Space Polypropulsion

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ABSTRACT

Hybrid space propulsion has been a feature of most space missions. Only the very early rocket propulsion experiments like the V2, employed a single form of propulsion. By the late fifties multi-staging was routine and the Space Shuttle employs three different kinds of fuel and rocket engines. During the development of chemical rockets, other forms of propulsion were being slowly tested, both theoretically and, relatively slowly, in practice. Rail and gas guns, ion engines, "slingshot" gravity assist, nuclear and solar power, tethers, solar sails have all seen some real applications. Yet the earliest type of non-chemical space propulsion to be thought of has never been attempted in space: laser and photon propulsion. The ideas of Eugen Saenger, Georgii Marx, Arthur Kantrowitz, Leik Myrabo, Claude Phipps and Robert Forward remain Earth-bound. In this paper we summarize the various forms of non-chemical propulsion and their results. We point out that missions beyond Saturn would benefit from a change of attitude to laser-propulsion as well as consideration of hybrid "polypropulsion" – which is to say using all the rocket "tools" available rather than possibly not the most appropriate. We conclude with three practical examples, two for the next decades and one for the next century; disposal of nuclear waste in space; a grand tour of the Jovian and Saturnian moons – with Huygens or Lunoxod type, landers; and eventually mankind's greatest space dream: robotic exploration of neighbouring planetary systems.

Keywords: POLYPROPULSION, PURE PHOTON PROPULSION, ENERGY BRIDGE, SANTIM

1. INTRODUCTION AND HISTORICAL PERSPECTIVE

Just as today's cars and jet aircraft are adaptations of the 1907 motor car and the Wright brothers engine powered airplane, the spacecraft of the future are likely to be an almost unrecognizable adaptation of today's chemical rocket dominated designs. The World War II German V2 rocket surprised and embarrassed Churchill's Science Advisor, Lord Cherwell (alias Oxonian physicist Prof. Frederick Lindemann) with its extraordinary liquid propellant improvement on the Chinese gunpowder rockets from the first Emperor Quing in the 5th Century. The V2 was a single stage projectile, but none the less effective. The multitude of rockets developed after 1945 were almost all multi-stage, multi-fuel systems: the Saturn V rockets that sent Apollo craft and astronauts to the Moon, the European Ariane V heavy lift rocket and the Space Shuttle all use multiple kinds of fuel and rocket engines to achieve their various tasks. It is quite remarkable that NASAs new plans for manned missions to the Moon and beyond, the latest Orion and Ares rockets are in effect, modern upgraded Saturn V's from the 1960s.

The various space agencies around the world do occasionally employ non-rocket methods for powering spacecraft trajectories: without gravity assists ("slingshot") many of the missions to Mercury, Jupiter, Saturn, Uranus, Neptune and Pluto would not have been possible, nor would the two Voyagers and two Pioneers be heading out of the solar system at such great speed. Likewise, the mass penalty of a rocket-powered descent to the surface of Mars or Titan makes aero-braking and parachute descent such desirable alternatives (although, possibly, also much more risky?). The only adventurous "new technology" aspect of the Spirit and Opportunity Mars rover landings were the balloon air-bags.

But other really novel and promising activities – rail guns, gas guns, solar-powered ion engines and solar sails, not to mention tethers, have been so under-funded as to virtually guarantee their "failure". (How many failed rocket launches did our forefathers experience before the technology was perfected?)

However, there have been recent advances in spacecraft propulsion technology. ESA recently demonstrated solar powered ion engines on its successful SMART-1 lunar mission[1]. Around the same time, NASA used ion drive on its Deep Space 1 mission and JAXA, the Japanese space agency, used ion engines on its Hayabusa asteroid rendezvous and attempted sample return mission. More powerful ion engines are undergoing ground testing and must await their

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opportunities for space deployment. Nuclear propelled missions have, perhaps understandably, fallen by the wayside. NASAs putative atom bomb propelled mission, coincidently also baptized ORION, was also curtailed. And last of all, the use of lasers for propulsion remains firmly "stuck in the doldrums." This mode of access to space was once deemed most promising by such luminaries as Eugen Saenger, Georgii Marx, Robert Forward and Carl Sagan. However, it has been totally ignored as a front-line research area for many years.

