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MASS BEAM PROPULSION, AN OVERVIEW

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An alternative to rockets is to push spacecraft with a reflected beam. The advantage is that it leaves most of the propulsion system mass at rest. Use of mass beams, as opposed to photons, allows great efficiency by adjusting the beam velocity so the reflected mass is left near zero velocity relative to the source. There is no intrinsic limit to the proper frame map velocity that can be achieved. To make a propulsion system, subsystems need to be developed to acquire propulsive energy, accelerate the mass into a collimated beam, insure that the mass reaches the spacecraft and reflect the mass. A number of approaches to these requirements have been proposed and are summarized here. Generally no new scientific discoveries or breakthroughs are needed. These concepts are supported by ongoing progress in robotics, in nanometre scale technologies and in those technologies needed to use of space resources for the automated manufacture of space-based solar power facilities. For mass beams specifically, work in particle sizing, acceleration, delivery and momentum transfer is needed. For human interstellar flight, a notional schedule to provide a mass beam propulsion system within a century is provided.

Keywords: Mass beam, pellet beam, particle beam, interstellar, propulsion

1. INTRODUCTION

Instead of reacting against its own exhaust, a beam-propelled spacecraft is pushed by something else. This general concept is sometimes called "momentum beam propulsion." This eliminates the exponential problems of mass ratio, exhaust velocity and power-associated mass that lead an interstellar rocket to be either very slow, or be many (perhaps thousands) of times more massive at the start of its journey than at the end; even with nuclear energies available. The agents of momentum transfer can be photons, objects of ordinary mass, or perhaps something like "dark matter" that physics has yet to describe will enough for propulsive uses. The system consists of a projector, the momentum transfer agents and the reflector on the spacecraft, as sketched in Fig. 1 for mass and photon beams. If the beam is made of photons, the beam-propelled spacecraft is a light sail of the sort about which Dr. R.L. Forward, among others, has written extensively [1].

Granting the enormous potential of laser sails, there is a significant advantage to using something that transfers more momentum per unit energy than a photon. A photon must travel at the speed of light and until relativistic velocities are reached, a reflected photon carries away almost as much energy as it started with. A massive particle's velocity, however, can be tuned so that the reflected mass is left almost dead in space relative to the beam generators, having surrendered almost all of its kinetic energy to the starship. One can, of course, imagine many options for reflectors, mass particles, beam drivers and space energy infrastructure for this concept.

Figure 1 compares the results of reflecting a TJ laser beam segment with the results of the reflection of mass with one TJ of kinetic energy in the sidereal frame of reference (0.67 TJ in the proper frame). The white area represents the sidereal frame (s.f.) of the system where the beams are generated and the gray area represents events in the spacecraft, or proper frame (p.f.) of reference. The light pulse frequency, and thus its energy E, is lower in the p.f. It delivers (approximately) a momentum change, dp = E/c coming and going for a net momentum change of 2 (E/c), [1] where M is the mass of the spacecraft and reflector, resulting small downshift in frequency and energy in the p.f., neglected in this illustration. The reflected light pulse, no going the opposite direction, is further downshifted with respect to the s.f. resulting in an approximate energy of 0.44 in the s.f. The physical particle's initial velocity of 0.8 c translates to an incoming velocity of -0.5 c in the p.f. In the approximation of an elastic collision it delivers a momentum of γ m vb to the reflector coming and going, departing at about 0.5 c in the elastic approximation. At this relative velocity, about 40% of the laser energy is lost, while almost all of the particle energy is delivered to the spacecraft.

Even a conjectural "space drive" that uses the rest of the universe, somehow, as its reaction mass would not perform as well as a mass beam propelled spacecraft if the mass of the energy source to power the "space drive" must be carried on the "space drive" starship. By $E = mc^2$, that energy has an inertial mass, $m = E/c^2$ [2] and so the "space drive" has a mass ratio similar to that of the rocket; it must lose mass to gain relative velocity. No propulsion system that must carry its own energy source can go faster than a system that can use the virtually unlimited energy of its home star.

In 1980, in a *JBIS* paper C.E. Singer [3] proposed an interstellar mass beam propulsion scheme that contains most of the elements of mass beam propulsion discussed below. Singer's work was noted in The Starflight Handbook [4] and James Early's [5] work on force beams. Landis included a short

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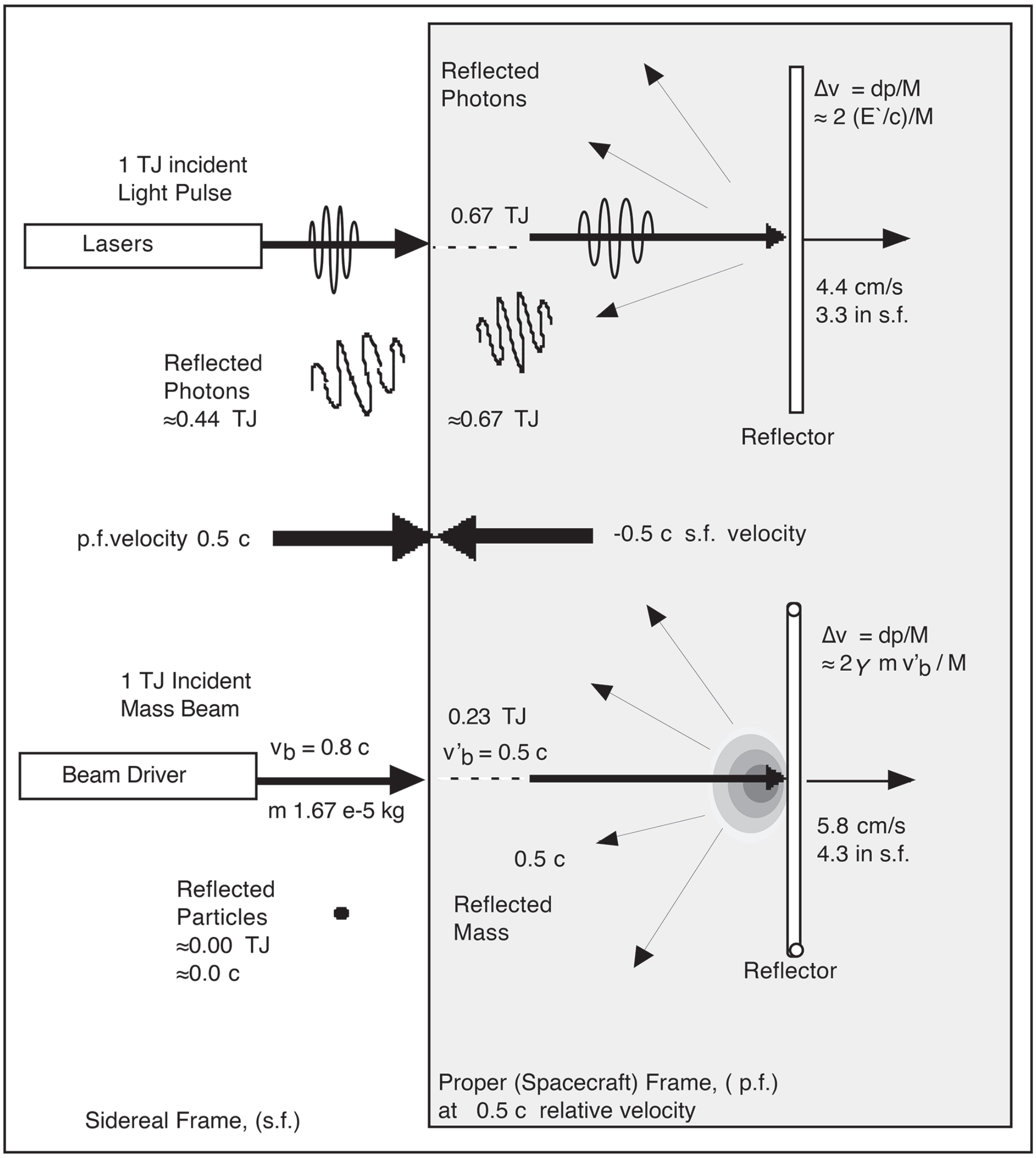


Fig. 1 Photon and Mass Momentum Beam Reflection.

suggestion of using mercury atoms to push sails in a paper on solar sails [6].

