point of view was the other type of experiments demonstrating enhanced momentum coupling either through the double pulse scheme or by 'volume ignition' of the fuel. The early micro-foil experiments were characterized by poor coupling. This was due to high target reflectivity. By illuminating the target with an intense 'pre-pulse', a 'sheath plasma' forms that protects the target from direct illumination by the main pulse. The sheath plasma absorbs most of the laser light, thus enhancing the coupling. (This technique has recently been used by Willi *et al.*[20] to improve laser fusion implosions.) A far simpler 'volume absorption' scheme is to manufacture the 'fuel' out of material that allows the laser to penetrate a medium skin depth. Phipps has demonstrated that by carefully choosing laser wavelength and intensity on target, C_m can then be tailored to correspond to optimum ratio of orbital to launch mass ζ with efficiency η values close to unity.[11,15]

The Strategic Defence Inititative Organization workshops on laser propulsion of the late 1980s were followed more recently by a series of biennial High Power Laser Ablation (HPLA) conferences, numbered I to VI, held in New Mexico, where laser propulsion is but one topic, under the auspices of the Society for Photographic Instrumentation Engineers (SPIE). There is also a specialist conference on beamed energy propulsion organized by A. Pakhomov and L. Myrabo. Regular contributions to both meetings come from W. Bohn and W. Schall of the DLR laboratory[16] and from Japanese laboratories.[17] In the German work (which lags the American only by a little), an energetic pulsed CO_2 laser (10 kW) has been used either to accelerate a bell-shaped target on a vertical trajectory or to measure coupling parameters for a single, 400-J pulse. These single-pulse experiments were the first to quantify an important feature of future laser-propelled missions: target deformation. Laser propulsion, as well as being exceedingly noisy, will require careful design to mitigate shock waves propagating in the spacecraft.

At HPLA IV (held in 2002), two Japanese demonstrations struck a novel note. In the first,[21] a water target demonstrated extremely high values of C_m and was used to propel a model aircraft. In the second, an optical system was used to reverse illuminate the target: the target moved towards the laser.[22] The latter has the great advantage that the fuel exhaust does not refract or absorb the laser beam and illustrates the obvious fact that the

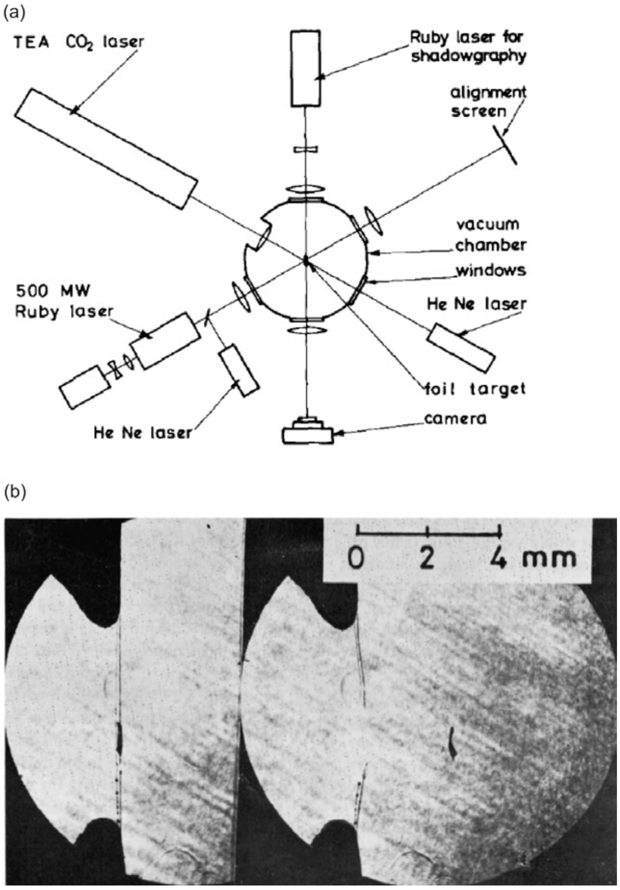

Fig. 9. A mid-1970s foil acceleration experiment at UKAEA, Culham Laboratory, Oxfordshire, England (from ref. 13): (**a**) Schematic illustration of target chamber, showing the delivery of the two laser propulsion beams (ruby and CO_2) together with a third (ruby) laser to generate the shadowgrams. The target was propelled by either laser so as to measure the momentum coupling dependence on wavelength. (**b**) Shadowgrams of 1-mm foil shown stationary and attached to the fibres (left) prior to laser propulsion, and 24 μs after laser propulsion (right). The distance covered in the elapsed time enables one to determine the velocity.