We argue here that far from employing the few alternative propulsion technologies only when absolutely necessary, we should be undertaking vigorous research campaigns for each one of them. This could enable such innovative and flexible missions as the one demonstrated by Hayabusa. And then, when "real" rail and gas guns, real solar sails, real laser propulsion to LEO and perhaps even real nuclear explosion powered craft have been experimented with, they could be combined to give unprecedented economic and eco-friendly access to space and enable mission scenarios currently beyond the reach of conventional rocket-powered missions.

Most of the proponents of alternative propulsion forms agree: chemical rockets are unecological, inefficient and inordinately expensive. "Polypropulsion" – a combination of several alternative propulsion modes, in parallel or in series – may one day make chemical rockets as obsolete as the steam engine.

2. WHICH MISSIONS REQUIRE POLYPROPULSION?

Which missions become more economic or just simply viable when we consider alternative propulsion methods and techniques? Table I and II and the rocket equation (modified for laser propulsion) help us to address this question. Table I lists the various types of propulsion. Also typical values for the payload ratio $\xi = M/m$ (Mass at launch / mass in orbit), exhaust velocity, advantages and disadvantages.

Table I. Forms of Propulsion. Only chemical and ion propulsion and occasionally gravity assist are routinely employed. Payload Ratio = ζ is remarkably high for chemical rockets and exhaust velocity rather low. Major advantages, disadvantages and status are listed.

Propulsion Technology	**ζ = M /m**	**V_E Exhaust Vel.**	**Advantages.**	**Disadvantages.**
Chemical rockets.	30 – 100	3-5 km/s depending on fuel – LOX or solid fuel.	Very high thrust. Tens of tons to LEO. Millenium old technology. Choice of fuels: Liquid = versatile Solid = High thrust at low cost.	Low exhaust velocity Unsuitable for high V_{Final} missions. (V_E should be = V_{Final}) Except for LOX, very polluting. V. high ζ Launch costs: \$20,000/kg.
Gas guns.	1	1-4 km/s	Most of the system mass stays on the ground.	Recoil problems. Large NASA gas gun project abandoned. (too many "g's")
E-M guns: rail/coil.	1.5	1-10 km/s	No wall contact. Staged acceleration possible with compact rotating machines.	Main problem: plasma arcs and rail erosion. No demonstrations yet.
Laser and Micro-wave propulsion.	2 to 10	Adjustable	Power plant stays on the ground. Can be made non-polluting.	Requires "light-craft" to be tracked over long distances, e.g. 200 km for LEO injection.
Ion Propulsion.	1.1	30 km/s	Minute fuel consumption as demonstrated by Deep Space I and the SMART-1 lunar mission.	V. long missions, e.g. SMART-1 took fifteen months to reach the moon. Low thrust.

				Grid erosion problem. Uses noble gases.
Gravity assist or "slingshot" + aerobraking.	1 unless perigee or apogee rocket manoeuvre.	Max. velocity gain is twice velocity of planet	Indispensible for long dist. missions. Combined with aerobraking Very versatile. Allows departure from ecliptic; e.g. Ulysses.	Long time scales: Cassini 10 years. Unacceptable for humans (radiation dose at Jupiter). May require chance alignment, e.g. "Grand Tour".
Tethers.	1		Possibilities: momentum exchange systems; electrodynamics; Moon & Mars elevators.	Embryonic stage: most experiments only semi-successful. Susceptible to debris.
Nuclear. a. Nucl. powered ion engine.	1 once in LEO.		Works beyond Jupiter where solar energy is diminishing rapidly.	Slow.
b. Fission or fusion bomb driven.	1.2 once in LEO.	30,000 km/s	Very high thrust and exhaust velocity. Disc shaped bomb creates cigar shaped plasma: opt for propulsion to 0.1c.	"Orion" ship mass 300 tons. 500 bombs reqd. Very polluting.
Solar Sail.	1		No fuel to carry. Continuous propulsion.	Very light payloads.
Terella applics and magnetic drive. Planetary magn. fld.	1		Lab. expts. No "fuel".	Futuristic.
Plasma "sail". (Magn. field deflects solar wind = sail)			No fuel to carry. Plasma provides protection for occupants – essential for Mars manned mission.	Not tested in space on full scale. Requires large amounts of electrical energy.
Antimatter.			Could be used as a high power transmitter. Very efficient use of mass.	Solid anti matter (SANTIM) not yet produced. Low generation efficiency of anti-hydrogen per shot.