In the late 1980's, Zubrin and Andrews [7, 8] and Vulpetti [9] studied using the solar ion wind to push magnetic sails. However, the rather tenuous and velocity-limited solar wind has obvious limitations on acceleration and ultimate velocity. Why not provide a much denser beam? Nordley [10] worked on variable beam-velocity dynamics and suggested self-steering pellets [11].

A conference on near-term robotic interstellar probes was held in 1995 and featured several mass-beam-related papers subsequently published in *JBIS* [12, 13].

Jordin Kare presented the idea of a two-stage propulsion system using laser-propelled sails to push a larger spacecraft in several papers following 2001 [14, 15, 16, 17]. At the International Astronautical Federation (IAF) Conference in Toulouse, France, in 2001, Nordley [18] outlined nano-pellet guidance. Forest Bishop documented his studies on particle size, guidance and acceleration in 2003 [19]. Andrews, in a 2003 paper [20] reiterated the point that mass beam propulsion works with known physics.

The mass beam propulsion systems described in the literature would be complex; decisions about some parts will affect other parts. Understanding the general kinematics leads to performance targets for reflectors, which in turn place constraints on the mass beams, their acceleration and projection system requirements. Some choices will result in greater technological challenges than others. However, at no point is any physical process needed that has not already been demonstrated and there are engineering models for much of it.

2. GENERAL KINEMATICS

The notional mission examples used in [10] assumed a constant acceleration. Constant acceleration makes mission studies easier, but it is probably what one wants to do anyway. For any particular reflector design, the more force it must withstand, the heavier it will be. So it makes sense to operate the reflector at its maximum design acceleration (with a reasonable margin of safety) for the entire acceleration period; one wants to get up to speed as quickly as possible, make the acceleration path as short as possible and make efficient use of any mass that isn't payload.

It is immediately apparent that a spacecraft propelled by reflected mass cannot go faster than the velocity of the mass propelling it. It is also apparent that starting out with a very high beam velocity would waste a great deal of energy in the form of the kinetic energy of the reflected particles; this is the basic efficiency problem of photon sails. The solution to this is to increase the beam velocity during the acceleration of the spacecraft.

For this velocity increase program, one needs to find the beam velocity in the originating frame of reference of the sun and other (relatively) "fixed" stars, (hence the "sidereal reference frame" or s.f.) as a function of the spacecraft position and velocity. If the spacecraft relative velocity is v and the mass beam particles arrive with a negative velocity, -v, in the spacecraft proper reference frame (hence "p.f."), after they are reflected inelastically, they are left with a zero residual velocity, "vr," in the sidereal reference frame. This means that all their kinetic energy and momentum has been transferred to the spacecraft. Numerical experiments with the model developed in [10] by Nordley and later replicated by Crowl initially indicated that the greatest momentum delivery efficiency was, as one would expect, at the relativistic equivalent of vp = 2 vs, where vp is the velocity of the particle and vs the velocity of the spacecraft.

An energy efficiency factor, "e", was added to account for reflected beam transverse velocities, reflection inefficiencies and particle losses. For a perfect colinear inelastic reflection of all particles, e=1. The efficiency maxima in specific cases as a function of residual velocity were broad (Fig. 2) however, and became broader as relative velocities got higher. For lower values of e, minima moved to higher values of vr.

It was apparent that as spacecraft velocity approached a gamma of two, where incoming particle relative velocities approaches those of cosmic rays, there was not much to be gained by further increases in relative beam velocity. Indeed, significant reduction in the final, peak, power needed can be had at little cost to efficiency by tolerating fairly high residual beam velocities. It was also apparent that in the very early stages of acceleration, the formula, combined with a constant acceleration, led to and extremely high mass flow rate at low relative velocity.

Numerical experiments indicated that a good result overall would be achieved with a beam velocity program that uses:

(a) a fixed beam velocity of about .01 c until a spacecraft velocity of 0.005 c is reached

(b) the vb ≈ 2vs law until significant relativistic velocities are reached and

(c) velocity increases as needed for a constant velocity relative to the spacecraft in the proper frame.

The velocity at which the beam velocity program changes from (b) to (c) above would be a trade that depends on specific beam and vehicle engineering parameters. Figure 3 illustrates the application of this program to accelerate a 1,000 ton starship to 0.866 c.

Note the difference between the pellet launch time and the beam power curves; high beam powers don't occur until late in the program. Because most of the energy consumed is in the high-velocity regime, the (c) strategy of maintaining a simple fixed velocity relative to the sail, as in Kare [16], is a reasonable compromise for first order analysis that results in high energy transfer efficiencies over a broad range of final vehicle velocities.

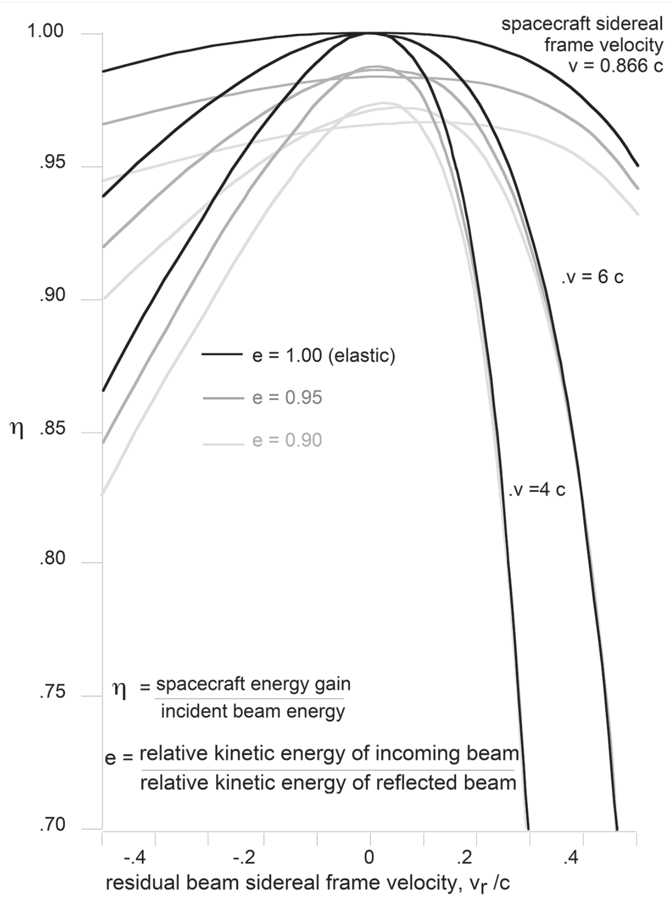


Fig. 2 Energy transfer efficiency η and power as a function of the s.f. frame velocity of residual beam mass. Three sets of three curves are shown, for spacecraft relative velocities of 0.4 c, 0.6 c and 0.866 c respectively. Each set has curves for reflection efficiencies, e, of 1.0 (upper curve, for no losses), 0.95 (middle curve) and 0.9 (lower curve).

3. REFLECTORS

Singer [3] proposed magnetic mirrors as reflectors and Nordley [11]] chose a magnetic mirror with two loops as a reflector (Fig. 4). This was inspired partly by Andrews and Zubrin's magsail work [8], but also by work on magnetic nozzles for nuclear and antimatter pulse spacecraft [16, 21, 22, 23] which work with similar peak relative particle velocities and field strength requirements.

To operate, a magnetic mirror requires the mass hitting it to have an electric charge. Most of the incoming mass must thus be converted into plasma as it approaches the starship; lasers, particle beams, or particle explosions could all accomplish this. If the impact plasma is dense enough once "ignited," it might even serve to ionize the incoming mass itself, as a plasma contained in front of the spacecraft might serve to vaporize interstellar dust particles, as proposed by Landis [24].

