

INTERSTELLAR PROBES PROPELLED BY SELF-STEERING MOMENTUM TRANSFER PARTICLES

Gerald D. Nordley*
Sunnyvale CA

ABSTRACT *Spacecraft propulsion by reflection of beamed particles or photons represents a highly efficient means of achieving high velocities for interstellar spacecraft because the reaction mass and energy source do not have to be carried by the spacecraft. For reasonable levels of acceleration, the distance between the source of the beam and the spacecraft--on the order of hundreds to a few thousands of Astronomical Units by the completion of acceleration--creates the practical difficulty of ensuring that the beam reaches its target. However, if the beam particles could steer themselves to a cooperating beacon on their target, this difficulty would vanish. The development of sub-micron technology gives hope that extremely small particles, bacteria-sized down to a few billions of atoms, might be made smart enough to perform their own course corrections. Anticipating that such homing systems would need to be as simple as possible, an algorithm for spinning particles was developed which requires only some means of photon absorption, energy storage, proportional circuitry, pulse triggering, and a flip flop. A two-dimensional model of its performance indicates that a beam of particles a hundred kilometers wide might be focused down to a hundred meters or less over an astronomical unit, using light emitting diodes for attitude thrusters and single atom ejectors for cross-range velocity changes. In addition to forward momentum, reaction mass for deceleration and high density information might also be delivered by beams of such particles. Given that relativistic velocities for interstellar probes may become accessible to humanity within a century, using scientific knowledge we already have, we would expect to find evidence of other civilizations which may have passed through a stage of industry and exploration similar to our own millions if not billions of years ago. Fermi's question of "Where are they?" thus becomes all the more significant.*

BACKGROUND

Motivation

Interstellar travel is generally conceded to be a far term prospect; however it has captured the imaginations of a great many writers and engineers. Part of the reason for this is that an answer to the question of whether or not we, or intelligences evolved elsewhere, can travel to the stars raises significant questions about the long term destiny of our species. Are we alone? Does the future include human settlements so far beyond the influence of Earth that they might be considered separate civilizations? Is there a prospect of answering questions about our origins and our place in the universe that can be answered only with physical samples from other stellar systems? The prospect of answering these questions motivates work on interstellar propulsion systems even though they are unlikely to be funded, or realized in normal human lifetime.

The main problem of interstellar travel at velocities that provide information within a human lifetime is basically energy. At a Lorentz factor ($\gamma = 1/\sqrt{1-(v/c)^2}$) of two, the kinetic energy of an interstellar vehicle relative to the sidereal frame of reference (the "fixed" stars) is equal to its rest mass energy. To go that fast requires both a source of the energy and a means to apply it to the starship payload.

Systems with difficulties

Rockets appear unreasonably massive for relativistic velocities. While they are reasonably efficient, the best exhaust velocity that can be mustered, through nuclear fusion, appears to be about a tenth the speed of light. Oliver among others has shown that this requires an enormous mass ratio, which in turn would require enormous engines to provide sufficient acceleration.¹

This author and others have looked at the use of antimatter to store propulsive energy. While this is attractive in principle because of an arbitrarily high exhaust velocity, there are immense practical problems in making a sufficient quantity of antimatter for interstellar travel² and applying the annihilation energy efficiently.^{3,4}

The interstellar ram jet proposed by Robert Bussard has difficulties with the low density of the interstellar medium and in getting fusion to run on interstellar hydrogen.⁵

Beam-pushed systems

The best solution appears to be to leave the massive engines and fuel supply at rest and accelerate only the vehicle through some kind of momentum transfer mechanism. Laser generated photons focused by huge lenses and lightweight, high acceleration smart mesh sails propelled by microwaves have been proposed by Forward.^{6,7}

*FBIS, Sr. Member AIAA. gdnordley@aol.com

Photons have a problem in that they transfer a relatively tiny percentage of their energy and momentum to their reflector and require huge lenses or mirrors to focus their beams on distant reflectors. A stream of particles would transfer momentum more efficiently and, in principle, be easier to collimate. This author's interest was provoked by Andrews and Zubrin's proposal to use large superconducting magnetic loops to "sail" in the solar particle wind.^{8,9} This particle wind, however, is not very dense and the acceleration would be low. But why not create an artificial wind?