From Table II, we see that if the space agencies decide, as we think they surely will, to capitalize on the great success of this decade and of the last century's missions to Mercury (Mariner, Messenger), Venus (PVO, Venera, Mariner) Jupiter (Galileo, Pioneer, Voyager) and the recent Saturn success (Cassini and the Huygens landing on Titan), they could consolidate and extend the knowledge of our planetary system with possibly as little as two or three very large scale polypropulsion ventures. This would obviate having to choose one Jovian moon or one Saturnian, from a range of equally promising targets.

We suggest that the major single component of each venture could be a nuclear pebble bed reactor powered tug with auxiliary solar power. Propulsion would be provided as in NASAs Prometheus project by several ion engines. The tug is assembled in Earth orbit from components launched as economically as possible with hybrid propulsion systems, e.g. gas or rail gun followed by laser propulsion. The nuclear fuel pebbles would be launched in small numbers to minimize the risk. The pebbles and pebble carrier can be designed to survive accidental re-entry. Once completely powered up, the tug acquires a whole set of specialized packages for each target as recently demonstrated by the comprehensive sequence of Saturnian moons visited by Cassini. Each target requires an orbiting module and a couple of landers. The tug continues towards the next target having released the packages. An important detail is that the packages carry small retro-rockets, so that the tug doesn't have to lose momentum unnecessarily. In this manner, we could place landers on all the exciting bodies in the solar system: Europa, Ganymede, Titan, Enceladus and eventually one of the Plutinos (dwarf planets) – Pluto, Sedna, Quaor or one of the yet to be discovered or unnamed Kuiper belt bodies. The same technology could of course be employed to prepare a Mars base for an eventual Martian colony. Such a tug was envisaged by Soviet scientists half a decade ago at the Obninsk NPL laboratory, but with a nuclear pumped laser propulsion unit rather than nuclear driven ion engines[2]. The tug would travel to and from Mars carrying freight, exactly as river barges or ocean-going tankers do, slowly but surely, as first envisaged in Obninsk. This approach contrasted with the conventional laser propulsion approach, also discussed at Obninsk[3].

Table II. List of unaffordable or technically difficult missions in order of importance.
Possible polypropulsion solutions are given with very approximate costs (in US $ 2008).

Mission	Polypropulsion Method	Comments & costs (V. approx).
Tug (Nuclear Electric - NE) All proposed polypropulsion missions rely on the assembly of a nuclear-electric master tug in LEO.	Assembly of NE pebble bed reactor (PBR) unit in LEO and bank of ion engines. The fuel is propelled by rail or gas gun in special containers to rendezvous with the tug. The orbit can be circularized by laser propulsion adjustment.	The massive reactor vessel components need to be lifted to LEO with conventional rockets. Tests with PBR fuel have demonstrated that it can be made rugged enough to survive re-entry, even without the container. The mission packages would not survive a gun launch. The highest costs would be the PBR rocket launch at $20000/kg. If the vessel weighs 50 tonnes: $1 Bn. Considerable future savings from cheap propulsion for the rest of the mission.
Return to Jupiter/Saturn. Rovers on Europa, Ganymede, Callisto, Titan, Enceladus.	Nuclear electric ion drive or solar ion drive (possible for Jupiter only)	For a mission with landers to multiple moons, Tug fabrication would be a prerequisite. Cassini-Huygens was designed in the 80's at a cost of $ 3.3 Bn and with Sp. Shuttle age technology. With nano-sat technology and minimal launch cost, it should be possible to do an order of magnitude more.
Dumping nuclear waste into Sun. Similar NE tug assembly and propulsion technology.	Instead of specialized packages, the waste is laser propelled (at low cost) to the tug. The transporter, partly solar powered, slingshot techniques to reach Mercury.	At Mercurial orbit, the tug propels the waste pellets backwards to return to Mercury and slingshot back to Venus and Earth. The pellets burn and transmute in the Sun.
Lagrange 1 Solar Heat Deflector (to reduce global warming).	To deflect 0.1% of solar flux, ca. 5000 tons of shield material needs to be placed at L1.	At 50 tons/mission and 10 p.a. this is feasible in a decade or two with several tugs.
Nuclear explosion powered mission outside the solar system. (Old NASA "Orion" proj).	Alpha Cent or Lalande 21185 or ε Eridani. "Old Orion" could be assembled in lunar orbit to minimize risk of large amounts of nuclear material. (500 bombs).	Nuclear bomb tests actually serendipitously demonstrated steel plate "propulsion" in Nevada desert: Surprising fact that steel plates were undamaged.