The outer loop, essentially, channels this incoming plasma to the inner loop, where most of the force is felt. Particles escape the field as they recombine and become neutral or follow field lines that merge with the galactic magnetic field. Some of the plasma squirts forward along the field lines running along the axis of the current loops. This is not necessarily a bad thing; the starship will thus be preceded in space by a "guard plume" of hot gas which will tend to ionize and perhaps deflect some of the already tenuous interstellar medium in front of it, reducing drag and making less work for shielding systems.

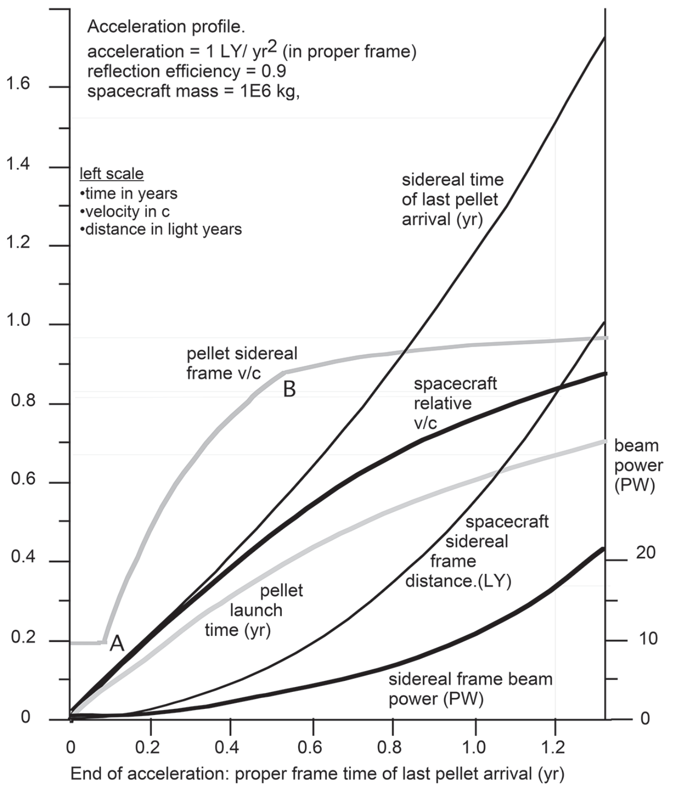


Fig. 3 Acceleration profile. p.f. acceleration. = 1 LY/Y², e = 0.9 M = 1 × 10⁶ kg.

For interstellar thrust levels, the loops would probably need to be superconducting and probably will have to be cooled. For larger pellet sizes, variations in plasma pressure will need to be considered, [14, 16] but how much energy this will require is a question for future science and technology. Higher temperature superconductors would be desirable, but aren't required. Kare [16] estimates a mass of about a metric ton for a sailbeam reflector with a loop radius of 100 m. Nordley's models use a 50 m radius loop.

For unguided beams, Landis [25] proposes that the size of the reflecting surface be increased by "inflating" an artificial magnetosphere as described by Winglee *et al*. [26] created by the superconducting loop with ions provided by the ionized beam mass, resulting in an impressively large target. The drag of this object on the interstellar medium would be significant, but the effective area of the sail would be reduced after acceleration.

In 1994, Nordley [27] proposed a non-superconducting aluminium toroid propelled by a neutral sodium beam for a Jupiter mission, as a first step toward more capable interstellar systems. The aluminium served as the hull of the spacecraft as well as the current conducting element.

An auxiliary power source will be needed to maintain the field and ionize the mass beam, at least at the start. Ordinary fission systems would work, but by the time such spacecraft are built, some kind of compact nuclear fusion reactor might be available. Once underway, one might be able to bleed off some

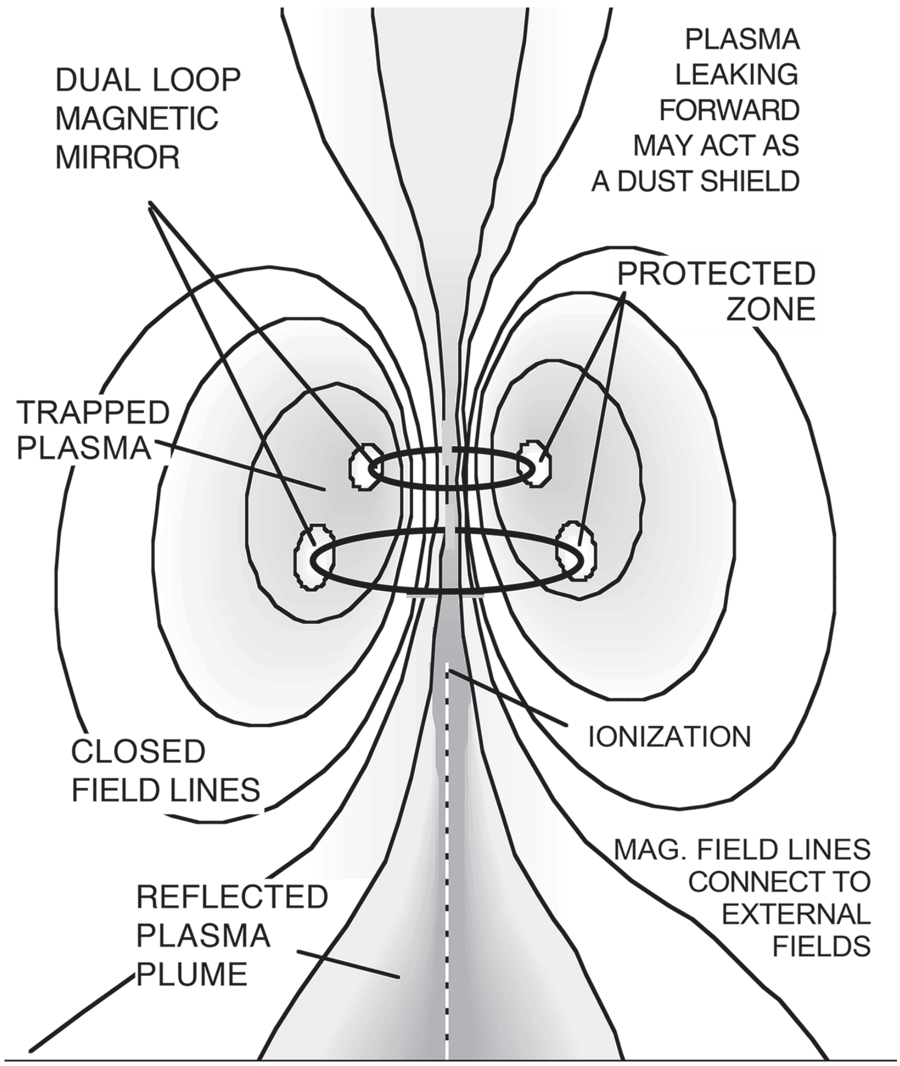


Fig. 4 Dual loop magnetic mirror reflector.

of the propulsion beam energy for additional power during the propulsion phase, if needed, with systems such as described by Hyde [21] for pulsed nuclear propulsion.

Note that the plasma temperatures, densities and pressures for higher accelerations will have much in common with such pulsed nuclear systems, though probably with smaller, more frequent "pulses." See Andrews [20, 22] and Lenard [22] about "Mini-MagOrion."

After the spacecraft reaches cruising velocity; the magnetic mirror will probably stay on. It is still needed to deflect relativistic "wind of passage" interstellar ions around or through the empty centre of the spacecraft. Also, there's significant energy in the currents of those loops; quenching them could be a nontrivial exercise in heat rejection. Finally, the magnetic mirror is needed to decelerate at the starship's destination. As discussed in Kare [16], the size of the mirror might be reduced for the cruise phase, then be greatly expanded for deceleration.

For voyages to previously settled star systems, the deceleration particle stream needs to be projected with only enough velocity to get it deployed in time for the incoming starship to use it, so its energetics would be trivial in comparison to launching a starship. It would not necessarily need to be a "smart" stream; since one is not pushing the deceleration stream to relativistic velocities, one could use a brute mass approach and flood the general area with nearly stationary mass at the needed density, a bit like a cosmic runaway truck lane.