Research revealed that C. E. Singer had proposed just such a system with a pellet stream.¹⁰ Also Ruppe had proposed such a scheme for interplanetary propulsion much earlier.¹¹ Such a system is also mentioned in Landis¹² and in Vulpetti.¹³ Lebon had looked at circulating particle streams to launch interstellar payloads.¹⁴

This author looked at particle beam propulsion kinematics.¹⁵ Andrews looked at the economics of a relatively near term version of this system.¹⁶

Forrest Bishop has also done work on a "mesoparticle" stream system, and has analyzed a number of other related propulsion concepts.¹⁷

Previous conclusions

In the 1993 JBIS paper, this author noted that by carefully arranging the impact velocity of the particles so that their reflected debris would be at rest in the sidereal frame, it was in principle possible to transfer all of the kinetic energy of the beam to the spacecraft.¹⁸ Since beams can be accelerated very efficiently through electromagnetic means, the total energy source-to-spacecraft efficiency of this system might approach unity more closely than other systems with inherent energy loss mechanisms (for example; accelerating fuel to be used later in the case of rockets or reflected beam energy in the case of photon sails).

Including some non-ideal assumptions about reflection efficiency and relativistic effects, however, led to the conclusion that the beam mass/velocity profile should have three stages:

- 1) an initial low constant velocity-high mass flow rate stage to get the vehicle moving until it reaches half the initial beam velocity,
- 2) a stage where the beam velocity is increased to keep the reflection velocity low in the sidereal frame, for maximum efficiency, until, subject to overall system trades, a point of diminishing returns sets in, followed by
- 3) a stage where the beam velocity is increased to keep the relative velocity with respect to the spacecraft constant

until the desired mission velocity is reached.¹⁹

To power the laser batteries needed for photon sails, Forward proposed vast arrays of space based solar power collectors. Singer mentioned this for beam projector power as well.²⁰ The author observed that the technology to make self-replicating systems using space resources (asteroids, Mercury regolith, etc.) will probably be well in hand by the time an interstellar system is attempted.²¹

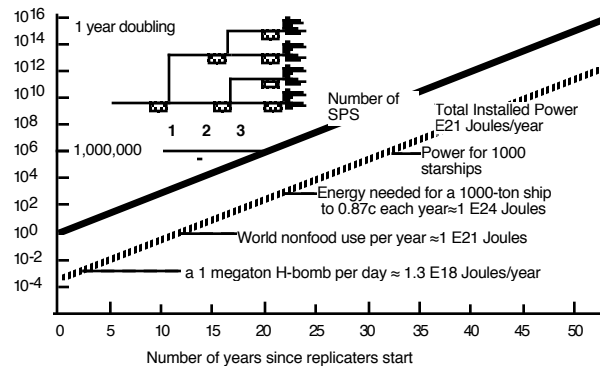


Figure (1) Energy for starflight

It should be noted here that nanotechnology is neither envisioned nor required for this; the unit of replication can, and probably would be, several hundred tons in size. In a very simplified analysis, it was observed that, once in space and started up, a system that could replicate itself and make a 1GW solar power station once every year would produce enough power to send a starship up to 0.86 c in about twenty-two years. Also it can be noted that use of self-replicating systems takes discussion of the energy requirements out of the realm of conventional economics.

The acceleration distance depends on the level of acceleration, but for reasonably quick trips, should be on the order of a thousand AU. The last particles launched would need to reach the spacecraft over this distance.