On the basis of the rail-gun/gas-gun and laser propulsion studies, we assume conservatively that polypropulsion launch costs are as low as $500/kg. If the tug's mass is a hundred tons, we see that the propulsion cost ($50M) is trivial, compared to the cost of the equipment. Even if the reactor has to be launched conventionally, the cost of the mission would still be comparatively low.

Another important mission that has received media and blog coverage is the disposal of hundreds of tons of nuclear waste in space. For energetic reasons most proponents of this mode of disposal advocate a region between Mars and

Jupiter. Solar incineration is regarded as energetically impractical. We believe however that the public will prefer solar incineration, whatever the costs. With the world wide renewal of nuclear fission activities as a means of reducing CO_2 emissions, it seems certain that disposal will become one of mankind's major detritus problems. If the space agencies learn how to operate nuclear powered tugs, the same technology can be adapted to propel waste into the Sun economically. The tugs could gravity brake at Venus and Mercury before releasing their charge into the chromosphere where it will be gasified. The heavy nucleides will slowly sink into the radioactive layers of the Sun where neutron bombardment will transmute them. The tugs will be configured to eject the waste pebbles as solid rocket exhaust. This simultaneously decelerates the waste so it reaches the chromosphere and can then be used to accelerate the tug back towards Mercury, Venus and Earth.

Table III . Some objects in the outer solar system. Nearby stars or stars of major interest.

Dwarf Planet or Star.	**Distance in light years (l.y.) or AU**	**Spec. Type and Effect. Temp. of Star**	**Comment**
Pluto Orcus Ixion Caruna Quaor Chaos Sedna Eris	30-49 40 40 43 44 45 89 97	G2V 5770	The presence of all these other bodies in the 40-45 AU range is what finally condemned Pluto into the dwarf planet category.
Alpha Centauri: A, B, Proxima.	4.2 to 4.3 l.y.	A: G2 5790 B: K0 5260 Prox: M5 3120	Nearest stellar system. Could be reached in a human life-time at 0.1c.
Barnard's star	5.96 l.y.	M4 3230	Once thought to have planets.
Wolf 359 (Leonis)	7.78 l.y.	M6 2900	
Lalande 21185	8.29 l.y.	M2 3500	Planetary system? So far one Jovian planet detected, with possible second and thirds. Could be our first target accessible in one life-time.
Sirius (α Canis Maj) A and B	8.58 l.y.	A1 and DA 9940 and 25000	There is a legend that the dwarf B may have been a red giant in early Egyptian records.
Luyten 726 A & B	8.73 l.y.	M5 and M6 3200/3100	
Ross 154 (Sagittar.)	9.68 l.y.	M3 2700	
Ross 248 (Androm.)	10.32 l.y.	M5 3120	
Epsilon Eridani	10.52 l.y.	K2 5100	Dust disc still present: young star (800My). One 1.5 Jovian mass planet. Planetary system?
Lacaille 9352	10.74 l.y.	M0.5V 3850	
Gliese 581	20.44 l.y.	M3 3360	Likely 3 planet system – 1 Neptune mass, 1 eight Earth masses and a third 5 Earth masses (but only 1.5 Earth radii).
Vega	26.3 l.y.	A0V 10800	In 12 ky Vega will be our North star. It has a dust disc but so far no pl. spotted.

Comments section lists those nearby stars with detected planetary systems or those with dust discs that might harbour planets. For comparison, distances to some dwarf planets in light-minutes (l.m.) are:- 1 AU = 8.32 l.m., Quaor – 366 l.m., Eris – 807 l.m.

Finally we propose that the same "Obninsk" tug philosophy could be applied to the well known Lagrange 1 solar deflector solution to global warming proposed by Livermore scientist J. Early. To deflect 0.1% of solar energy arriving at Earth as envisaged, would require transferring some 5,000 tons of deflector foil material to the L1 point.

(Assuming the same figure of 0.1 g/m^2 as currently employed for solar sails). It would take about a decade to assemble enough material for the 100 km diameter deflector at L1. This is also then an application of the technology required to deploy solar sails for propulsion.