Of course, the first spacecraft to reach an uninhabited star system will not have a cooperating beam of particles coming out to meet it to help it slow down. First missions may be entirely automated, go more slowly than subsequent travellers and their mass may consist mainly of systems to slow themselves down. Deceleration systems include magnetic sails, Forward's giant retro mirrors that reflect photon beams focused all the way from the solar system and various forms of nuclear rockets. Two or more of these systems might be combined; a magnetic sail might be used in the initial stages, of deceleration, followed by a nuclear pulse system like Mini-MagOrion. Dr. Gerald Smith [28] has worked on an antiproton-ignited fission/fusion system that may be easier to do than many other pellet fusion systems.

However a first mission decelerates, once in the target planetary system, the vehicle would locate a suitable source of mass and energy and its replicators would then start gathering materials and replicating. They would gather information, manufacture an infrastructure for subsequent exploration and send out the slowdown path for the next set of visitors.

It is essential for the mass beam be turned into plasma as it approaches the starship for two very important reasons: magnetic fields only reflect charged mass and the impact of uncharged, undeflected relativistic mass propulsion mass on the spacecraft could be disastrous. Generally, one approaches such a situation with several layers of contingency planning.

For atomic beams, lasers can readily ionize the incoming mass. If not, interaction with the dense plasma trapped in the reflecting magnetic field may do the job. If the spacecraft has a toroidal geometry (and particle guidance is good), un-ionized mass flux will go through the central hole. Finally, an extra layer of water (such as a swimming pool) at the bottom end of particularly vulnerable parts of the spacecraft could be a last defence against wind-of-propulsion radiation.

For actively guided particles (see below) the particles can be composed mainly of metastable, explosive material designed to detonate and vaporize given the correct signal and/or conditions. Unexploded pellets/particles with guidance intact will pass through the central hole of a toroidal geometry. Unexploded pellets/particles without functioning guidance systems are likely to miss the spacecraft by a wide margin. For the very few that survive all the above, sufficient aft-end mass should serve to prevent disaster as long as impacts are few.

Reflectors deliberately designed for impact would be simple but would erode over the course of the mission and so be massive and need to be replaced after every voyage (but this could be a trivial chore, all considered). Simple sails designed for use with low-relative-velocity neutral atomic beams have also been proposed.

In a very advanced system, the reflector could be a coaxial frictionless electromagnetic launcher (EML). These could (in principle) be run in reverse to catch incoming relativistic pellets, bend them around and send them back again. Nordley [29] described a much more modest system to, in sense, react against the gravitational field of a planet, albeit at much lower relative velocities by sending mass in a retrograde orbit around it.

In an interstellar version, it has been noted that one starship's returned pellet stream could perhaps to serve as the deceleration path for the next accelerator/starship, whose deceleration would provided the energy and pellet stream to accelerate yet another starship. If this could be done with perfect efficiency, the traveling accelerators could bounce back and forth between stars trading energy with pellet streams, becoming, in effect, a "free" interstellar transportation system. Some of the ideas mentioned by Lebon [29] for "Magnetic Shepherding of Orbital Grain Streams" might be applied to this. Of course, in practice, there would be both energy and pellet losses to be made up, but there would a great energy multiplier effect over non-recycled pellet streams.

"Flying Dutchman" starships could roam the galaxy, deflected by beams from star to star instead of being decelerated, carrying data between civilizations in much larger chunks than could be managed by lasers or masers. Passengers could be picked up and delivered to such starships for a fraction of the energy that would be needed to accelerate/decelerate complete starships. The pellet guidance accuracy for this would be, of course, much greater than that needed for simply hitting an extended starship reflector.

4. MASS BEAM DELIVERY

The major problem for a mass beam propulsion system is to hit the starship with momentum particles at distances that approach a light-year at the end of the acceleration period. Even a hundred-meter-radius reflector is a target of only about 2×10^{-14} radians as viewed from a beam driver half a light-year away; think of a three-millimetre ball bearing at the distance of the Sun from Earth.

There are two types of particle trajectory error to be considered for correction: a systematic error due to insufficiently accurate pointing of the beam driver and random dispersion or spreading of the beam due to cross-beam velocity differences of individual particles, either initially, or caused by impacts with interstellar gas.

The first kind of error could be solved by the starship moving toward the beam centre as the beam centre drifts. However, the end of the beam might be hard to chase; toward the end of the acceleration period the starship may be tenths of a light-year from the projectors and if beam pointing changes by microradians even on the scale of weeks, the beam centre might move at several kilometres per second, too fast to chase with a reasonable on board fuel supply. For an unregulated beam, pointing stability, as opposed to absolute accuracy, would be essential [6, 23, 26].

The second kind of error is beam spreading, sometimes called the beam "temperature" since, in a frame of reference traveling along with the beam, the random velocities of the particles look like thermal expansion. Redirecting these velocities toward the beam centre is called "beam cooling." Singer [3] proposed to use lasers stationed along the acceleration path to push errant pellets back into line.

Andrews [p.7, 20] proposed using accelerations up to 200 gravities to keep the spacecraft close enough for an unguided plasma beam that follows interplanetary field lines. A crew in such a starship would have to be totally immersed. Even a depth of 0.20 m at such a g load would be the equivalent to scuba diving at a depth of 40 m. Bracing, but perhaps survivable.

Landis' neutral mercury beam is cooled to interstellar effective temperatures. The beam is "stiff" relativistically and may effectively reduce its dispersion velocity by condensing into more massive mercury droplets in route. Andrews [20] mentions hydrogen as beam material. Nordley [27] used sodium atoms for a near-term interplanetary suggestion.

Laser cooling techniques such as a photon field lens, described by Minogin [31], could be used during acceleration, immediately after acceleration and possible along the route of the beam to improve collimation. A photon field lens is basically a set of four tuned lasers pointing at the atomic beam path. The lasers are tuned just below a significant absorption frequency of the atoms; if the atoms stay on the beam, they don't absorb a photon. If they move toward the laser, the doppler shift of their motion brings them into resonance with the laser and they get pushed back.

While the neutral beam cooling infrastructure needed to see that the atoms/cluster hit the reflector would be complex, this might be a candidate for near term systems in that it doesn't require anything that hasn't already been built, at least on a laboratory scale.

Nordley [11], with a nod toward the milder forms of nanotechnology, proposed that the beam particles steer themselves to the spacecraft following a homing beacon. The manoeuvre capability of the beam particles would be limited - as Kare points out [16], one wants them to hit the starship with some mass left! - but so would the "thermal" dispersion velocities, particularly for more massive particles.

The circuitry would be much smaller and simpler than today's integrated circuits [18, 32], but a similar kind of thing. The particles could all be identical and stamped out in the billions and billions by automated facilities. This would tap into the burgeoning interest in nanotechnology and its possibilities, as described in Drexler [33, 34] or Vinge [35].