There are two kinds of errors in particle direction, pointing errors and particle dispersion. Beam pointing errors affect all neighbor particles in the stream. Changes in beam direction might be handled by the starship "riding" the beam, creating a slight angle to the reflected velocity to allow it to move laterally to follow the beam.

Dispersion addresses velocities of beam particles transverse to the center of the beam. Dispersion in beams of atoms or molecules is generally characterized as "beam temperature" with a transverse velocity, v , characteristic of an ideal gas of a certain molecular weight, m , and temperature, T , according to:

$$v = \sqrt{3 \cdot k \cdot T / m} \quad (1)$$

where k is the ideal gas constant. Collimation of such beams is referred to as "beam cooling."

This is not strictly accurate for a collection of large nonintersecting particles but should give a rough order of magnitude comparison of the results of beam cooling techniques on the particle stream.

Dispersion may result from differences in velocities from particles from, say, different beam projectors, or from interaction with the interstellar medium. Singer treated the effects of the interstellar medium on beams.²² This author believes his conclusions are valid for the size of pellets he considered and can probably be extended to somewhat smaller masses. With smaller particles, the sparseness of the beam should be such that collisions would affect only the pellet struck, and likely remove that pellet from the beam entirely. In this paper, the effect of particles removed by interstellar medium is included, mathematically, in an efficiency factor—the fraction of particles incident on the reflector divided by the number launched by the beam projector.

Let us assume that the dispersion velocities of the particles as they exit the beam drivers are given by equation (1). Figure 2 is the result.

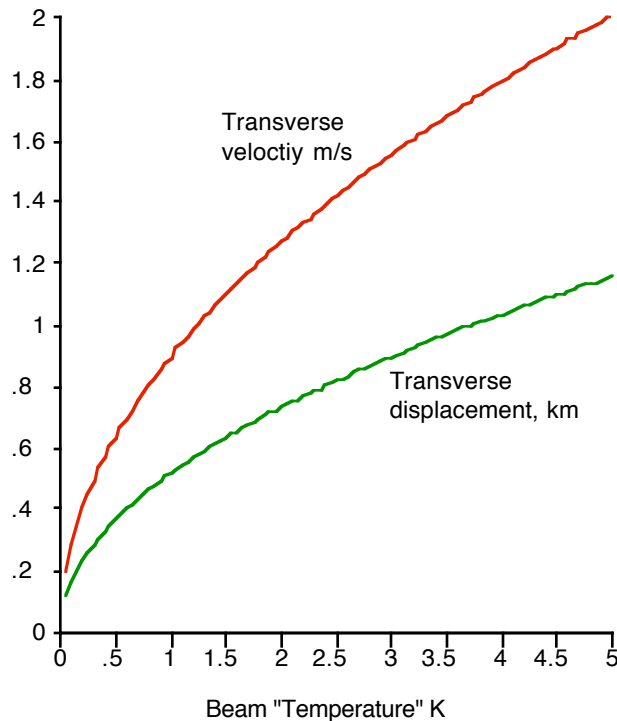


Figure (2) "Thermal" dispersion of beam particles

The first question to ask is: how much beam cooling/steering will be needed? Beam cooling technology has produced millikelvin temperatures in beams of atoms and molecules.²³ Landis has proposed assembling what amount to forming pellets from mercury atoms in flight, to reduce dispersion due to beam temperature.²⁴ A beam temperature of 50 mK would result in a particle dispersion of about 100 m at 1000 AU. One could argue that particle steering might not be needed at all.

However, the space transversed by the particles is not that cold. Sunlight and starlight photons will kick each particle a bit. Depending on the nature of the surface of the particles, this could result in beam temperatures in the range the graphs depict. One approach to handling dispersion, of course, is to simply do the best job of collimation one can at the source and increase the volume of beam to make up for losses. Another would be to build very large (several kilometers) reflector "sails" of the sort originally envisioned by Zubrin and Andrews.²⁵

Singer proposed that beam spreading could be controlled by placing laser stations along the acceleration route to detect and push errant beam particles back in line.²⁶ This would work, but requires a lot of solar system infrastructure specific to one stellar destination.