3. ROBOTIC EXPLORATION OF EXTRA-SOLAR PLANETARY SYSTEMS (ESPS)

Mankind's boldest space dream is the exploration of neighbouring planetary systems. We mentioned in the historical perspective, how unimaginably quickly new transportation systems developed. Who in 1907 could have foreseen that the Wright Brothers' daring first flight would lead a century later, to passenger aircraft with wings as long as the distance Orville flew? "Experts" and their public have been consistently wrong about their own scientific inventions. Newton, Rutherford, Einstein, Fleming, Lindemann, Hounsfield, Cormack, Heisenberg, Motz, great scientists as they were, failed utterly to estimate the development of satellites, nuclear power, lasers, antibiotics, rockets, CAT-scans, atom bombs, undulators and free electron lasers, respectively. Why should it be any different for photon propulsion and solid anti-matter (SANTIM)?

In Table III, we list the furthest currently known dwarf planets, the nearest ESPSs, together with some other nearby stars. We will now briefly survey recent progress with powerful lasers and beam transmission that makes photon propulsion as first envisaged by Eugen Saenger[4,5], Georgii Marx[6], and later by Robert Forward[7] and Carl Sagan[8], more plausible. We modify Marxian photon propulsion theory to take into account an "Energy Bridge". We end by briefly surveying the remarkable progress in the creation of anti-hydrogen and its manipulation.

Table III gives approximate distances to the furthest known dwarf planets/Plutinos and to the very nearest stars together with their effective surface temperature and spectral type. Table III should be viewed as extremely provisional, given the extremely rapid progress made in the last couple of years in searching for (and, indeed, identifying) new dwarf planets Similarly, despite rapid progress, we are as yet unable to detect Earth size extra-solar planets (although extra-solar planets of only a few Earth masses have now been detected). It is at least reasonable to assume that systems with Jovian size planets at reasonably large distances from their parent star would also actually harbour smaller brethren? In fact astronomers have already identified an Earth-like planet in a nearby star system – Gliese 581. This star is just 20 light years away. Obvious targets are already appearing: the α Centauri complex, Lalande 21185 and ε Eridani. The α Centauri complex would provide our first "close up" of three stars other than the Sun: A is similar to the Sun; B and C are very different and much colder and smaller. Both the Lalande 21185 and ε Eridani stars have planetary systems and are less than 11 light years away.

Since Marx's seminal paper in Nature[6], "Interstellar Vehicle propelled by Terrestrial Laser Beam" or what one might term "Robotic Interstellar Mission" (RIM), serious criticisms have been levelled at RIM by Redding (also in Nature)[9] and by Simmons and McInnes (SMI) writing in American Journal of Physics[10]. Although SMI refuted Redding's criticisms of Marx's work, they too stated that RIM was essentially impossible.
(SMI showed that "Marx's Mistake" was simply not to have taken the retarded time – i.e. satellite time – rather than Earth time. This correction essentially gives the laser light time to catch up). But all three authors, even Marx himself, agreed that RIM required such demanding parameters as to eliminate RIM from serious consideration. In our view, RIM has moved from the impossible (for engineering reasons) to the improbable (for economic reasons). That is to say that in a century or so RIM may be reconsidered for the three following reasons.

3.1 Laser systems

Though the average power of laser systems has changed very little over the last decade, pulsed power has escalated from terawatts to petawatts and there is even talk of exawatts and zettawatts. (10^{18} – 10^{21} W). Although the capital costs of the first of such systems rendered them quite unaffordable for industrial purposes and the number of "shots" was a few per day, pulse repetition frequencies are now moving from Hz to kHz. The ASTRA laser at the Rutherford Appleton Laboratory, for instance, can generate multi terawatt pulses at tens of Hz. Given "unlimited funding" it is probable that both the necessary average and pulsed powers will eventually be achieved simultaneously. Thus Marx's kilometre aperture X-ray laser may no longer be necessary. A vast nuclear pumped laser on the Moon, might well have the average power, the pulsed power and the beam quality necessary to reduce the irradiation distance to a fraction of Marx's 0.1 l.y.