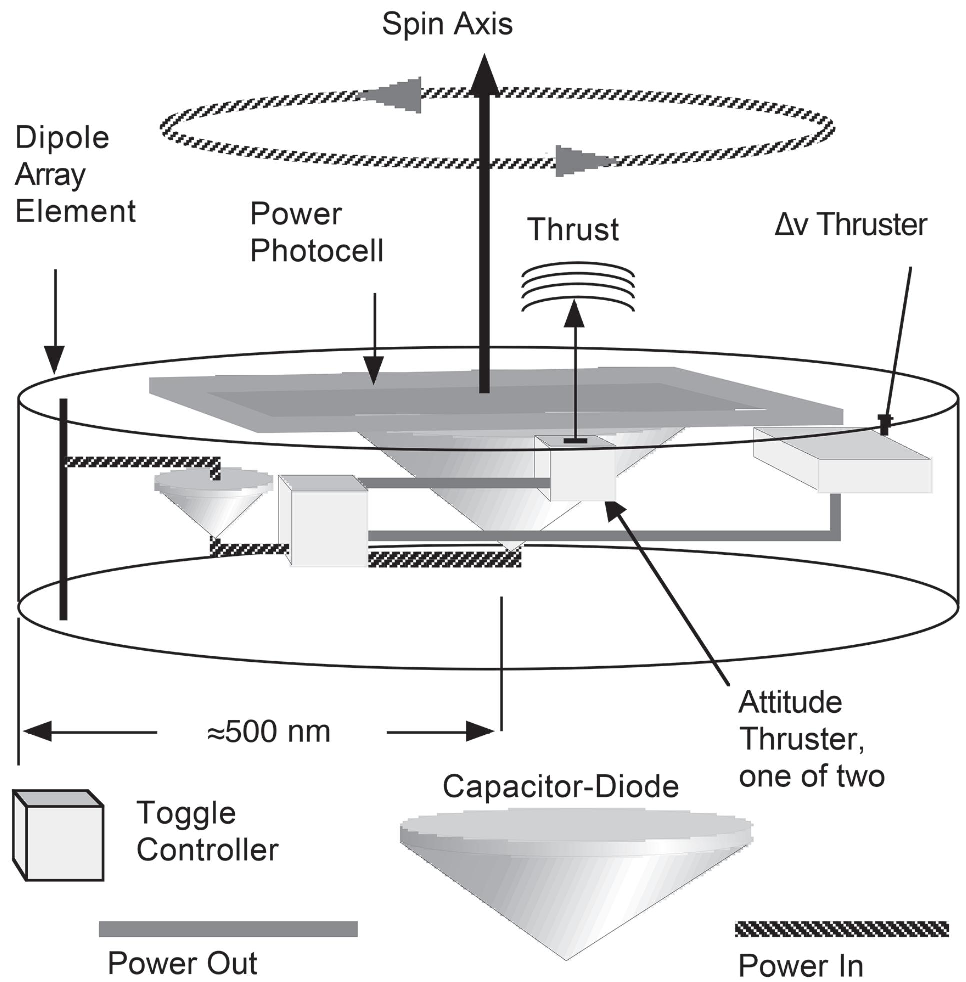


Fig. 5 Notional self-steering pellet architecture.

Figure 5, from [18, 32], shows an approach to a self steering particle. The particle would spin with its spin axis nominally pointed at the spacecraft, which would provide a homing beacon. If all is well, the error sensors on the sides of the particle don't see the beacon and it doesn't do anything. With the right choice of manoeuvre size, a very simple sequence of alternating attitude and velocity manoeuvres might eventually bring the particle back on a path to the beacon. If it works, the "computer" that alternates manoeuvre modes could be a simple one-bit flip flop, reset each time the propulsion capacitor discharges. This means the particle homing system could be extremely small.

In this particular example, the particle would have a radius of about 500 nm and a mass of 1.66×10^{-16} kg. Even at this small mass, most of the particle would be some form of structural matrix. It would be useful if this bulk could be made of something fairly easy to turn into plasma, or perhaps it could be made of materials endothermic enough to facilitate their own decomposition into a plasma or at least an ionizable vapour as the enters the plasma behind the magnetic mirrors.

Bishop [19] and Kare [16], have proposed manoeuvrable momentum transfer particles at opposite ends of the size spectrum. Bishop's "meso particles" might consist of only a few million atoms while the microsails of Kare's sailbeam are large enough to tolerate repeated collisions with the interstellar medium.

Kare [16] discusses terminal guidance options for his sailbeam that also would apply to other self-guided particles and points out that techniques that work at radio frequencies for aircraft precision guidance could be downscaled to optical dimensions for mass beam particles.

Because much less mass would be needed to simply provide a directional reference for self-steering particles than to actually push them back into line, the starship could carry and shed such reference stations along the course of its progress, as shown in Fig. 6.

How small to make momentum delivery particles is a future design trade. The smaller the particles, the easier it will be to accelerate them to relativistic velocities, the smaller the target they make and the easier it will be to steer them back on course. The larger they are, the less sensitive they will be to collisions with atoms of interstellar gas. Beam pellet/particle interaction with the interplanetary/interstellar medium was and continues to be a significant concern for Ruppe [36], Singer [2] and was a primary consideration for the size of the Pellets described by Singer.

Atomic nuclei are very small compared to atoms, thus impacting atoms would almost always pass completely through the particle, transferring only the momentum of their stripped electron shell. Whether this would be a survivable event in terms of momentum transfer is not clear. If it is, the particles should contain a passive nano-damping mechanism in case an impact with an interstellar gas atom causes precession. There are also very rare interstellar dust motes, but should a small beam particle strike one of these, one can presume it lost from the beam entirely. One simply adds sufficient beam particles to make up for such losses.

While this paper is primarily concerned with the other end of the space vehicle, there are an excellent and cautionary discussion of interstellar wind of passage in Andrews [37] and in Martin [38]. Landis has proposed a plasma shield and calculated that it would actually become more effective at higher velocities [25]. Note also Arthur Clarke's fictional response to the problem; i.e., to place what was essentially a large iceberg in front of his spacecraft [39]. When all else fails, given a sufficiently large source of beam-driver energy, one can always throw more mass at the problem. Matloff and Fenelly (as reported in the Starflight Handbook [p.115, 4]) investigated forward-pointed ultraviolet lasers to increase interstellar media (IM) ionization for ram scoop purposes. The same technology would be used to ionize most of the neutral IM for deflection purposes.

It is also important to note that the particle beam is not passing through virgin interplanetary or interstellar space. It is propagating through the wind-of-passage shadow of the starship, its magnetic fields and associated effluvia, as qualitatively illustrated in Fig. 7. The relatively high temperature reflected mass should quickly vacate the volume behind the starship.

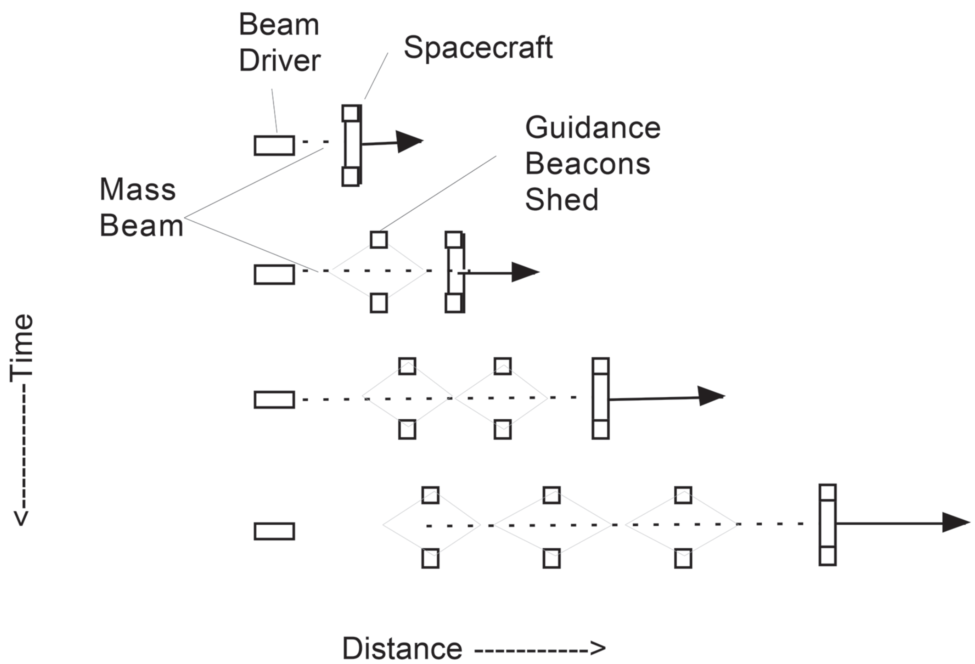


Fig. 6 Spacecraft shedding guidance beacons.

The charged particles deflected by the ship's magnetic field should do a fairly good job of sweeping away the ions in the interstellar medium. Any matter ahead of the ship that is not initially ionized should be ionized by onboard lasers by the time it gets near the ship, though deflection by neutralized atoms in the forward -leaking propulsion boom may be significant as well. It is not clear how rapidly the "hot" component of interstellar medium, mainly protons, will fill in behind the starship because, for one, it is not clear how much of a void will be initially created. This all needs to be modelled.