This author proposed self-steering pellets that could home in on a beacon provided by the spacecraft.²⁷ The balance of the paper will address aspects of that approach. For purposes of the guidance simulation below, it was assumed that the particles are no more than a few kilometers off the beam line as they approach the spacecraft.

BEAM PARTICLES

The objective of this work was to examine a particle guidance concept. To do that, at least a straw-man design of a particle is needed. What follows should be considered a first look at particle characteristics and not a design study. If ever built, actual particles may vary from the characteristics assigned below by orders of magnitude as a result of detailed engineering.

Design of self-steering particles would involve a number of trades.

The heavier the particle, the longer the accelerator needed to accelerate it. Singer envisioned fairly heavy pellets that would require accelerators possibly thousands of kilometers long; not a huge improvement in practicality over the planetary-sized lenses and mirrors needed for photon pushed systems.²⁸ With the advent of very small and ubiquitous microtechnology and visions of nanotechnology, it seemed that the size of the particles could be pushed down to something more in line with

what conventional accelerators could push. However, because the accelerators would be produced with the same kind of robotic systems that produce the power stations, this is probably not a significant issue. The longer accelerators would take longer, of course, to redirect to another destination.

If the particle is going to follow a beacon, there is a concern when the dimensions of the particle approach the dimensions of the particle receiver. The problem is conceptually similar, perhaps, to that of designing a directional radio antenna of dimensions similar to the received wavelength.

In an effort to make the particles wide with respect to their mass, a "snowflake" design might be adopted. This design might also lend itself to acceleration by resonant photon pressure wherein the photons are trapped in a tube between the particle and a reflector so that the same photon hits the particle many times, greatly increasing the efficiency of the acceleration process.

Another size issue is the number of beacon photons available to the "sensors" on the particle.

Assuming that, to a first order of magnitude, this is proportional to the physical area of the particle, it is soon apparent that the beacon must be very powerful or that the particle must be able to do what it needs to do with rather few photons. For example, if the beam of a 2 MW beacon were spread out over a 20-km circle, it would have an average intensity of only about 1.6 mW per square meter. For a particle 1 micrometer in diameter, the intercepted power would be 6.25×10^{-16} W, which, at a 750 nm wavelength would be about 4700 photons per second. It is possible that the power requirements could be reduced by a pulsed laser beacon that would provide the needed intensity for a limited time.

As miniature space vehicles, self-steering particles will need an attitude-velocity control system (AVCS) consisting of sensors, controls and thrusters. To simplify the control problem, it made sense to spin the particles. Attitude and velocity maneuvers could be made by pulsing the appropriate thrusters when they are pointed in the right direction. Single photon emitter regions could serve as thrusters, or atomic cluster ejectors could be used, assuming velocity change requirements are not too high. Energy for the maneuvers could be accumulated from beacon photons and stored by capacitance. Capacitance scaling formulae for the range of particles considered have been worked out by Drexler.²⁹ The system envisioned would have several capacitors, power receptors, and sensors linked together with analog circuitry and one digital element, the $\Delta A/\Delta v$ flip flop, as illustrated in figure (3). Papers on design and fabrication of micrometer to

nanometer (mesoscale, in Bishop's terminology) devices has become commonplace and a certain amount of practical work has been accomplished.³⁰ What is being asked of the circuitry in these particles is much less than is contemplated for much smaller devices.