satellite does not have to espouse a fixed laser line: a downwind laser station could take over from another. A chain of LP stations could be situated on top of a series of high mountains either on one continent or on several.[23] This point is elaborated on in an accompanying article on LP work in South Africa.[24]

A review of laser propulsion would be incomplete without consideration of the first LP variety to be proposed by Saenger, but which has since disappeared from general view: nuclear pumped laser propulsion (NPL–LP). There are three main reasons for this disappearance: Saenger's early demise and that of the Soviet Union, where NPLs were strongly researched, and recently the anxiety with which nuclear applications are perceived throughout the world. Suffice to say that NPLs have demonstrated moderate conversion of nuclear into laser power energy. Once laser propulsion has been demonstrated with conventional lasers, NPL–LP may well be reconsidered as the most effective means of laser-launching massive payloads.

A powerful NPL at the Institute for Physics and Power Engineering (IPPE) at Obninsk near Moscow has demonstrated[25] 3% conversion of nuclear into laser energy at infrared wavelengths ($1.7\,\mu$m and $2\,\mu$m). This was by nuclear pumping gaseous media, such as He–Ar–Xe. G.H. Miley and co-workers[26] have studied many aspects of NPL technology; for instance, thermal lensing in laser gases heated by nuclear power. Whether the immense power of nuclear reactions will be permitted for this application is an open question: possibly it is already a military research activity.

At first glance, NPLs look far too massive for LP applications other than those where the laser is situated on the ground as envisaged by Miley.[26] Most of this terrestrial mass can, however, be attributed to shielding. Gulevich and colleagues at IPPE have recently developed[25] a concept for a 20-ton spacecraft in which the NPL is distance shielded from the freight by a long tether. Their calculations, backed by unique NPL practical experience, indicate that such a system could be used to propel tons of equipment from low Earth orbit to geostationary orbit (GEO) over a few months. (This slow mode of propulsion was successfully demonstrated in 2005 with the ion-engine-driven SMART-1 mission to the Moon.) Typical figures are as follows: reactor uranium mass, pulse energy and repetition frequency of 50 kg, 5 MJ, 1 Hz, respectively; laser power, duration and energy: 180 MW, ½ ms and 90 kJ, respectively; specific impulse and tether tension: 2000 s and 100 N; initial and ablated masses: 20 t and 4.3 t, respectively. Similar designs will obviously apply to inter-planetary goods transportation, equivalent to that of terrestrial canal barges.

Myrabo's 'lightcraft' and other programmes

The only 'lightcraft' to have demonstrated 'outdoor' capability and to have flown 'as high as Goddard's first rocket' or 'as far as the Wright brothers' (30 m) is Myrabo's, shown in Fig. 10. Light from a military (20 kJ × 10 Hz) laser is ring-focused by the craft into a region where new air is continuously channelled in a manner somewhat similar to a ram jet engine. The lightcraft is stabilized by pre-spinning it and also by the geometry of the laser focus.

The DLR flier differs from the Myrabo device in that a parabolic mirror serves to point focus the laser: presumably this requires less energy, but could be less stable. The Phipps *et al.* reference flyer envisages a system of 'Venetian blinds' as well as computer-controlled fuel orientation. One thing is certain: lightcraft stability is becoming a crucial subject.

A relatively new form of pollution is 'space junk' or 'space debris'. There are now around half a million pieces of such debris in Earth orbit with cross sections greater that 5 mm. Such a piece of debris travelling at average orbital velocity (8 km/s) packs kilojoules of destructive kinetic energy — several hundred times that of a high-speed rifle bullet. This can destroy the electronics of a communications satellite (it is blamed for the de-masting of the French Cerise satellite), perforate fuel tanks and cryogenic vessels and damage solar panels. But most serious of all, the International Space Station has a 10% chance of a serious 'hit' every five years. And of course astronauts on EVAs (activities outside their spacecraft) are always at risk. Even more worrying is the 'debris chain reaction' studied by Flury[27]: near-Earth orbit (NEO) would become a 'no go' volume. Phipps and colleagues, including one of us (M.M.), suggested[3] nearly a decade ago a relatively inexpensive method for 'clearing near-Earth debris' with a 20-kW, 530-nm, Earth-based, repetitively pulsed laser — this has become known as the Orion Project. This work addressed the following topics: debris density and risk to space assets; target acquisition; appropriate laser wavelength; effect of target spinning and motion; laser spot size and range; debris orbital mechanics; acquisition with sunlight or laser and subsequent tracking; laser system concept; atmospheric turbulence and Raman beam degradation; adaptive optics, and finally, potential high mountain sites such as Kilimanjaro or Mauna Kea.