Particle shape is also subject to trade analysis; Fig. 8 shows a "hockey puck" but an open ring, or a "snowflake" like Bishop describes for his mesoparticles, or a miniature net like Forward's Starwisps [40] might work better. R. L. Forward suggested that his starwisps could be used in this fashion this to Nordley.

The Benford experiments [41] demonstrated levitation of carbon film sails at one gravity albeit with thrust mainly derived from outgassing. Building sail beams of high temperature materials that can radiate absorbed energy effectively may prove an effective strategy for high acceleration microsails and thus sailbeams.

5. MASS BEAM ACCELERATION

Many people are already studying how to throw very small things very fast. Machines like the relativistic heavy ion accelerator at Brookhaven National Laboratory already exist and experiments with ultrahigh velocity cluster ion impacts have been also been conducted. The Brookhaven machine accelerates bunches of billions of gold atoms up to a gamma of about 100 [41]. Beam luminosities of nearly a mole per second have been achieved (though for intervals of much less than a second). This in itself exceeds the velocity and mass luminosity needs for simple particle beam propulsion by orders of magnitude, though machines like the Brookhaven Relativistic Heavy Ion Collider are not designed for continuous operation nor necessarily for efficiency at the levels desired by propulsion engineers.

The process of accelerating a physical object will be substantially different than that of a bunch of heavy ions; however, some of the same techniques, such as stochastic cooling [42], might be used to lower beam temperature during the acceleration process. Particles large enough to have homing systems might also be made with permanent or accelerator energized magnetic dipoles, providing a way other than electrostatic charge for accelerator fields to interact with them.

Singer [4] proposed a linear accelerator for his pellets that would be of planetary dimensions (say, 10,000 km, of 1/4 the circumference of the Earth) in length. These would be anchored to convenient asteroids. In the weightless vacuum of space and given space resources to use, the construction effort required for such accelerators would be much less than their size implies and much, much less than required for, say, the superconducting supercollider on Earth. Many would be needed and economies of mass production would ensue.

For self-steering particles of less than a billion atomic mass units, it may be reasonable to think in terms of hundreds rather than tens of thousands of kilometres of beam line. Bishop

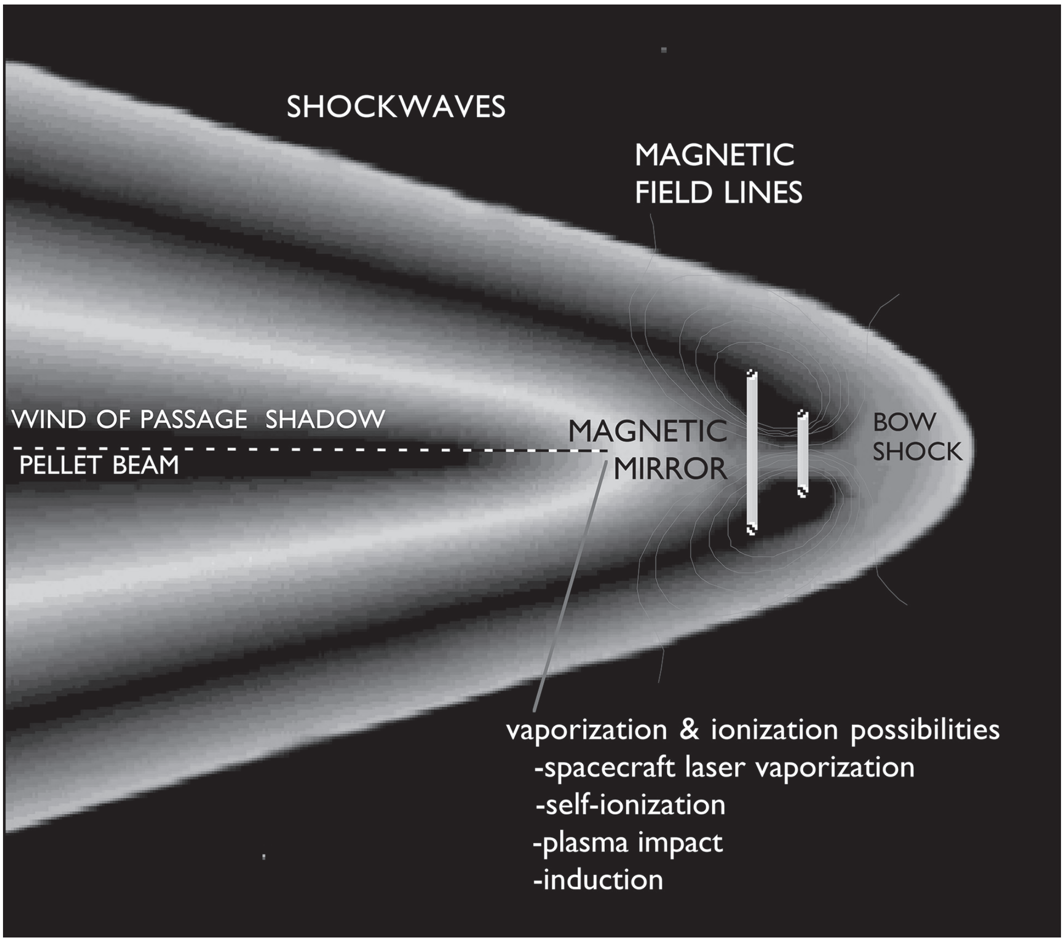


Fig. 7 Wind shadow and Bow Shock waves.

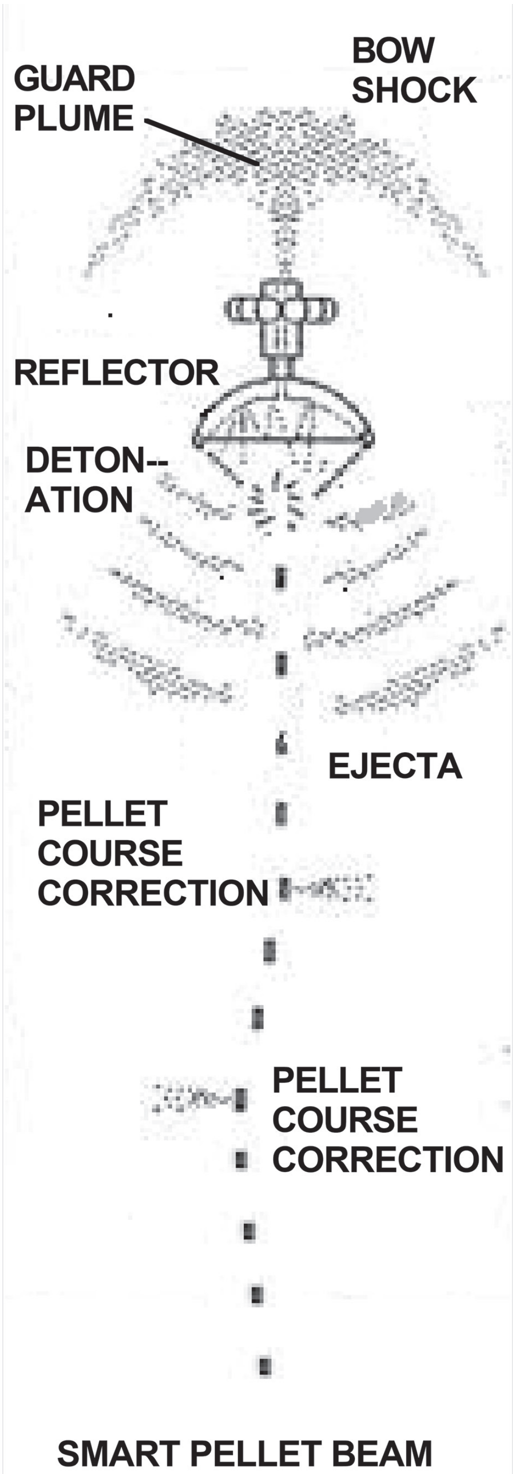


Fig. 8 Smart pellet beam.