3.2 Stepping stones to the stars

Marx, Redding and SMI all envisaged a single laser station, which was the main reason for Marx's choice of X-ray laser wavelength and kilometric aperture. Now that numerous bodies are being discovered beyond Pluto, is it not conceivable that advanced mankind will set up several "laser way-stations" in the Kuiper Belt and beyond, in the

Oort Cloud. This would dramatically reduce the difficulty of applying pure photon acceleration – given of course that most of these dwarf planets will be poorly situated for any particular mission.

3.3 A plethora of nearby RIM targets

Nor could the earlier authors have known that there are truly exciting extra-solar planetary targets closer than 11 l.y. How many will we find within 30 l.y.? Vega, for instance has a disc of dust, discovered by IRAS and could harbour a Uranus-like planet. In the next section we revisit Marx's theory in the light of new laser developments and of the "Stepping Stones".

4. POLYPROPULSION TO NEAR-RELATIVISTIC VELOCITY: "CONVENTIONAL" POLYPROPULSION, PURE PHOTON PROPULSION. (PPP) AND THE ENERGY BRIDGE TO THE PPP REGIME

As mentioned above, even before the invention of the laser, the great German rocket pioneer Eugen Saenger had conceived a pure photon propulsion space-craft. The « exhaust velocity » was of course the speed of light and Saenger, being conscious of the problem of low energy transfer, also imagined a powerful antimatter source of light – later prophetically upgraded to a nuclear pumped laser (NPL) at a time before such things existed. As also mentioned above, just after the invention of the laser, Prof. Georgii Marx of the Roland Eotvos University in Budapest, wrote the first PPP paper in Nature (1966) followed by illuminating controversy. In his article, Marx calculated for the first time the efficiency of PPP and demonstrated that PPP becomes very effective at high $\beta = v / c$. Marx's theory also gives an expression for β as a function of what we now call Marxian time $\tau = I\,t\ / Mc^2$ the ratio of laser output to the mass of the space-craft x c^2. The resultant equations are given below as well as the graph (Figure 1) which displays the instantaneous and total efficiencies of PPP as a function of β. With $\beta = v/c$, the instantaneous PPP efficiency, η_i, is given by:

$$\eta_i = \frac{2\beta}{1+\beta}$$

While the total PPP efficiency, η_t, is:

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

Also, with $\tau = It / Mc^2$ we have:

$$\beta = \frac{(1+2\tau)^2 - 1}{(1+2\tau)^2 + 1}$$

So at low β, $\eta_t \approx \beta$ and $\eta_i \approx 2\beta$ and the PPP efficiency is extremely low.

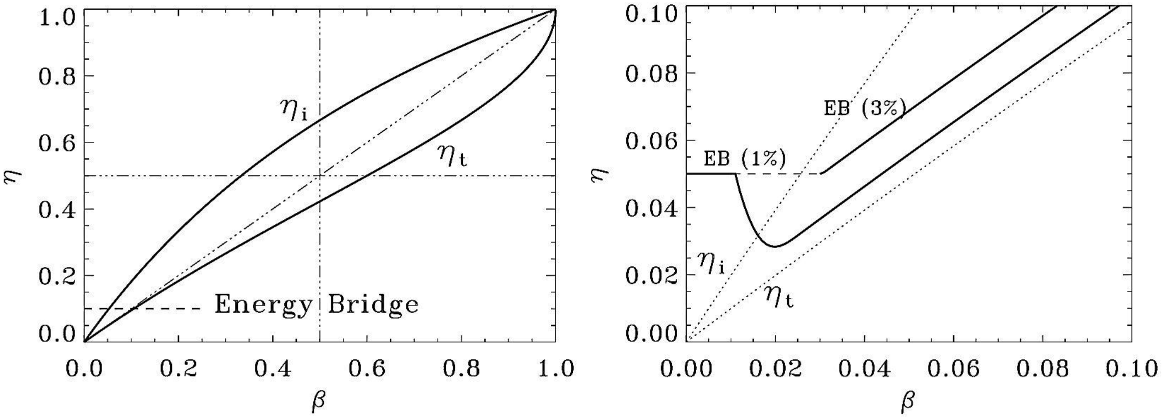

Figure 1. (a) Total and instantaneous efficiencies for PPP according to Marxian theory. (b) Detail of the three regimes of energy bridge efficiency: constant EB efficiency, drops down to the low PPP efficiency but recovers to a higher level due to high η_{PPP} at high β (= v/c). The lower curve is for β_0 = 1% while the upper curve is for β_0 = 3%. η_i and η_t are the instantaneous and total efficiency as a function of the relativistic speed.