Recently, STARSAT, a joint NASA/U.S. air force project for laser calibration of small objects in space, was initiated by Campbell.[28] This would involve deploying a micro-satellite equipped with GPS from a space shuttle. A high power laser system (HI-

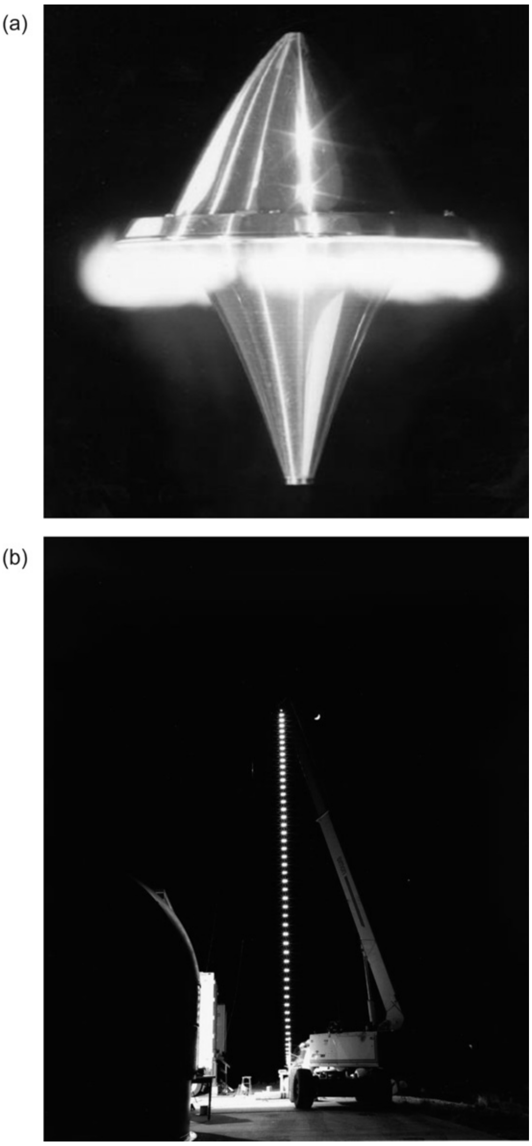

Fig. 10. The Myrabo lightcraft: The only lightcraft to have demonstrated 'outdoor capability'. (**a**) Close-up of the aerodynamic lightcraft and the resulting plasma formation after illumination from a single high-energy laser pulse. (**b**) Vertical acceleration of the lightcraft. The plasma created after each pulse can be used to track the trajectory of the lightcraft. Figures courtesy of NASA.

CLASS/AEOS), together with a 3.67-m-diameter telescope fitted with an optical tracking system would locate and then illuminate the satellite. The complete system is located on the summit of Haleakala, Mauni, in Hawaii. Together with some obvious military applications, STARSAT would give America the potential to implement space debris removal, and is a demonstration of the first stage of the Orion concept discussed earlier. Slightly longer term, the U.S. air force-sponsored 'laser ramjet' research was described at HPLA V by Hasson.[29] Apart from the lightcraft programme, there is now a new line of 'real world' research, into laser stabilization of satellites with laser-driven micro-thrusters. Most satellites make use of gas jet systems to stabilize or change their orientation. Gas jets operate with low exhaust velocities, typical for chemical combustion and consume appreciable amounts of fuel, limiting the life-time of the satellite. New international agreements also require satellites to move away from their operational LEO or GEO orbits at the end of their mission to reduce the debris problem. This makes it important to develop high exhaust velocity propellants, which require an order of magnitude less fuel. One such is the colloid thruster with microfabricated liquid emitters. Another is that developed by Phipps and Luke.[2] In this laser micro-thruster, a reel of thin film runs past the focus of the on-board laser. The film is transparent on the laser side so that the material ablates away from the laser.

We end this section by mentioning near-term and long-term American and Japanese plans. In the near term, Myrabo is aiming to couple a large laser with an adaptive-optics telescope with the aim of reaching kilometre altitudes. Campbell *et al.* will launch a debris simulator from a space shuttle to test the Orion concept. The Japanese are planning one of the most ambitious programmes of all: a diode pumped airborne laser project. Megawatt lasers on Antonov aircraft would be used to propel spacecraft from LEO to GEO. The Japanese civilian programme mirrors the U.S.A.F Boeing 747 airborne laser (ABL) project. The ABL uses three different types of laser for target acquisition and a powerful multi-channel chemical oxygen iodine laser (COIL) laser for remote demolition.[30]

Laser propulsion in the far future

Pure photon propulsion

A common misconception is that the Crookes radiometer rotates due to photon rather than gas pressure. In fact, the very first pure photon pendulum experiment was carried out by American laser propulsion enthusiasts Myrabo, Knowles, Bagford, Siebert and Harris.[31] The photon pressure is minute: the photon force on a 10-cm^2 target illuminated by a 9-kW CO$_2$ laser is found from:

$$F = pA = \frac{AI}{c} \cong 0.03\mu\text{N},$$

hence the need for an ultra-delicate pendulum equipment, as well as for a high-power laser source!