[19] has proposed miniature linear accelerators of only a few millimetres diameter for his Starseed Nanoprobes and would use similar machines to launch mesoparticles to push mass beam sails. Millions of accelerators would be needed, but their total cross sectional area would be only a few square meters.

Lasers are simpler to build and techniques for ganging together solid state lasers offer the hope of relatively high efficiency as well. Thus, a two-stage process, ensues whereby micro photon sails are pushed at very high acceleration and fairly good efficiency by photons at higher gamma values. The sails then transfer their momentum to a larger, slower vehicle. Kare [15, 16] and Andrews [14, 20] have written extensively on this. If the sails are substantially conductive, they may inductively self-vaporize on encountering a Tesla-class magnetic field at relativistic velocities.

6. ENERGY FOR MASS BEAM PROPULSION

At a gamma of two, the kinetic energy of a starship equals its rest mass energy, mc^2. A thousand-ton starship moving at a gamma of 2 would thus have a kinetic energy of 9×10^{22} joules, about a hundred times as much as the current total annual world nonfood energy consumption, or about two million one-megaton nuclear weapons.

To get this amount of energy into the starship, considering inevitable conversion and transportation inefficiencies, several times that much energy would need to be collected, let's say around 5×10^{23} Joules. While this is an awe-inspiring number, it is not characteristic of mass beam propulsion; *it would be true of any starship of that mass moving at that velocity*. Note that a million-ton "generation" starship moving at a gamma of 1.001 (0.045 of light speed) is equivalent in this respect. Due to the relative efficiency of the processes involved, mass beam-driven spacecraft are likely to need less total energy to get a starship up to relativistic velocities at accelerations compatible with short trip times.

Where will all the energy for interstellar travel come from? A breakthrough in fusion power technology might bring the moons and atmospheres of the giant into play, but solar energy seems the most straightforward choice. This is generally the choice of photon sail designers, such as Forward [1], who envisioned vast arrays in solar orbit to gather energy for the lasers that would power such systems.

Figure 9, from [18] shows the growth of installed solar power capacity with time, assuming each factory system reproduces itself and a 1-gigawatt (a U.S. billion watts) solar power array each year. The mass of a few medium sized asteroids could provide the matter needed to make the collection area.

This would be a huge, but repetitive, construction project suited for robotic means. It could be done by a system of devices that, collectively, have the following two properties: First, it can make all necessary hardware out of raw solar system materials (asteroids, lunar regolith, etc.). Second, it can assemble said hardware to produce solar power stations, particle beam drivers and copies of themselves. If a reproductive unit of the system, call it a "factory," can reproduce itself and one solar power station each year, then the necessary energy collection hardware can be in operation within a few decades. The cost would be that of making the first factory and supervising the subsequent operation.

The engineering details of which solar energy conversion systems are most appropriate, how big the robots should be and so on, can be left to the future. Today's solar power conversion systems will get better, simpler and more efficient with time. Machines that make parts of machines are an increasingly relevant part of daily life in these times, as are (human scale) robotic assemblers. Already solar-array farm manufacturing/ installation machines can operate largely autonomously.

Obviously, a real system won't produce exactly one replica and exactly one gigawatt-class power station in exactly one year. Nor would it be fully autonomous - some human supervision

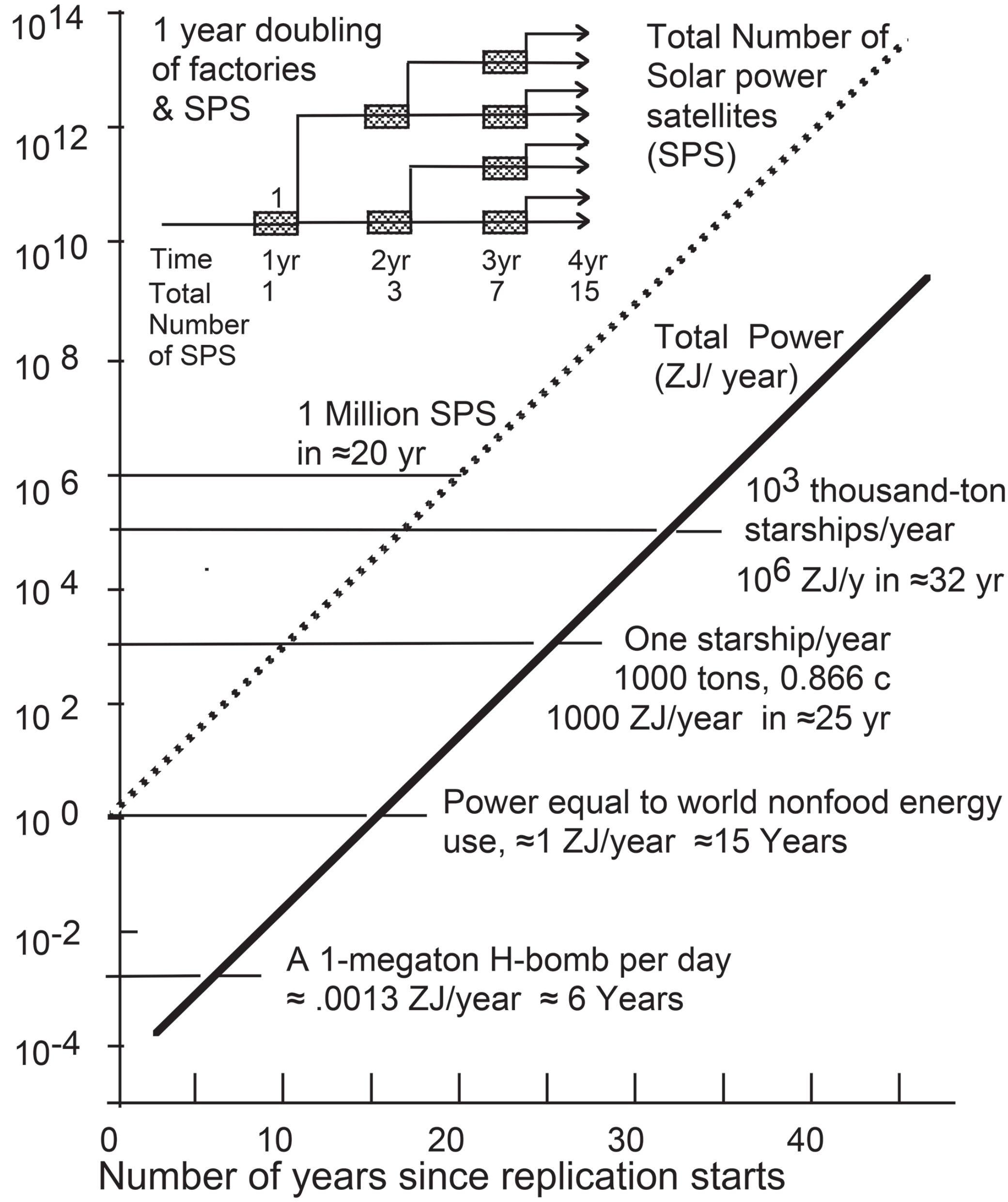


Fig. 9 Exponential growth of power supply.

will be needed - a figurative hand on the "off switch," for instance. However, this calculation illustrates the power of self-sustaining exponential growth to acquire the energy needed for star flight.

The arrays could be placed at one or both of the Sun-Venus equilateral Lagrange points (Venus L4 or L5). A hundred thousand terawatts of solar arrays, 2,000 kilometres across, would stretch 100,000 kilometres across its orbit (a little larger than the width of Jupiter) and would probably be visible as a bright tiny filament in Earth's sky. These threads in the sky would grow longer and longer as the capability to send more starships is added, eventually surpassing Venus in its brilliance in the Earth's sky.

The beam projectors would be reaction engines in themselves, of course and affect their own orbits. They could be anchored to asteroids; they might be attached to the solar energy stations that power them; they might be scheduled so the recoil effects cancel over an orbit, they might circulate masses [28] around a planet or the sun to counter-recoil perturbations…many solutions to this engineering issue may emerge.