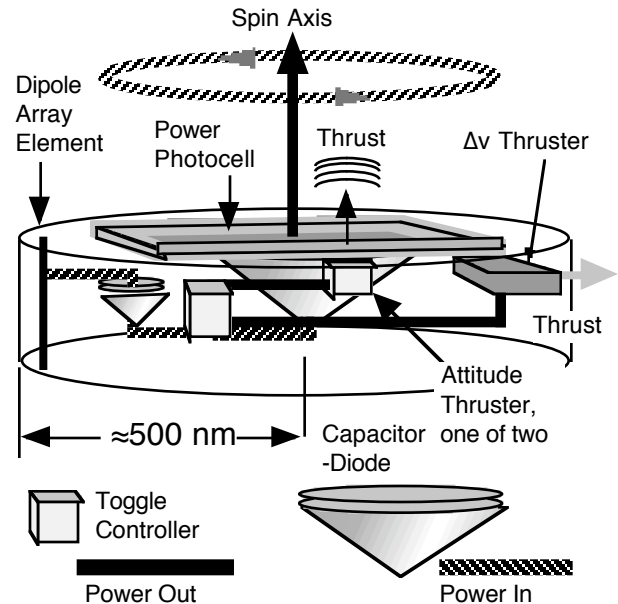


Figure (3) Simulated particle schematic

For the purpose of the guidance simulation, the following particle physical characteristics were assumed:

- radius: 500 nm
- thickness: 100 nm
- number of atoms: $\approx 100 \times 10^9$
- mass: 1.66×10^{-16} kg
- rotation: 1×10^6 radians/s (159152 rotations/s)

The number of particles needed will depend on their mass and velocity profile. Roughly, at a constant relative velocity of half the speed of light, the mass flow rate that would accelerate a 1000 ton starship at 1g for 1 year (proper frame) would be approximately 65 mg/s. If each particle were composed of 100 billion atoms, 1.2×10^{22} particles would be needed. The total mass of the particles, however, is a relatively modest 2023 metric tons.

It cannot be emphasized enough that the scale of a fast interstellar mission of any kind involves large numbers. Here, fully automated systems are envisioned to collect the resources and manufacture the factories, the solar arrays to power the beams, the pellet accelerators, and the pellets. This is a scenario that would appear to be well beyond traditional human labor-based economics.

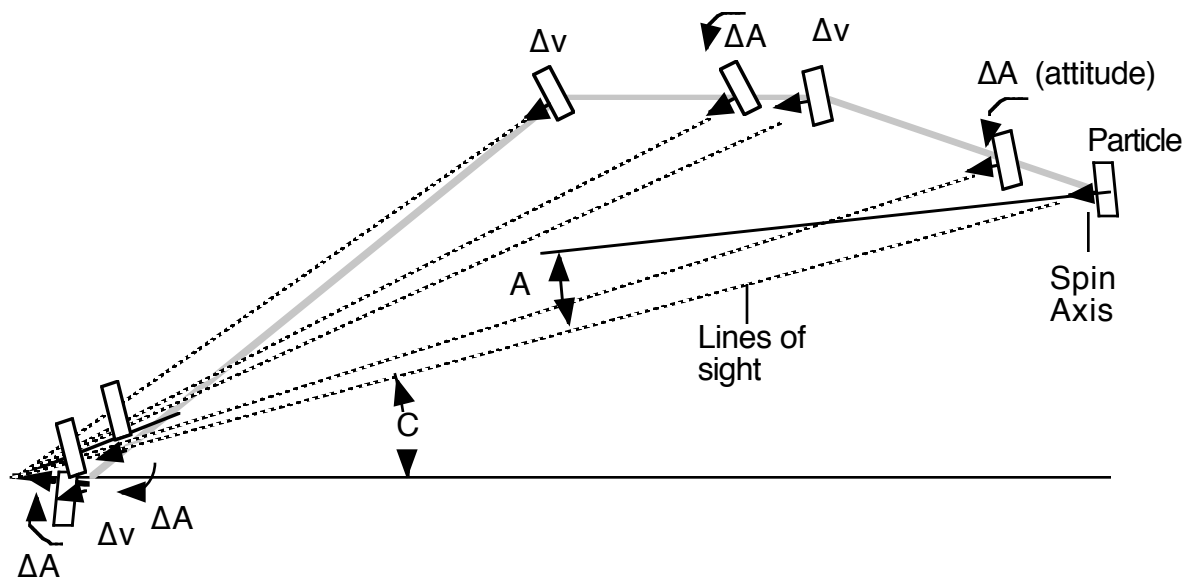


Figure (4) Alternate $\Delta A/\Delta v$ particle guidance concept.