In marked contrast to the Myrabo experiment is the prediction made nearly 40 years ago by Marx that pure photon propulsion (PPP) couples 100% of laser energy into a target moving at the speed of light and over 60% to a target moving at half this speed. Marx arrived at this surprising conclusion after a brilliantly simple argument reminiscent of Hugoniot's derivation of the shock wave equation that bears his name. Marx's argument parallels Hugoniot's in that the actual physical interactions are ignored. Conservation of momentum and energy are all that are needed to show that the efficiency of instantaneous energy transfer and total energy transfer are respectively ($\beta = v/c$):

$$\eta_i = 2\beta/(1+\beta) \text{ and } \eta_t = 1-\sqrt{(1-\beta)/(1+\beta)}.$$

Unfortunately, brilliant as it was, Marx's derivation contained an error: it neglected to take into account that while the PPP spacecraft travels, the volume of beam space separating it from the laser source is being filled with energy. J.P. Redding (somewhat mercilessly) stated that 'these equations are constructed with reference to a terrestrial frame and are incorrect'.[32] Redding showed that taking the spatial energy into account, the maximum efficiency becomes $\eta_i = 0.34$ with $\beta = 0.414$. It took a quarter of a century for 'Marx's mistake' to be put into context, by an article in the *American Journal of Physics*, which showed that Redding's argument was 'wrong or at the very least misleading.' Simmons and McInnes (SMI) showed via some special relativity calculations that Marx's main mistake was to have considered laser time rather than the 'retarded time':[33]

$$dw = (1-\beta)\,dt.$$

Causality arguments (the fact that the target only 'feels' the laser at the retarded time w) show that Redding's correction factor $(1-\beta)$ drops away if one considers the energy that eventually reaches the target, rather than that beamed out by the laser. SMI derive a similar equation to Marx's for β attained as a function of e, the total energy put out, in units of $mc^2/2$:

$$\beta = \left[(1+e)^2 - 1\right] / \left[(1+e)^2 + 1\right].$$

Interstellar propulsion

Two recent events make it appropriate to revisit briefly the question of whether interstellar propulsion (ISP) is possible. The first is the fact that it is already happening: the Pioneer 10 and 11 spacecraft are already leaving the inner Solar System. Pioneer 10 is on its way through the Kuiper belt and will arrive in the region of Aldebaran in about two million years. Unfortunately, the on-board nuclear power supplies are already failing. And the cosmologically exciting question of what caused the unexpected Doppler shift in the transmission signal may never be answered by the Pioneer spacecraft. This aptly illustrates two needs: that for non-chemical propulsion and acceleration to a fraction of the speed of light within the Solar System; and the need for a different means of transmitting signals from interstellar or near-interstellar space.

More importantly, a long-awaited method of concentrating energy for various applications, especially ISP, is on the horizon. Two teams at CERN, the ATRAP team led by Amoretti[34] and the Athena group of Gabrielse,[35] are on the verge of trapping antihydrogen. ATRAP already claim to have measured 10^5 antihydrogen annihilations.

These recent experiments give credence to a scheme for generating solid antimatter (SANTIM) first proposed by Robert Forward in 1980 and examined in greater detail by one of us and R. Bingham. For a detailed list of procedures and problems and ways of addressing them, we refer the reader to ref. 19.

The reason we find these developments exciting in the context of interstellar propulsion and communication as well as for more rapid travel to the outer regions of our Solar System is as follows: for PPP to fulfil its promise, one needs to give the spacecraft an initial boost to, say, 5% of the speed of light. And this boost has to be carried out swiftly before laser divergence renders PPP ineffective. An 'Energy Bridge' (Fig. 4b) is needed to take the craft to the right portion of the Marxian efficiency curve.[36] Could a 'fuel' 1800 times more energetic than plutonium help solve this problem? Forward and Saenger thought so.

Conclusion

Recent space tragedies as well as the continuous threat posed by space debris demonstrate that conventional launch methods are risky as well as uneconomic. Laser propulsion promises an order of magnitude reduction in launch costs, an improvement in the quality of combustion material ejected into our overloaded atmosphere as well as a means of de-orbiting some half million pieces of space junk. It should also be considered by smaller nations looking for an independent route to space.

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