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Roundtrip Interstellar Travel Using Laser-Pushed Lightsails

Robert L. Forward*
Hughes Research Laboratories, Malibu, California

This paper discusses the use of solar system-based lasers to push large lightsail spacecraft over interstellar distances. The laser power system uses a 1000-km-diam. lightweight Fresnel zone lens that is capable of focusing laser light over interstellar distances. A one-way interstellar flyby probe mission uses a 1000 kg (1-metric-ton), 3.6-km-diam. lightsail accelerated at 0.36 m/s^2 by a 65-GW laser system to 11% of the speed of light (0.11 c), flying by α Centauri after 40 years of travel. A rendezvous mission uses a 71-metric-ton, 30-km diam. payload sail surrounded by a 710-metric-ton, ring-shaped decelerator sail with a 100-km outer diam. The two are launched together at an acceleration of 0.05 m/s^2 by a 7.2-TW laser system until they reach a coast velocity of 0.21 c. As they approach α Centauri, the inner payload sail detaches from the ring sail and turns its reflective surface to face the ring sail. A 26-TW laser beam from the solar system, focused by the Fresnel lens, strikes the heavier ring sail, accelerating it past α Centauri. The curved surface of the ring sail focuses the laser light back onto the payload sail, slowing it to a halt in the α Centauri system after a mission time of 41 years. The third mission uses a three-stage sail for a roundtrip manned exploration of ϵ Eridani at 10.8 light years distance.

Introduction

A FLIGHT system capable of traversing interstellar distances must be orders of magnitude better than our present interplanetary flight systems. Even the launching of a one-way, flyby probe to the nearest star is a major undertaking. Although it will take many decades before the necessary machines are engineered to the scale necessary for interstellar flight, it is interesting to note that there are a number of emerging technologies that can be expected to give an interstellar flight capability, if the technology were steered in that direction and enough resources were applied.

There have been many propulsion systems proposed for interstellar flight. A complete bibliography can be found in Section 2 of the bibliography on interstellar travel and communication by Mallove, Forward, Paprotny, and Lehmann.[1] The present paper explores the potential of one specific propulsion system. It is a form of beamed-power propulsion in that the "engines" of the vehicle are left behind in the solar system and the power and reaction mass are transmitted out to the rest of the vehicle that carries the payload. This system will use large solar-pumped lasers to convert sunlight into coherent radiation, large lightweight optics to transmit the coherent laser beam over interstellar distances, and large lightweight reflective sails carrying the payload that are pushed by the momentum of the reflected laser photons. We will show how these systems can be designed so that the outward thrust of the solar system-based lasers not only can push the lightsails up to relativistic velocities, but also can be used to bring the lightsails to a stop in the target system, and then bring them back again.

Laser-Propelled Lightsails

The concept of using a spacecraft with a large lightsail appears to have been first conceived by Tsander[2] in 1924, possibly based on suggestions by Tsiolkovskiy.[3] These spacecraft were to obtain propulsive power from reflected sunlight and were called solar sails. The first American author to discuss solar sails was Wiley[4] in 1951, writing under a pseudonym in a science fiction magazine. The first detailed technical studies of the solar sail concept were papers by Garwin[5] and Tsu[6] in 1958 and 1959, respectively. These papers showed that the solar sail had a significant propulsion potential in the inner solar system, but since the solar light flux drops off as the square of the distance to the sun, the propulsion capability drops rapidly if one attempts to "sail" very far out in the solar system. As rocket ships, however, solar sails are unique in that these "rockets" require no reaction mass, no energy source, and no engine, and can operate continuously without refueling. Presently solar sails are being seriously considered for high-energy, deep-space missions, such as comet and asteroid rendezvous missions.[7]

The first operational laser was invented by Maiman in 1960.[8] Within months there were many other lasers operating at a variety of wavelengths in the infrared and visible. Many had output light fluxes that were many times the solar flux. Thus, lasers with their high flux of coherent light, can solve the decreasing-strength-with-distance problem of incoherent sunlight and would be a means to transmit energy from the sun to a distant lightsail leaving the solar system.

The first discussion of the use of lasers to propel a lightsail over interstellar distances was published by Forward in 1962.[9] At that time it also seemed obvious that the concept had to be limited to one-way flyby missions, since all the laser could do was push the lightsail away from the solar system and there was no way to stop the sailcraft at the target star. Even the time-integrated light pressure from a very bright star is not enough to decelerate a sail with a near relativistic velocity.

The concept of laser-pushed interstellar lightsails was reinvented by Marx[10] in 1966. Since Marx was unwilling to consider a laser aperture greater than 1 km^2, he was forced to assume the use of hard x-rays in order to obtain the operational ranges needed for interstellar flight. The impossibility of constructing both an x-ray laser and a lightweight sail to reflect those x-rays led to Marx's highly pessimistic conclusion about the feasibility of the concept. If Marx had been willing to consider a larger transmitter aperture, then his laser frequencies and sail requirements would have been much easier.

Marx's paper was followed by a paper by Redding[11] in 1967. Redding corrected an error in Marx's equations for the

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*Senior Scientist. Associate Fellow AIAA.

extreme relativistic case and concluded his paper with a reminder that there was still no way to decelerate the sailcraft at the target star system.

In 1969, however, two concepts that had been previously published by Forward, laser-propelled lightsails[9] and the use of electrically-charged spacecraft to turn in the interstellar magnetic field,[12] were combined by Norem[13] into a laser-pushed interstellar flight system that could stop at the target star. Norem's unique concept was to launch the lightsail with solar system-based laser, but not directly at the target star. Once it was up to speed, the sailcraft would let out long wires to increase its self-capacitance. Then, using either radioactive isotopes or a particle generator, an electrical charge would be induced on the spacecraft. As Forward had shown previously,[12] the charged spacecraft would experience a Lorentz force from its motion through the interstellar magnetic field that would cause it to move in a large circle. If the initial direction of the sail were chosen properly with respect to the orientation of the interstellar magnetic field, then the curving trajectory would take the spacecraft around behind the target stellar system and bring it in from the rear with the spacecraft velocity vector pointing at the solar system. The solar system laser would be turned on again, decelerating the sail and bringing it to a stop at the target star. The process could then be reversed (with a reversed electrical polarity) to return the spacecraft to the solar system. Norem's technique has the disadvantage that the total mission path length (and mission time) is increased by a factor of 3 or more by the circuitous path. There is also some doubt whether the interstellar magnetic field is strong enough to provide a reasonably small turning radius.

In this paper we propose another technique for rendezvous with and return from a target stellar system using a lightsail and a solar system-based laser. This technique uses a "multistage" lightsail, and is an expansion of our idea published previously[14] for a laser-pushed interstellar lightsail with deceleration capability. For a one-way rendezvous mission, there would be two stages, with only the smaller payload "stage" stopping at the target system. For a roundtrip mission there would be three lightsail stages. One stage would be used to bring the other two stages to a halt in the target system, then the second stage would be used to return the payload stage to the solar system. Many versions of these systems could be designed. The ones proposed here can deliver significant payloads to the nearest stars with reasonable mission times.

Sail Film Thickness Optimization

To optimize the performance of the laser propulsion system, maximum acceleration must be obtained out of the lightsail for a given laser power without wasting laser power or overheating the sail material. The acceleration of a vehicle of mass M and reflectance η driven by an incident laser power P is

$$a=\frac{2\eta P}{Mc} \tag{1}$$

where c is the velocity of light and the factor 2 comes from the double momentum transfer to the sail by the reflected photons.

The mass of the vehicle consists of the mass of the payload and structure plus the mass of the sail. If we assume that the ratio of the payload and structure mass to the sail mass is constant (typically ⅓ to ⅔), then for the optimization procedure we include the payload and structure mass in the effective density ρ of the sail material. The mass of the spacecraft is then just equal to this effective density times the area A and thickness t of the sail

$$M=\rho A t \tag{2}$$

When we substitute this into the acceleration Eq. (1), we get

$$a=\frac{2P}{cA}\frac{\eta}{\rho t} \tag{3}$$

where we have separated that portion of the equation $(\eta/\rho t)$ that depends on the parameters of the sail material. Thus, for maximum acceleration a sail material is needed that has high reflectance at low thicknesses and a low density. A brief search through handbooks on the reflectance of materials versus thickness, plus consideration of the ease of making thin films of those materials, leads rapidly to aluminum because of its high reflectance and low density compared to other highly reflective malleable materials such as silver, gold, copper, and platinum. These metals may have slightly higher reflectance than aluminum at some wavelengths, but are many times denser.

Once the density is fixed by the choice of material, then the important material parameter that remains in the acceleration equation is the ratio of the reflectance to the thickness, η/t. The reflectance of a thin film is not constant, but decreases from its bulk value with decreasing thickness. In Fig. 1 is plotted the reflectance η, transmittance, and absorption α versus thickness of thin films of aluminum for light at 650 nm wavelength. (We would have preferred Fig. 1 to be at 1 μm wavelength, since later we will assume a nominal laser wavelength of 1 μm, but 650 nm was the longest wavelength at which data was available.) The reflectance and transmittance were taken from a handbook,[15] and the absorptance was calculated from those values. We can see from the plot of the ratio η/t in Fig. 1 that if we are only concerned with maximizing the sail acceleration, then we want to make the sail thinner and thinner until η/t reaches the plateau below 4 nm (40 Å), where the reflectance falls off linearly with thickness.

At this infinitely thin sail limit, however, most of the laser power is passing through the sail and is wasted. A better optimization parameter would be one that includes the efficiency of a transfer of laser energy to the sail. Since this is proportional to the reflectance, a good choice would be to maximize the parameter η^2/t. This is also plotted in Fig. 1. As can be seen, this parameter peaks at 8 nm (80 Å) thickness. At this thickness, the reflectance is 63%, which, not surprisingly, is $(1-1/e)$.

Note, however, that the absorptance is not constant, but is higher than the bulk value at these thicknesses. This is because a good deal of the light is passing through the material where it can become absorbed instead of nearly all of the light being reflected. This absorbed power has to go somewhere, or else the aluminum film will rise in temperature until it melts. The only reasonable method of getting rid of the excess heat is to radiate it away. Under these conditions, the acceleration of the sail is limited by the power it can radiate.Equating the power absorbed in the sail with the power radiated by the surface of a sail of temperature T, emissivity ϵ, and two-sided area $2A$, we get[16]

$$P\alpha=2\sigma\epsilon A T^4 \tag{4}$$

where $\sigma=5.67\times10^{-8}$ W/m² K⁴ is the Stefan-Boltzmann constant. This equation assumes laser power in from only one side but thermal power out from both sides, and that the 2.7°K temperature of space is essentially zero. Combining Eqs. (3) and (4) to eliminate the laser power P, we get the acceleration as limited by the sail temperature

$$a=\frac{4\sigma}{c}\frac{\epsilon\eta T^4}{\alpha\rho t} \tag{5}$$

(Note that the emissivity ϵ is the value at the radiation wavelength peak at temperature T, while the reflectance ρ and the

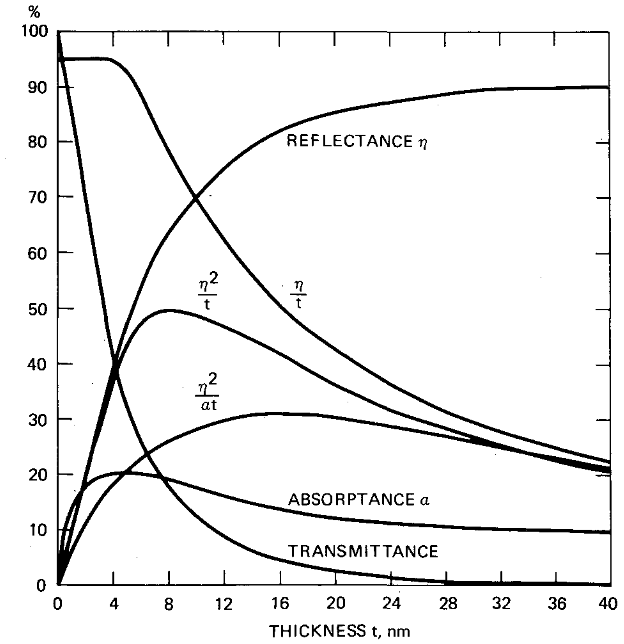

Fig. 1 Optical and thermal properties of thin aluminum films at 650 nm.

absorptance η are the values at the laser wavelength.) The emissivity of thin aluminum films is not well-known. The few measurements available on films indicate values not too far from the bulk emissivity of a polished sample ($\epsilon = 0.06$). The emissivity is known to increase slightly with temperature and should vary with thickness. Further measurements in this area are needed.

The emissivity of a surface also depends upon its microstructure. For example, a razor blade is quite reflective and has a low emissivity, but from edge on, a stack of razor blades looks like a black body. The thermal properties of a lightsail could probably be improved with negligible increase in mass by covering the back side with tiny aluminum whiskers with spacing and length tuned to the peak IR wavelength at the operating temperature of the sail. Experimental work needs to be done to verify this concept.

If we assume that the density of the sail material is fixed, and the emissivity and operational temperature of the sail do not vary much with sail thickness (they probably do, but the experimental evidence is lacking), then the important parameters that influence the choice of sail thickness for maximum acceleration are η, α, and t. If we want to optimize efficiency as well as acceleration, then the parameter we want to maximize is $\eta^2/\alpha t$. This parameter is also plotted in Fig. 1. We can see because of the increase in absorptance at low thicknesses, that this parameter peaks at a sail thickness of 16 nm (160 Å). At this thickness the reflectance is 82%, the absorptance is 13.5%, and 4.5% of the laser light passes through the sail material.

This choice for the sail thickness will vary with the wavelength of the laser (a similar analysis at 400 nm wavelength resulted in an optimum sail thickness of 20 nm), and further information or experimentation on the emissivity. For the rest of this paper, however, we will assume a thickness of the sail material of 16 nm (160 Å) of aluminum.

Since the density of aluminum is 2.7 g/cm³, this thickness of 16 nm gives an areal density β of the sail material of

$$\beta = \rho t = 0.043 \text{ g/m}^2 \tag{6}$$

The structure to support such a thin film has been designed by Drexler,[17,18] using a slowly rotating hexagonal truss of wires with ballast weights to provide tension. The structure mass for a sail greater than 10 km in size is estimated by Drexler to have an areal density of only 0.03 g/m². Thus, the total areal density for structure plus sail is 0.073 g/m². If we assume that the payload mass is approximately 1/e of the sail plus structure or 0.027 g/m², then the total sail density, including structure and payload, comes to 0.100 g/m². We will assume this value for the rest of the paper.

Temperature Limitations

Aluminum melts at a temperature of 660°C or 933°K. Long before those temperatures are reached, however, the ultrathin aluminum film in the sail will fail by agglomeration. Agglomeration occurs because thin films have a large ratio of surface to volume, permitting them to reduce their surface energy substantially by forming droplets.

Boiko et al.,[19] have heated a self-supported 1-cm² aluminum thin film 98 nm thick to 725°K and annealed it for 2 h at 700°K without agglomeration. Silver films agglomerated at 500°K, despite the fact that the melting point of silver at 1234°K is higher than that of aluminum. Drexler[17] feels that an aluminum oxide layer keeps the aluminum film from agglomerating. Boiko does not mention problems with agglomeration of aluminum below its melting point, but it is probably significant that in Boiko's paper emissivity data are given for five samples ranging in thickness from 67 to 115 nm before annealing at 700°K, while there are only data from two samples (98 and 105 nm) after annealing.

Since very long operational lifetimes are required from these films, temperatures should probably be kept below 600°K and the films should be exposed to some source of oxygen after space fabrication to produce the protective aluminum oxide layer. More study obviously needs to be done in this area, not only for laser lightsail propulsion, but for operation of high-performance solar sails in the inner portions of the solar system.

Laser Subsystem

The laser subsystem to provide the propulsion power for our interstellar sailing ships is the least well-defined part of the overall system. The power levels that will be needed are greater than we would want to generate on earth, since there exist better uses for the fuel. To get the power, it will be necessary to go into space and generate the necessary energy from sunlight. High-power lasers in space are reviewed in seven articles published in a special issue of *Astronautics and Aeronautics*.[20] In those papers, a number of candidate laser power systems are discussed. Some examples are carbon dioxide electric discharge lasers with 10 to 20% "wallplug" efficiencies at 10.6 μm wavelength;[21] directly solar-pumped iodine lasers with a 16% closed-cycle system efficiency at 1.315 μm wavelength;[22] and free-electron lasers with efficiencies between 30 to 50% at essentially any chosen wavelength.[23]

The very real problems of extending laser cw power levels from the present kilowatts and low megawatts to the gigawatts and terawatts needed for interstellar travel are not trivial. First, there are the engineering problems of scaling the present lasers to higher power levels, then making large numbers of these lasers operate as a coherent, phase-locked array. Second, there is the political problem of making the decision to spend technological resources for interstellar flight, rather than for some other goal. The purpose of this paper is to show that interstellar flight by laser-pushed lightsails is not forbidden by the laws of physics. Whether it can be engineered and is financially or politically feasible is left for future generations to determine.

As higher-power lasers are developed for use in laser fusion, laser rocket propulsion, and laser power transmission, it will be discovered which system is most practical for high-power, solar-pumped cw operation. At that time the operational wavelength will be fixed (unless the free-electron laser wins out). In the meantime, we will assume for the rest of this paper a nominal laser wavelength of 1 μm.

The size of the final transmitter aperture for an interstellar laser propulsion system must necessarily be large because of the large distances the light beam must be thrown. The final aperture of the laser transmitter subsystem does not have to be a solid lens. It can be a phased array of lasers or a thin-film holographic or Fresnel lens. The Fresnel lens approach seems to be the most feasible and is discussed in detail in the following section. Although a slightly smaller aperture might do for some missions, we will assume a diameter of 1000 km for the final laser array or lens.

If we assume laser radiation with a wavelength λ of 1 μm and a laser aperture with a diameter D of 1000 km, the aperture will focus the laser light at a distance s to a spot size d given by

$$d=2.4\,s\,\lambda/D \tag{7}$$

where the 2.4 factor indicates that the spot size diameter d is not measured at the half-power points, but at the points of the first null in the Bessel function for a circular aperture. (Actually, only 84% of the power is inside this first diameter, but for simplicity in the rest of the analyses, we will assume it is 100%.) For the 4.3 light year distance to α Centauri, this spot size is 98 km, or only 1/10th the size of the transmitting aperture, so the laser beam from a 1000 km aperture is still converging at 4.3 light years. The spot size for a 1000 km aperture would be equal to the aperture diameter at a distance of 44 light years.

The Thinned Array Curse

It might be thought that the construction of a 1000 km diam. aperture could be made easier by using an array of phased lasers in the shape of a circular annulus or a cross with a major dimension of 1000 km, leaving most of the array empty. This type of "thinned array" is known to produce high-resolution images in radio astronomy where the problem is to resolve a few "bright" sources in an otherwise "dark" sky. Unfortunately, thinned arrays do not work for power transmission and collection.

The reason for the failure of a thinned array to collect all the power passing through it is obvious. Any transmitted power that goes through a "hole" in the thinned array is lost. Thinned arrays also do not work as power transmitters, although the reason is not so obvious. Since, to our knowledge, the simple proof has not been published elsewhere, we will include it here.

To illustrate what O'Meara and Bridges call the "Thinned Array Curse",[23,24] assume we have n coherent radiators packed into a filled circular array with element spacing L. The diameter d of the array is then proportional to the square root of the number of elements times the array spacing

$$d \propto n^{1/2} L \tag{8}$$

This small-diameter filled array will radiate a wide beam whose diameter D between half-power points is inversely proportional to the array diameter

$$D \propto 1/d \propto 1/(n^{1/2} L) \tag{9}$$

On the axis of the array, each of the elements contributes a radiation field intensity e that is in phase with all the other radiation fields. (That is what is meant by the term "on axis".) The n elements in the array, therefore, contribute a total peak field intensity along the axis of

$$E=n\,e \tag{10}$$

The total power in the wide beam of the small filled array is then proportional to the peak power on axis times the area of the beam at its half-power point, or the square of the peak field times the square of the diameter of the beam at the half-power points

$$P \propto E^2 D^2 \propto n\,e^2/L^2 \tag{11}$$

If the n elements are now separated into a thinned array with element spacing m times larger, than the larger array diameter d' is given by

$$d' \propto n^{1/2} m\,L \tag{12}$$

The larger array gives a tighter beam, with diameter between its half-power points that is

$$D' \propto 1/d' \propto \frac{1}{n^{1/2} mL} \tag{13}$$

The peak field in that narrower beam, however, has not increased. There are still only n elements, each contributing a radiation field e on axis, so the peak field in the beam is still the value given by Eq. (10). Thus the total power in the narrowed beam is down by the factor m^2 or the ratio of the filled area to the empty area

$$P' = E^2 D'^2 \propto \frac{n\,e^2}{m^2 L^2} = \frac{P}{m^2} \tag{14}$$

The missing power, of course, will be found in the sidelobes. Thus, because of the "thinned array curse," filled arrays, lenses, or reflectors must always be placed at both ends of a power transmission system.

Beam Combiners

There will probably be an optimum size for a single laser generator and its solar energy conversion system. To get the total power needed for propulsion, the separate beams from each laser must be combined into one single coherent beam. Systems to do this have been designed for laser rocket propulsion.[25] The laser frequencies can be locked by using a common oscillator laser beam or stabilized oscillator lasers. These oscillator lasers are then followed by high-power lasers used as amplifiers. The separate laser beams are then sent to a segmented final mirror with each segment assigned to one beam. The phases of the different laser beams are then matched by varying the position of the reflector segment for each beam using phase detection methods and beam wavefront control techniques that have been developed by engineers working on laser fusion, laser rockets, and other high-power laser systems.

The lasers and the beam combiner will probably be in Earth orbit for early systems and closer to the sun for the later, high-powered systems. The lasers and their solar collectors could be in orbit about the sun, but more likely would be tied gravitationally to the mass of Mercury, so that the large light concentrators will not be "blown away" by the pressure of the sunlight. It might, however, be possible to design the collectors so that they use the reflected sunlight to "hover" above the sun rather than orbiting it. If so, then the pointing and tracking problem will be significantly easier.

Since the lasers will probably be in constant orbital motion about the sun while the direction to the target star (and the interstellar lightsail) stays fixed, there will be a significant pointing and tracking problem to be solved. To aid in tracking, the lightsail will carry a small pilot laser that will be aimed back at the solar system. Although primarily for tracking, the pilot beam could also be modulated for communication back to Earth. The pilot beam will run backwards through the entire optical system, including the turbulent gases in the driving lasers themselves. Any distortions along the whole beam path will show up as a distortion in the received pilot-beam wavefront. These distortions can be measured and the beam wavefront control mirror segments adjusted to insert a compensating distortion in the outgoing power beam so that the beam arrives at the lightsail undistorted. An alternative tracking technique that could be considered would be to use a beam-riding sail design and boresight the transmitter laser on the target star.

O'Meara Para-Lens

A suitable final-stage transmitting aperture for the laser subsystem would be a version of a Fresnel zone lens studied by O'Meara.[26] It is called a para-lens because of its similarity to a drag parachute used for stopping aircraft and race cars.

The basic structure of the para-lens is defined by radial spokes and cross members of wire in a spiderweb pattern. Attached to these wires are concentric rings of ultrathin plastic sheets of varying width that alternate with empty ring-shaped regions to form a Fresnel zone lens. The thickness of the plastic sheet is chosen so that the excess pathlength frequency through the plastic at the laser frequency is a half-wavelength of laser light.

The focusing effect of a Fresnel zone lens is illustrated in Fig. 2. If we assume a plane wave coming in from the left, then for some specific laser wavelength λ there is a certain point at a distance f along the axis that is the focal point for that wavelength. The distance from the center of any zone of radius r_n to that point is an integer number of half-wavelengths. At the focal point all the light rays from the even n zones are in phase with each other. In addition, since the plastic in the odd zones adds an extra half-wavelength to the path difference, the odd zones are in phase also. Thus, except for a slight bit of scattering due to the binary nature of the plastic phase plates, the para-lens acts like a solid disk lens.

The index of refraction n of all plastics is about 1.5. The half-wave thickness needed for the alternate phase-zone sheets is then

$$x = \frac{\lambda}{2(n-1)} \tag{15}$$

For a wavelength λ of 1 μm, and an index of refraction n of 1.5, this thickness is equal to the laser wavelength, or 1 μm. If we assume the use of a structurally strong but heavy plastic, like Kapton, with a specific density of 1.42, then the mass of a 1000 km diam. lens, with alternating rings empty and half-wave plastic, is 560,000 metric tons. This mass will vary, depending on the laser wavelength finally chosen. This is a significant mass, but not too much, considering the lens is a macrostructure that is one-third the diameter of the moon.

We will assume the para-lens is constructed between Saturn and Uranus at 15 AU (2.24×10^{12}m). The lens is not in orbit, but is either freely falling or "levitated" in place by rockets and/or by the momentum push from the portion of the laser light passing through it. At 15 AU from the laser source, the f-number of the lens is very large. With this large f-number, the required control of tolerances in the fabrication of the lens and the control of its shape during use, is surprisingly lenient. From the geometry of Fig. 2 we can derive a simple relation between the focal length f, the laser wavelength λ, and the radius r_n of the nth zone

$$f^2 + r_n^2 = (f + \frac{n\lambda}{2})^2 \tag{16}$$

or

$$r_n^2 = n f\lambda + \frac{n^2\lambda^2}{4} \approx n f\lambda \tag{17}$$

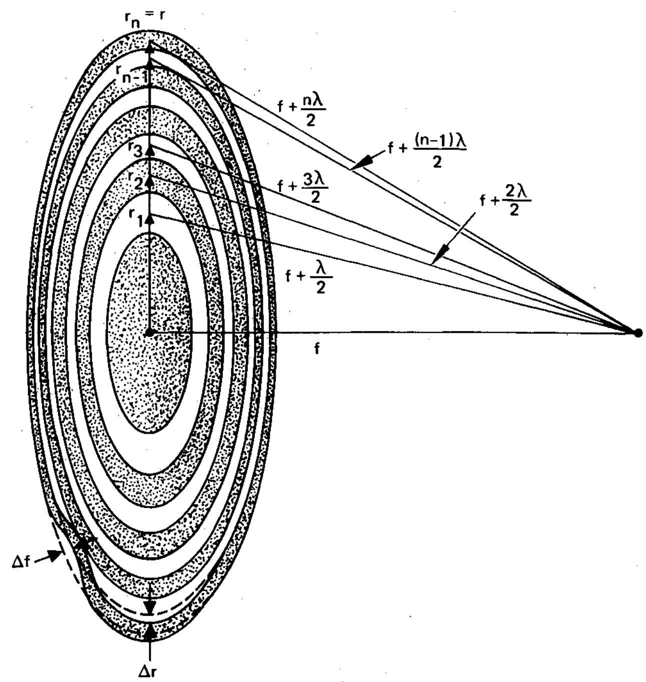

Fig. 2 Fresnel zone lens.

since $n\lambda \ll f$. From this relation, we see that the number of zones is

$$n = \frac{r^2}{f\lambda} = 111{,}410 \tag{18}$$

and the radius of the first zone is

$$r_1 = (f\lambda)^{1/2} = 1.5 \text{ km} \tag{19}$$

The spacing S between the centers of two adjacent rings (one empty and one with plastic film) is

$$S_n = r_n - r_{n-1} = [nf\lambda]^{1/2} - [(n-1)f\lambda]^{1/2} \tag{20}$$

Since the number of rings is large ($n \gg 1$) this can be approximated by

$$S_n = \tfrac{1}{2}(f\lambda/n)^{1/2} \tag{21}$$

or substituting Eq. (18) for n

$$S_n = \frac{f\lambda}{2r_n} \tag{22}$$

Thus, the spacing between the outer two zones (or equivalently the width of the plastic ring in the outermost zone) is

$$S = \frac{f\lambda}{2r} = 2.25 \text{ m} \tag{23}$$

showing that the fabrication of the rings will not require cutting the plastic to optical tolerances.

O'Meara[26] has derived from straightforward sensitivity analyses the fact that lens distortions causing changes in the distance to the focal point of Δf or changes in lens radius Δr (see Fig. 2) will cause a phase error at the focal point of

$$\Delta\psi = \frac{\pi r^2}{\lambda f}\frac{2\Delta r}{r} - \frac{\Delta f}{f} \tag{24}$$

If the phase error is to be less than $\pi/4$, then the sum of the lens errors must be less than

$$\frac{2\Delta r}{r} - \frac{\Delta f}{f} < \frac{\lambda f}{4r^2} \quad (25)$$

This means that the in-plane variations of the ring dimensions should be controlled to

$$\Delta r < \frac{sf}{8r} = 56\,\text{cm} \quad (26)$$

and the out-of-plane variations to

$$\Delta f < \frac{\lambda f}{4r^2} = 5000\,\text{km} \quad (27)$$

We see from these numbers that because the focal length of the lens system is very long, the wavefront is practically plane as it passes through the lens, so there is no concern for out-of-plane "flapping" of the lens. A simple slow rotation to keep the web structure taut and the axis of the lens lined up on the target star should provide sufficient stability. To keep the variations in ring radius below 0.5 m will be slightly more difficult, but by "tuning" the stretch of the spoke wires with adjustable ballast weights along the strands, it should be possible to make the rings circular to the required degree. (Note that it is only the variation in the ring radius about the mean that needs correction. An overall expansion or contraction of the lens is equivalent to a slight shift in focal length, which is easily compensated for.)

One-Way Interstellar Flyby Probe

The first interstellar mission to be sized is a near-term, one-way, unmanned, flyby probe mission to the nearest star. This mission will be limited in acceleration by the maximum temperature that the sail can take. If we assume a maximum operating temperature T of 600°K, a reflectance η of 0.82, an absorptance α of 0.135, an emissivity ϵ of 0.06, and an areal density of sail, structure, and payload β of 0.1 g/m^2, then the thermally limited acceleration is

$$a = \frac{4\sigma}{c}\frac{\epsilon\eta T^4}{\alpha\beta} = 0.36\,\text{m/s}^2 = 0.036\,\text{gravities} \quad (28)$$

If we assume a minimal weight probe with a total mass m of 1000 kg (roughly one-third each of sail structure and payload), then the diameter d of the sail is

$$d = \left(\frac{4m}{\pi\beta}\right)^{1/2} = 3.6\,\text{km} \quad (29)$$

The power needed to push this 1000-kg sail at the acceleration a of 0.36 m/sec^2 is

$$P = \frac{mca}{2\eta} = 65\,\text{GW} \quad (30)$$

While this is a great deal of laser power, it is well within future capabilities. Higher power levels than this are generated by the Space Shuttle rockets at liftoff. If the acceleration is maintained for three years, the interstellar probe will attain the velocity

$$v = at = 3.4\times10^7\,\text{m/s} = 0.11c \quad (31)$$

at the distance

$$s = \tfrac{1}{2}at^2 = 1.6\times10^{15}\,\text{m}$$
$$= 0.17\,\text{light years} \quad (32)$$

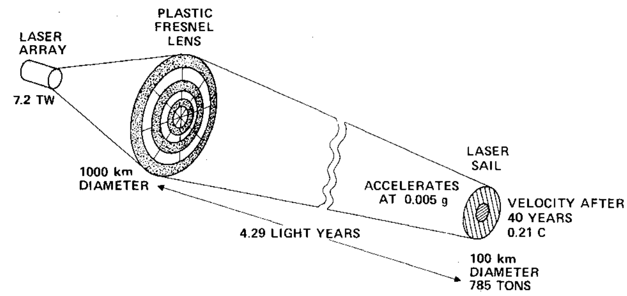

Fig. 3 Interstellar rendezvous mission-acceleration phase.

At this distance, the spot size d' of the laser beam as focused by the para-lens with diameter D of 1000 km is

$$d' = 2.4\,s\lambda/D = 3.8\,\text{km} \quad (33)$$

so that nearly all the laser power is still being captured by the 3.6-km-diam. sail. The laser is then turned off and the interstellar probe coasts to its target, reaching α Centauri at 4.3 light years' distance in 40 years from launch.

Interstellar Rendezvous Mission

If the discoveries made by the flyby probe generate interest in further explorations of the target system, the next phase of interstellar exploration would be to send a larger, unmanned spacecraft to rendezvous at the target star and explore it in detail. It might seem that since all the laser can do is push the lightsail, it would not be possible to use a solar system-based laser to stop the sail at the target system. By separating the lightsail into two parts, however, and using one part to reflect the laser light back toward the solar system, that retrodirected laser light can be used to decelerate the other portion of the lightsail.[14,27]

At launch, the lightsail for a rendezvous mission will have an initial diameter d of 100 km. With an areal density β of 0.1 g/m^2, the mass of the lightsail is 785 metric tons. If lightsail technology is assumed to have improved so that the back of the sail has microstructure that produces the effect of a nearly black body, then the average emissivity of the sail will be about 0.50 (0.95 on one side and 0.06 on the other). Maximum temperature-limited acceleration is now

$$a = \frac{4\sigma}{c}\frac{\epsilon\eta T^4}{\alpha\beta} = 3.0\,\text{m/s}^2 = 0.3\,\text{gravities} \quad (34)$$

With this improvement in maximum allowed acceleration capability, thermal considerations are no longer limitations, but maximum laser power limitations and mission time considerations are. Data should be returned from the mission in less than 50 years. Since 4.3 years are required to radio the information back from α Centauri, and a number of years to explore all the planets in the three-star system, only about 43 years should be spent getting there. This in turn implies an average trip velocity of 0.10 the speed of light c.

To minimize the laser power needed, we will assume a constant acceleration over the whole distance, rather than a high-power acceleration period followed by a coast period. Assuming an acceleration a of 0.05 m/s^2, the laser power required to push a 100 km diameter lightsail with a mass of 785 metric tons is

$$P = \frac{mca}{2\eta} = 7.2\,TW \quad (35)$$

(see Fig. 3). It should be noted at this point the total power output of the entire world is about 1 TW. This amount of laser power is not trivial and will require a significant commitment to build a large array of solar-powered lasers in space.

The diffraction limited spot size of the 1000 km diameter para-lens at 4.3 light years is

$$d' = 2.4\,s\lambda/D = 98\ \text{km} \tag{36}$$

which is less than the diameter of the lightsail, all the laser power is thus striking the lightsail and the acceleration remains constant during the boost phase. Under a constant acceleration of 0.05 m/s^2, the time it takes to travel the distance of 4.3 light years is 40 years. At the end of this constant acceleration period, the lightsail has reached the velocity of 0.21 c. The rapidly traveling lightsail is now approaching α Centauri and now must decelerate.

The lightsail is built in two sections, an outer doughtnut-shaped ring, and an inner circular section 30 km in diameter. This 30 km payload section of the sail has a mass of 71 metric tons, including a science payload of 26 metric tons. The remaining, ring-shaped "decel" stage has the mass of 714 metric tons, or ten times the smaller payload "stage".

The central payload section of the sail is detached from the larger stage and turned around so that its reflecting surface faces the reflecting surface of the ring-shaped portion (see Fig. 4). At a time 4.3 years earlier, the laser power from the solar system was upgraded to 26 TW (there are 37 years to get ready for this increase in power). The stronger laser beam travels across the space to the larger ring sail. The increased power raises the acceleration of the ring sail to 0.2 m/s^2, and it continues to gain speed. The light reflected from the ring sail is focused onto the smaller sail, now some distance behind. The light rebounds from the 30-km sail, giving it a momentum push opposite to its velocity, and slowing it down. Since the smaller sail is 1/10 the mass of the larger one, its deceleration rate is 2.0 m/s^2, or 0.2 g. The light flux on the smaller sail has increased considerably, but it is only two-thirds of the maximum light flux that the sail can handle.

At a deceleration rate of 2.0 m/s^2, the time required to bring the payload sail to a stop in the α Centauri system is only 1 year, making a total trip time of 41 years. The distance the two portions of the sail have separated during the deceleration period, with one portion increasing its speed and leaving the star system, and the other decreasing its speed and stopping, is only 0.12 light years. The spot size for the ring sail lens with a diameter of 100 km at a distance of 0.12 light years is only 27 km, so all the light from the larger sail is captured by the 30 km diameter payload sail during the entire deceleration period.

There are many versions of this basic concept. One of them uses higher initial laser power to get the sail up to the 0.2 c coast velocity sooner; the laser is then used to launch other probes while the first coasts out to the target star. All versions need further study.

Roundtrip Journey by Interstellar Lightcraft

If the reports from the interstellar rendezvous probes are favorable, then the next phase would be to send a human crew on an interstellar exploration journey. Although a typical interstellar mission will literally last a lifetime, and a reasonable case could be made for a one-way journey,[27] increasing the capabilities of the laser lightsail system will get the crew to its objective and back as fast as possible.

More than just the nearest star system will be ultimately explored, so we will design the laser lightsail system to allow roundtrip capability out to 10 light years, e.g., to ϵ Eridani at 10.8 light years (see Fig. 5). We will assume the diameter of the lightsail at launch to be 1000 km, the same size as the transmitter lens. With an areal density of 0.1 g/m^2 it will mass 7.85×10^7 kg, or 78,500 metric tons. The crew must be transported as fast as possible, so we will accelerate at the thermally limited acceleration of 3.0 m/s^2. The power needed

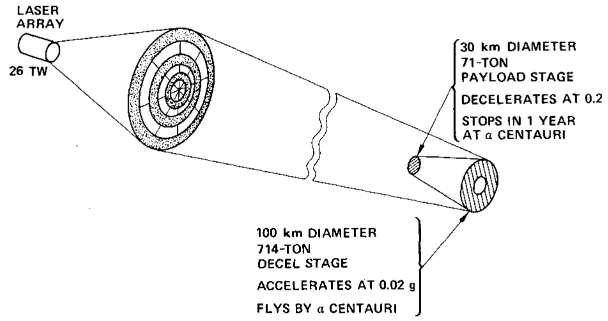

Fig. 4 Interstellar rendezvous mission-deceleration phase.

during the launch phase is formidable

$$P = \frac{mac}{2\eta} = 4.3 \times 10^{16}\,W = 43{,}000\ TW \tag{37}$$

At this rate of acceleration the lightsail will reach a velocity of half the speed of light in 1.6 years. We could continue accelerating to higher cruise velocities, but for this preliminary analysis we will assume a 0.5 c cruise velocity. (There are also going to be severe problems with radiation and damage from interstellar particles and dust at these speeds.)

At a velocity v of 0.5 c, the relativistic factor

$$\gamma = (1 - v^2/c^2)^{1/2} - 0.87 \tag{38}$$

is a 13% correction to the mass of the lightsail and the aging of the crew, while the Doppler effect has lowered the frequency and energy of the laser beam by the ratio

$$\frac{v}{v'} = \left(\frac{c - v}{c + v}\right)^{1/2} = 0.58 \tag{39}$$

Thus, if we want to provide a constant acceleration, the laser power would have to be increased from 43,000 TW at the start to 75,000 TW or more at the end of the acceleration phase. The distance covered during the acceleration period is only 0.4 light years, so the remainder of the 10-light year trip to the outskirts of ϵ Eridani at 0.5 c will take 20 years earth clock time and 17.3 years crew clock time. At 0.4 light years from the star, the 320-km-diam. rendezvous portion of the sail is detached and the deceleration technique described previously is applied. The 320-km-rendezvous sail has a mass of 7850 metric tons, of which about 2900 metric tons is the mass of the crew and habitat, supplies, and exploration vehicles. This is more than sufficient to land on and explore a number of planets, especially since the rendezvous sail can use the starlight from ϵ Eridani for transportation within the planetary system.

The incident laser power needed to decelerate this 320-km-diam. lightsail at the thermally limited acceleration of 3.0 m/s^2 is one-tenth the initial launch power or 4,300 TW. The 245-km-diam. spot size of the laser beam focused by the 1000-km-diam. lens at 10.8 light years is smaller than the 320-km-diam. sail, so all the transmitted photons in the main beam are collected by the lightsail.

The power emitted by the laser system based on Earth will have to be significantly larger than 4,300 TW. First, there is the 16% of the laser power that is outside the central spot in even a diffraction-limited system. Then there is the 11% loss of laser energy through the central hole of the decelerator-stage ring sail, plus the 13% excess relativistic mass of the sail at the start of the deceleration period. Finally, there is the decrease in energy of the photons by the Doppler redshift. This Doppler shift varies with time and is complicated by the reflection of the laser light from the moving mirror of the ring sail. At the beginning of the deceleration period, the 0.5-c

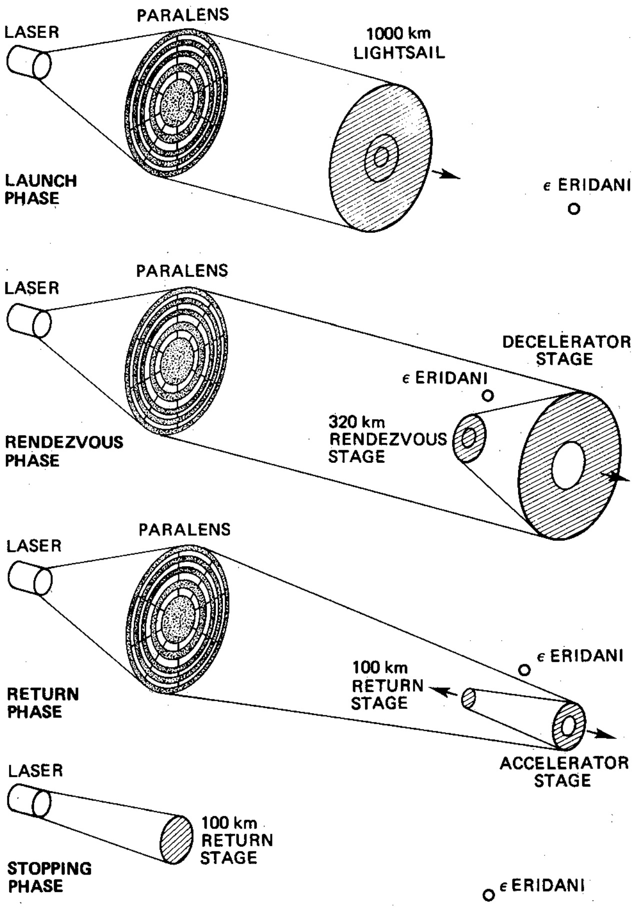

Fig. 5 Propulsion phases of roundtrip interstellar travel using laser-pushed lightsails.

velocity of the two lightsails causes a frequency shift in the laser light to 58% of the original laser frequency [see Eq. (44)]. At the end of the deceleration period, the rendezvous sail and the laser have the same relative velocities, but the laser, as seen in the reflecting mirror of the decelerator-stage ring sail, moving away at a velocity V of 0.5 c, has an effective retreating velocity of

$$v=2\,V/(1+V^2/c^2)=0.8\,c \qquad (40)$$

and the energy of the redshifted photons is down by a factor of 3.

If we assume that the laser power emitted in the solar system is varied to maintain constant sail acceleration, the deceleration time will be the same as the acceleration time or 1.6 years. This gives a travel time to ε Eridani on Earth clocks of 23.2 years for the 10.8-light year distance and slightly less time (20.5 years) on the lightcraft clocks.

After the crew has explored the system for five years or so, it will take time to bring them back. To do this, we separate a 100 km return sail from the 320 km rendezvous sail. Moving it a short distance away, the return section is rotated to face the larger, ring-shaped sail that remains. The light from the lasers back in the solar system, having been turned on 10.8 years previously for a period of 1.6 years, has generated a 1.6-light year-long slug of laser light that strikes the ring sail. Both lightsails accelerate, the return sail acceleration of 3.0 m/s^2 being nine times the acceleration of the more massive "accel" stage ring sail. After 1.6 years, the return sail with the crew and their return samples has been accelerated to 0.5 c. As the sail approaches the solar system 20 Earth years later, it is brought to a halt in the solar system by a final burst of laser power. The members of the crew have been away about 51 years (including 5 years exploring), and have aged about 46 years.

Conclusion

Laser-pushed lightsail systems provide a method for traveling to the stars that use known laws of physics and fairly reasonable engineering extrapolations of known technologies in thin films and laser power generation and transmission. They have a highly significant advantage over a standard rocket system in that the vehicle does not have to carry any reaction mass or energy source. In addition, the parts of the "engine" under the most stress and need of maintenance, the laser power generators, remain in the solar system where they can be repaired, replaced, and upgraded as the mission proceeds.

Laser lightsail systems are wasteful of power, since the high "exhaust velocity" of the reflected photon "reaction mass" is poorly matched to the spacecraft velocity, except at near-relativistic speeds. They also require the construction of very large but lightweight structures, since the optics must be of the order of 1000 km in diameter to enable us to carry out rendezvous and return missions from the nearest stars.

The pointing and tracking requirements look formidable, especially considering the years-long time delays in the control loops, but with the use of a pilot beam they should be solvable. Making the ring-shaped lightsail act as a focusing lens in order to achieve the rendezvous and return missions is also a major unstudied problem. The present sail designs are not known for their optical quality, and to get focusing will require sensing and shape control systems or reflective holographic or Fresnel lens construction that will add weight.

It may be that other techniques will be developed for interstellar travel that will require less power and mass, and be faster and less risky than subjecting an ultrathin spacecraft to 600°K for years at a time. But it is good to know that there exists at least one method, laser-pushed lightsails, that can take humans to the nearest stars and back in a reasonable time.

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