SIMULATION

Guidance Concept

The approach of the particle to the spacecraft is illustrated in figure (4). It starts with an initial attitude error A with respect to the ideal beam line direction and a displacement from the ideal beam line. This results in an angle between the spin axis of the particle and the beacon of C . If C exceeds some threshold value T , the particle fires attitude thrusters at the appropriate phase angle until C is driven below the threshold. At the end of this maneuver, the maneuver system is reset for velocity change. As the particle continues to approach the spacecraft, geometry causes C to grow greater than T again. This time, the particle fires its cross range thrusters until its energy supply is exhausted. The maneuver system is reset to do attitude maneuvers. C is driven below the threshold again. If the particle's new flight path takes it away from the spacecraft, C will grow again and another velocity maneuver will be performed. In principle, it will keep doing this until C no longer grows above the threshold, or time runs out.

Simulation Inputs

What are realistic numbers for thruster performance and attitude error detection? One would like the particle to start attitude corrections sooner rather than later. At a distance of 2 AU from the spacecraft, a 6 km offset from the beam line, without any other attitude error, would result in a C of $6E3/3E11 = 2E-8$ radians. Is such a small angular error detectable by a particle 500 nm in radius with a beacon wavelength of 500 nm?

Figure (5) shows the antenna radiation pattern of a half-wave dipole antenna.³¹ The nulls at either end of the antenna are extremely sharp, theoretically zero at the ends. In principle, if the null were pointed directly at the beacon, photons would not be absorbed above a particular rate, but if it were off even a little, some net photons would be absorbed. An array of several hundred such antennae embedded in the particle could be perfectly aligned by the particle matrix crystal structure and might possibly, subject to further analysis, be linked to form a null detector of the required angular sensitivity.

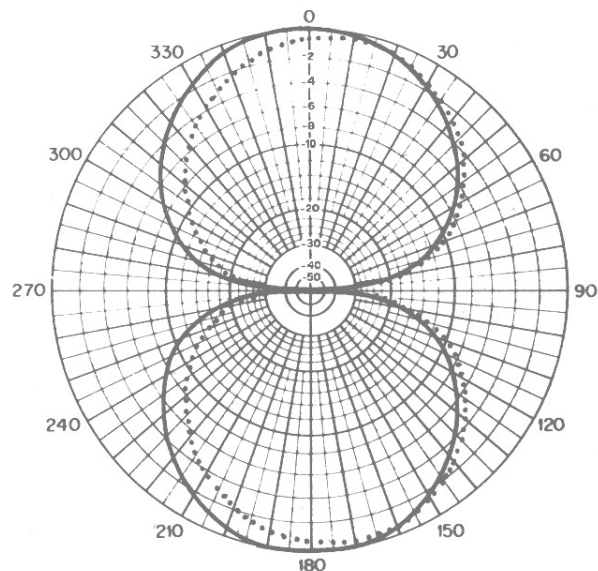


Figure (5) Free space dipole antenna gain.

But if the particle cannot detect its displacement error on approach based on the beacon incidence angle, alternatives exist. The spacecraft beacon itself could be structured to provide that information, for instance by using two or more colors with different angular widths. The relative intensity of the colors, which I'll call a "color index" would vary as the particle departs from the beam line. With some increase in complexity, the particle could "know" its displacement from the relative voltage on capacitors storing energy from each color.

This latter system would require an algorithm slightly different from the one simulated here, probably looking to wait for a change in color index to begin velocity maneuvers again. A constant color index would indicate a constant angle-off, the condition for an intercept.