At HPLA IV we considered briefly the problem of low energy transfer and suggested an "energy bridge" (EB in Fig. 1a) to fill the gap between high efficiency conventional propulsion up to velocities of a few tens of kilometers per second, and the c / 30 , ten thousand km/s range where Marxian high efficiency PPP could take over. The semi-conventional polypropulsion starter or energy bridge would require a huge amount of energy to get into a useful PPP regime, for example β of 5% or 3 %

Let us calculate the total efficiency for the combined energy bridge and PPP and also how much power is required for both the semi-conventional "starter" and the PPP phases.

4.1 Total (POLYPROPULSION + PPP) efficiency calculation

Assume low $\beta = v / c$ and especially low $\beta_0 = v_0 /c$, τ_0 is the "EQUIVALENT ENERGY BRIDGE TIME", i.e. the time it would have taken PPP to get to Marxian time τ_0 corresponding to β_0. For tiny β_0, τ_0 we have:

$$\beta_0 \approx \frac{(1+2\tau)^2 - 1}{(1+2\tau)^2 + 1} \approx 2\tau_0$$

We write for the TOTAL EFFICIENCY (POLYPROP. + PPP):

$$\eta_t = \frac{\eta_B E_B + I\int_{\tau_0}^{\tau} \eta_i(t)dt}{E_B + E_L}$$

where $E_L = I(t - t_0)$, and $\tau = I\,t /Mc^2$ (Marx time). η_B is then the energy bridge efficiency, E_B is the energy bridge energy and E_L is the laser energy. For small β and τ we can write $\eta_i \approx 2\beta \approx 4\tau$ and therefore

$$I\int_{\tau_0}^{\tau} \eta_i dt = Mc^2 \int_{\beta_0}^{\beta} \beta d\beta = \frac{Mc^2}{2}\left(\beta^2 - \beta_0^2\right)$$

$$\eta_t = \frac{\eta_B E_B + \frac{Mc^2}{2}\left(\beta^2 - \beta_0^2\right)}{E_B + \frac{Mc^2}{2}\left(\beta - \beta_0\right)}$$

For non–relativistic polypropulsion we have: $\beta_0 = \sqrt{\frac{2\eta_B E_B}{Mc^2}}$

4.2 Energy calculation for a typical situation

Now let us calculate how much energy/power will be required in a concrete case? We show first that "conventional" delivery will not work for the energy bridge. Assume "conventional" polypropulsion to $\beta = c/30 = 10^7$ m/s and several stages (possibly 5) of P.P.P. to achieve $c/15$ or $c/10$. For a 1000 kg spacecraft, our technically very advanced descendants will need

$$E_B = \frac{1}{\eta_B}\left(\frac{1}{2}Mv^2\right) \approx 20\frac{1000}{2}10^{14} = 10^{18} J \qquad \left(\eta_0 \approx \frac{1}{20}\right)$$

for the energy bridge. (The relativistic correction is too small to be of importance). If we imagine 10 dedicated lunar mega powerstations producing 10^{12} Watts, it would take 10^6 s to transfer the energy, i.e. ≈ 10 days and the spacecraft would have traveled to 200 AU to the edge of the solar system.

The energy transfer therefore has to be pulsed but not so quickly as to damage the craft with accelerations of thousands of "g's". A little consideration shows that the only sources capable of delivering energies in the 10^{18} range are nuclear. Designs already exist for nuclear propulsion units, for example Prometheus, a reactor driven system conceived under the direction of eminent Princeton physicist Freeman Dyson. There was also a bomb propulsion

scheme, slightly confusingly called "Orion", which imagined propulsion to $c/10$ for a 20 ton spacecraft propelled by some 500 disc shaped atom bombs.
There is also the possibility of polypropulsion with a gas gun, followed by a rail gun, followed by laser ablation. G. Miley has discussed "Laser Fusion Driven Lasers", i.e. a fusion variety of NPL which could be pulsed to drive the final laser ablation stage. This is not the place to discuss ways of rapidly reaching the edge of the relativistic regime, save to remark that there are myriad options, none of them simple.