The energy requirements for star travel are so high that it is difficult to see how it can happen without self-replicating systems. Also these systems, applied in other ways, would have other profound implications for economics and social organization. When considering the "cost" of interstellar travel, one needs to consider the implications of automated replicators and tens of thousands of terawatts. When humanity has what it needs to go to the stars, its concerns in many areas will be very different to those faced today.

In the fullness of time, one could do more than just travel between local stars. One could look on the energy collection system as the first step toward a "Dyson sphere," where a star is totally enclosed by solar energy conversion systems. From the standpoint of a Dyson sphere, the energy requirements for interstellar travel are small; as a star like the sun puts out about 3.9×10^{26} watts. Imagine that the solar power factories run for forty years. If ten thousand kilometres wide, the array they could make would stretch across almost 30 degrees of Venus' orbit. It would intercept an impressive 3.75 millionths of the Suns output and produce 1.75×10^{28} Joules per year (about 20 million times what is produced on Earth today). This would be enough for some 38,000 flights a year up to a Lorentz factor of 2.

It would also be enough to send several thousand-ton payloads a year up to a Lorentz factor of 40,000. Assuming one could make the appropriate beam projectors, that would get a ship to the M31 galaxy in Andromeda, in about 50 years of shipboard time.

Is it reasonable to think that humans will be able to build such space-based self-replicating systems in the next 50 or 60 years? If so, they may be able to send out the first relativistic starships in the next century and be conducting a full-fledged interstellar commerce before its close. Given progress in life extension, some people alive today may live to see it.

7. A NOTIONAL MASS BEAM PROPULSION DEVELOPMENT SCENARIO

Figure 10 describes a notional first-order technology roadmap to a mass beam propulsion launch capable carrying passengers to the Alpha Centauri System one hundred years from now.

In the beginning years, It builds on technological advances in superconductors, robotics, self-replicating 3D printing and space resource refinement that are likely to occur for reasons other than star flight, but will substantially contribute to creating the technologies mentioned above.

In parallel with these developments, over the next twenty years or so, the plan envisions an effort in design and analysis directed toward mass beam propulsion with, initial experiments performed in the 2030s with simple neutral atom beam hardware descended from designs for missile defence systems.

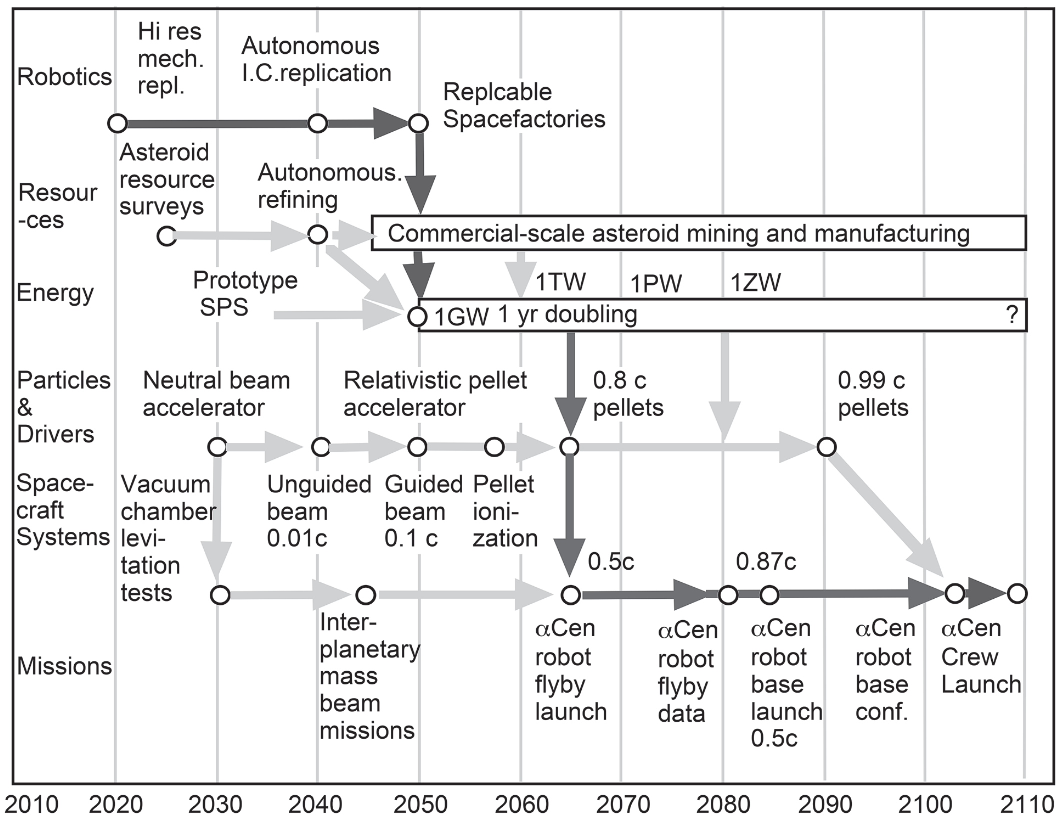
The current loops would not need to be superconducting if the conductor cross sectional area is large enough. A toroidal aluminium hull [27] for instance, would suffice.

Assuming that a more robust mass beam of some kind (passive pellets, smart pellets, sailbeams, etc.) proves desirable, accelerators for these could be developed over the next twenty years, increasing in throw velocity over time as power is installed. The first stages of commercial asteroid mining efforts are already in progress, and on a schedule fully compatible with the notional timeline, if not actually a little in advance of its projections. [43]

For a 2110 launch of a crew, one wants to know that a deceleration system is in place. The robotic precursor system that would build the deceleration system would likely have to travel more slowly, with the capacity of an unassisted deceleration. It is estimated that the robotic system achieves a cruise velocity of 0.5 c and takes about 18 years to reach the Alpha Centauri system, including deceleration time. This allows three years to construct a system to deploy a low velocity deceleration particle swarm for the human-rated vehicle and 4.3 years to report it. Backing away from 2111, the launch of the precursor system should take place not much later than 2085.

The peak power for a 1000-ton payload to 0.5 c would be about 3 PW (see Fig. 3) and the robotic precursor might mass less than a third of the crewed ship. One petawatt should be easily available by that time. The critical path (dark arrows) nexus turns out to be the flyby probe needed to get the data to build and program the robotic precursor. To get data back from this in the 2080 time frame, a five ton 0.5

Fig. 10 A notional top level program plan for human starflight by 2110.



c probe will need around 20 TW at end of acceleration. It could go slower, earlier or faster, later, with about the same results, thus the self-replicating solar power stations should start about the year 2050. This allows about 39 years to develop the particle, reflector and beam driver technology, with the major investments coming later (in the 2040's) and with significant constituencies (rapid interplanetary travel, resource exploitation and astronomical probes) other than starflight to provide near-term payoff.

8. CONCLUSIONS

Given plausible developments in robotics and use of space resources, mass beam propulsion could let people travel to the nearest stars in less than a decade, a time scale of perhaps only two or three times that of early intercontinental ocean voyages. This is based on known physics and anticipated extensions of known. While new science might be helpful, particularly in the area of superconductors, it is not needed.

That is not to say that there is not a lot of work to be done, nor that some other system won't prove superior in the future. It would be remarkable if starship propulsion in the 2100s looks as much like what is described here as the Apollo project resembled Jules Verne's space gun. However by demonstrating that the question of interstellar travel can be decoupled from the concerns of rocketry; exhaust velocities, mass ratios, etc., the future of interstellar travel ceases to be a marginal concern limited by rocket mass ratios to slow "generation ships."

By building small fractions of a Dyson sphere with automated labour and space materials, civilizations could send out thousands of starships a year at nearly the speed of light and create an interstellar culture that could percolate through this and other galaxies in a few hundreds of millions of years. Humanity may happen to be the first to do this. Or they may find others waiting.

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