More complex algorithms can be imagined for larger particles, of course. For example, beacon intensity, if standard, could provide range information.

To perform either attitude or velocity maneuvers in the right direction, the particle must have some azimuthal information concerning the azimuthal direction of the beacon. Providing an external reference beacon off to the side does not really help, since it does not provide a reference to the location of the beam line; a particle could, for instance be either closer or further from the beam line than the side beacon. The antenna radiation pattern suggested an approach, however; even for very slight angular errors, the probability of a photon being absorbed on the side tipped toward the beacon would be higher than that of the side tipped away.

The simulation software fires thrusters when a photon is absorbed by an attitude sensor, on the other side in the case the velocity thrusters, and a quarter circle antispinward in the case of the attitude thrusters. Even with a very large standard deviation, the central limit theorem³² would drive the result in the approximately correct direction with a large enough number of photons.

Another possibility is that the particle stream itself could provide a reference; to a particle several kilometers away from the main stream, the stream could be made to look like the milky way in an appropriate frequency range. The particle would pulse ever time it received a photon of the right frequency from one of its siblings.

For simulation purposes, it was assumed that the standard deviation was pi, and the pattern was integrated over the circle and normalized, since the circular geometry cuts off the tails of the normal curve. The result was that as the number of photons got into the thousands, the direction of the maneuver was within a few degrees of the correct azimuth, but the efficiency of the maneuver was reduced to about 0.09 by the effects of pulses of the wrong azimuth. From an engineering standpoint, one simply designs the particle to take this into account.

Ideally, the delta-V of the particle should be sufficient to null any cross beam velocity the particle has picked up and put it on a constant angle-off trajectory in time to intercept the reflector. At half the speed of light, from two astronomical units away, it has 2000 seconds to do this. This seems like a short time to us, but it's a small eternity for microelectronics, let alone nanoelectronics. In terms of particle rotations, it has $2E3 \times 1.59E5$ of $3.2E8$ rotations.

Returning to figure (4). The Δv required to put the particle on the intercept path is given by:

$$(\Delta v + v_y)/v_b = \sin(D) \approx (y/s)$$

$$\Delta v = v_b \cdot (y/s) - v_y \quad (2)$$

where v_b is the beam velocity, D is the angle between the ideal beam line and the particle position $[s,y]$ and v_y is the initial velocity away from the beam line. Putting in the numbers for the start of the simulation gives a Δv of 3.1 m/s.

Let us increase this by a factor of ten to account for the inefficiency of determining the direction, and another factor of 10 to allow for multiple maneuvers due to overshooting. A Δv capability of 300 m/s should handle the situation.

Let us suppose that we can store a maximum of $1E-14$ J and split this into 100 pulses of $1E-16$ J each. A photon thruster would produce a $\Delta v = (\Delta E/c)/m = 3E-9$ m/s per pulse and $3E-7$ m/s per each capacitor discharge. While the recharge rate would increase rapidly as distance decreases, there would not seem to be time for $1E7$ such maneuvers. For this reason, it was decided to sacrifice some particle mass and eject atoms or clusters of atoms instead.

If the ejected mass was a C_{60} molecule, for instance, it would have a mass of $1.2E-24$ kg (720 amu). The ejection velocity at fifty percent energy efficiency would be 7.9 km per second. This is actually much better than is needed to produce a 3m/s deltaV; the mass ratio (fueled/empty mass), by the rocket equation is:

$$R = \exp(\Delta v/v_x) = 1.00038. \quad (3)$$

For the attitude maneuver using a photon thruster: The impulse, $I = (\Delta E/c)$ is applied at a torque radius $r = 500$ nm from the particle spin center producing a torque of $I \cdot r$. The classical angular momentum of the a spinning disk is given by:

$$L = .5 \cdot m \cdot w \cdot r^2 \quad (4)$$

where w is the angular velocity of the disk. The attitude change per pulse would thus be:

$$dA = I \cdot r / L = 7.2E-9 \text{ rad} \quad (5)$$

This is about a third of the desired angular sensitivity of $2E-8$ radians. A full discharge of the capacitor would result in an attitude change of $7.E-7$ radians, so this is fine tuning. It is not intended to try to recover particles from collisions with stray gas atoms, which would knock

particles this size well out of the beam in any event. However, with larger particles, such as those considered by Singer, ion collisions might be expected and survivable, and attitude recovery would be needed. This would likely require atom ejectors instead of photon thrusters for attitude control.