Having reached say $c/100$ or c /30, one is now ready to enter the Forwardian PPP sail regime. (We note en passant, that new Fullerene materials might considerably strengthen and simplify sail design, which could be more like parachutes, to employ the multi giga-Pascal tensional strength of "Bucky-tubes"). We now apply the calculation of section b to the case where the final velocity is c / 15. (This would make missions to the newly discovered planetary systems at less than or around ten l.y., possible within two or three human lifetimes). Figure 1(a) plots the total PPP efficiency as a function of β assuming an energy bridge efficiency $\eta_B = 5$ % up to about $c/100$ or $c/30$. As soon as the conventional polypropulsion phase is over and the PPP is switched on, the total efficiency drops rapidly towards the low PPP efficiency. However, by $c/15$ the efficiency has recovered to a value well above that of the energy bridge. This feature of the η_t dependency on η_B and η_{PPP} deserves some explanation with the help of Figure 1(b). The horizontal section corresponds to the semi-conventional propulsion stage. Once β_0 is reached, PPP takes over with its characteristic low instantaneous efficiency for low β. This PPP efficiency is $2\beta_0$ for the small values of β_0 achievable with semi-conventional polypropulsion. However η_t will not drop immediately to this value as there is still a reserve of efficiency left from the EB phase. In fact η_t will never drop to $2\beta_0$, because $\eta_{PPP} = 2\beta$ is busy recovering linearly as β increases. η_t will as a result be appreciably higher than if there had been no energy bridge. The other reason for the energy bridge is that without it, the Marx time would become impractically long.

Even with the energy bridge, a little consideration gives typical PPP acceleration values up to several thousand "g's" for a single PPP station. Multiple PPP stations will be required to reduce this to the acceleration range experienced by most robotic space-craft. Perhaps these PPP stations will be based on some of the dozen newly discovered "Plutinos", like Sedna, Quaor, Eris etc. ? Bearing in mind of course that they all lie in or near the ecliptic and that few will be perchance, strategically positioned for the necessary stellar target. Nonetheless, astronomic bodies do sometimes happen to be favourably located as in the planetary "Grand Tour" of the 1970s and 80s, only made possible by a chance arrangement of our own planets. "Marx's optimism"[6,10] – much criticized in the past – has, we think, become a little less incredible. With the advent of short pulse petawatt lasers, long pulse terawatt systems, and who knows what CW powers in the future, and with nuclear pumped or even atom bomb pulsed lasers as first demonstrated by the Soviets (Obninsk), interest in Marx's ideas will grow. And pure photon propulsion will surely be researched in laboratory experiments similar to those of pure photon pressure by Myrabo's group[11].

But then there is a further difficult question: even if Marxian propulsion can be realized, how will the information be beamed back? Again we point to recent unexpected developments which whilst not yet removing the difficulties make their eventual elimination plausible. Eugen Saenger visualized an antimatter driven laser as a propulsion unit. Little could he have realized that less than half a century later, millions of antihydrogen atoms would be routinely created in the Athena, ATRAP, AD and ALPHA experiments at CERN. We simply point the reader to an article on Solid Antimatter or "SANTIM" written two decades ago along the lines first laid down by Robert Forward[7,12]. In our earlier work, we listed about a dozen difficult technical problems on the route to generating SANTIM. Suffice to say that the CERN experiments have overcome at least half of these. What one eminent critic termed "the long haul to generating the first atoms of anti-hydrogen" is over. It remains to be seen whether the "even longer haul until it can be solidified" will not be dramatically shortened by the ALPHA experiments aimed at trapping neutral anti-hydrogen. Once SANTIM is created, will it not be the ideal means of beaming the information back, via a Saenger antimatter laser and the same Forward sail that was used to reach ε–Eridani or α–Centauri?

5. CONCLUSION

Our immediate space environment is becoming more interesting with the most recent discoveries being made by the latest robotic missions to the Jovian and Saturnian systems along with Earth-based discoveries of exciting new dwarf planets (Plutinos) in the inner Kuiper Belt, added to the equally exciting discoveries of new extra solar planetary systems within eleven light years of us. However, the distances to these new frontiers are on quite a different scale to those we had to overcome in the present and recent past. Conventional rocketry will clearly no longer suffice. We have to start looking for more efficient and practical alternative technologies and to allow the next generations to explore the outer solar system this century. Extra-solar planetary systems may come within robotic range of Marxian pure photon propulsion much later in the millennium.

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