Simulation results

The particle steering algorithm illustrated in figure (4) was programmed into the procedure window of TK Solver, a commercially available math modeling program, and run with a variety of cross beam velocity and displacement inputs. Some of the results are displayed in Appendix A. Generally, the simple algorithm did cause the particles to converge, but not necessarily as close at the end as might be desired for an actual beam particle. This model, however, was not particularly sophisticated, and the author is hopeful that a serious engineering effort would greatly improve both the simulation and the results.

LARGER IMPLICATIONS

This effort was undertaken mainly to raise the possibility that a workable interstellar propulsion system that could achieve relativistic velocities and allow trips to the nearest stars well within a human lifetime could be assembled from science and technology components that are already known or reasonably foreseeable. There seem to be no difficulties that can't be overcome with sufficiently clever engineering as opposed to "unobtainium" materials or new science. What are needed:

1) Materials processing systems that can convert raw space materials into solar power stations and other high tech products. They don't have to be particularly efficient processes, but rather straight forward enough to be supervised by the kind of insect-like artificial intelligences that we can predict with a fair amount of confidence. These are certainly physically possible; insects exist. The engineering of these artificial "insects," writ large, remains as a challenge.

2) Accelerators, possibly patterned on current accelerators that can accelerate bacteria-sized particles to relativistic velocities. There are technical challenges, but it is basically a scaling-up exercise.

3) Particles with enough circuitry to home in on a cooperative target. Because beacon wavelength considerations would push these toward the micro as opposed to nanotechnology scale, their design and replication should be approachable with existing technology. Research into the behavior of systems in the "mesoscale" should greatly aid these design. For the system described above, the particle matrix material should be readily convertible into plasma or gas as the particles approach the spacecraft.

4) A suitable reflector on the spacecraft. At this writing, a large "magnetic mirror" composed of superconducting loops appears to be the best candidate.

One suspects that interstellar systems, when they are built, will not be any closer to what is described above than Jules Verne's moon cannon was to the Apollo program. However, let us consider that something of this nature or better can be built.

Unless we are unique in terms of intelligence, others will have built such systems. The time it takes for representatives of such intelligences to send probes with living or cybernetic intelligences the farthest corners of the galaxy would be in hundreds of thousands of years rather than hundreds of millions.

Physically visiting other star systems allows intelligent beings to interact with whatever is in that star system in real time and send the results of this interaction back to the home system in only a little longer than a single exchange of electromagnetic messages. There would also be the possibility of observing and interacting with beings who have not developed an outward-looking viewpoint, or are in an earlier stage of technological development.

Any such alien exploration probes that might have journeyed here either have not come, or are not speaking to us. "Why?" remains an unanswered question--but the answer is probably not that rapid interstellar travel is physically impossible.

CONCLUSIONS

The guidance algorithm for self-steering momentum transfer particles will converge with plausible values for all particle characteristics except attitude error detection. More work needs to be done to justify detection of sub-microradian beacon/spin axis angles. Alternative systems, somewhat more complex, may be needed for the particles to recognize divergent trajectories. While this work was geared toward extremely small particles, the basic arguments should be applicable to significantly more massive particles, if needed.

The system proposed rests on known science and technology that generally exists in various parts, though not yet as integrated and not yet on the scale needed for large relativistic starships. It and other beamed propulsion systems support the idea that rapid interstellar travel is physically possible

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Appendix A: Selected results from simulations:

