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Laser Elevator: Momentum Transfer Using an Optical Resonator

Thomas R. Meyer*
Boulder Center for Science and Policy, Boulder, Colorado 80306
Wayne R. Pryor†
University of Colorado, Boulder, Colorado 80309
Christopher P. McKay‡
NASA Ames Research Center, Moffett Field, California 94035
and
Paul M. McKenna§
National Telecommunications and Information Administration, Boulder, Colorado 80305-3328

In principle, spacecraft that do not carry their own propellant but are propelled by the transfer of momentum of photons can be accelerated to very high velocity. The subject of this research is a laser propulsion system utilizing the momentum of photons recirculating in an optical cavity that consists of a mirror on the spacecraft and a mirror fixed at the laser source. This configuration allows the photons in the beam to be recycled, thus multiplying the effective power of the laser. The gain of this system over a conventional lightsail depends on the number of times the photons can be recycled. We analyze the physics of this propulsion method, compare it with rockets, and examine its use for several cases of interest. We find that improvements in thrust on the order of 1000 over conventional lightsails may be feasible using mirrors whose reflectivity is 0.9995, but that diffraction sets the limit on system performance as the cavity expands. However, a system not too far from the current state of the art could reach Pluto in about 6.5 years. Other potential applications include rapid interplanetary delivery, reconnaissance of a new comet, and probes beyond the solar system.

Nomenclature

a = acceleration of the payload, m/s^2
c = speed of light, m/s
D = laser diameter, m
d = mirror diameter, m
E = total optical energy in the laser beam, J
E_R = energy for an idealized rocket to achieve a velocity Δv, J
E_S = energy for a one-bounce laser sail to reach velocity Δv, J
e_R = energy per unit payload mass for rocket to reach velocity Δv, J/kg
e_S = energy per unit payload mass for one-bounce sail to reach Δv, J/kg
F = force exerted by optical energy on payload, N
$\mathcal{F}$ = fraction of energy in Airy pattern enclosed by sail
g = acceleration of gravity, m/s^2
h = Planck's constant, J
k = atmospheric extinction coefficient, m^{-1}
L = total power loss, W
L_a = atmospheric extinction power loss, W
L_r = reflectivity power loss, W
m = mass of the entire payload with reflector, kg
m_f = final mass of empty rocket, kg
m_0 = initial mass of rocket including fuel, kg
N = ratio of E_R to E_S
P = laser optical power in the upward moving photons, W
P_i = input power supplied to the laser system, W
Q = figure of merit of optical cavity
S_d = diffraction distance, m
t = time, s
u = rocket exhaust velocity, m/s
v = payload velocity, m/s
v_c = crossover velocity, at higher Δv the laser sail is more efficient than a rocket, m/s
z = distance between target mirror on spacecraft and fixed mirror at laser source, m
α = absorptance of the mirror
β = numerical factor of order unity characteristic of beam divergence
ε = efficiency of laser elevator
η = reflectance of the mirror
η_s = fraction of reflected light that does not reach the opposite mirror
$\eta_\perp$ = fraction of the reflected light that reaches the opposite mirror
θ_d = divergence angle (from perpendicular) for beam, rad
λ = wavelength of laser radiation, m
ν = frequency of laser radiation, s^{-1}

Introduction

CONTINUING advances in high-power lasers and mirror technology make laser propulsion an attractive way to propel spacecraft from a distance. One approach, called laser thermal propulsion, uses lasers as the energy source to accelerate a propellant from a rocket.[1] A review on work in this area[2] indicates that laser thermal propulsion is a promising technology. A system for low-cost launch to orbit has been described in Refs. 3 and 4.

A second approach, laser lightsail propulsion, uses the momentum of photons in the laser beam to provide thrust without the use of fuel. Forward[5] has reviewed laser lightsails in the context of nearly light-speed interstellar travel. Meyer et al.[6] considered the physics of delivering payloads of 10 kg to Mars in 10 days using a laser lightsail vehicle delivery system. The lightsail would be accelerated to a velocity of ~175 km/s by a ground-based or orbiting high-power laser. The properties of efficient lightsail reflector materials have been discussed by Matloff,[7] Forward,[8] and Landis.[9] High reflectivity omnidirectional dielectric thin film reflectors have been

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*Senior Research Associate, Propulsion Research Group, P.O. Box 4877; meyertr@colorado.edu. Member AIAA.
†Research Associate, Laboratory for Atmospheric and Space Physics.
‡Research Scientist, Space Science Division. Member AIAA.
§Electronic Engineer, Institute for Telecommunications Sciences, 325 Broadway.

proposed by Fink et al.[10] Extremely lightweight high-temperature carbon microtrusses for use in fabricating lightsails have been described by Knowles et al.,[11] and lightweight truss boom technology for solar sails has been discussed by Brown.[12]

The concept described in this paper was first introduced in 1987 (Ref. 13), but advances in high-power lasers and optics have only recently begun to make applications potentially feasible, thus motivating the preparation of this paper.

In this paper, we consider laser lightsail propulsion and present a conceptually new approach called the laser elevator, which has the potential for significantly greater efficiency than conventional lightsail propulsion. By conventional lightsail propulsion, we mean a system where a laser beam, emanating from a source external to the spacecraft, is directed against the reflective sail of the spacecraft. This system is highly inefficient because the beam is discarded after one reflection and must be continuously replenished. Furthermore, due to the unfavorable relationship of momentum to energy for photons, only a small amount of the energy from the beam is transferred to the spacecraft, and most of the energy remains in the beam after reflection.

The system considered in this paper is one where the reflected energy is recycled. The basic configuration is one in which the laser beam is made to oscillate between two opposing mirrors, one on the spacecraft and the other fixed at or near the laser source. Because the laser beam is made to oscillate between the two mirrors, the photons transfer momentum to the payload each time they recirculate. Because of the analogy between a mirrored platform being raised on a column of light and an elevator whose platform is raised from beneath by a piston, this propulsion concept is called a laser elevator.

The principal theoretical advantage of lightsail propulsion, even conventional lightsail propulsion, is that its energy efficiency exceeds that of rockets when accelerating payloads to sufficiently high velocities. This advantage results from the fact that, although lightsail systems can be inefficient, they are not subject to exponential energy requirements to achieve increasingly high velocities as are rockets because lightsail craft do not carry their own propellant. However, the theoretical velocity crossover point at which conventional laser lightsail systems become more efficient than rockets is sufficiently high (about 60 km/s in the case studied) that even the most modest payloads (tens of kilograms) require impractical laser power levels (tens of gigawatts) for rapid delivery (10 days) over interplanetary distances [1 astronomical unit (AU)] (Ref. 6). By contrast, systems such as the laser elevator, where the laser energy is recycled, offer the potential for one or more orders of magnitude improvement in energy efficiency over conventional lightsails, thus making them potentially competitive with rockets for objectives such as launch to orbit, orbital transfer, rapid interplanetary delivery of small payloads, and probes beyond the solar system.

To appreciate the design challenges of the laser elevator it is useful to consider briefly some of the fundamental aspects of lasers. Laser resonators differ from those used in the microwave field (masers) in that the cavity is open and the resonator dimensions ($\sim$1 m) are much greater than the wavelength ($\sim 10^{-6}$ m). The large size of the resonator compared to the wavelength of light used allows for an enormous number of modes. A laser operates by the successive amplification of those few modes corresponding to a superposition of waves traveling nearly parallel to the resonator axis; all other modes will be lost after a single pass due to the open cavity.[14] Stability of the resonator requires that the beam does not walk off the mirrors after repeated reflections or from a small misalignment. Mirror configurations that are stable, and for this reason the ones most widely used in lasers, have two concave mirrors (or one concave and one flat mirror) with large radii of curvature (2–10 times) compared to the separation between mirrors.

The problems associated with the design of the laser elevator are greatly increased because the separation between the mirrors in the resonator cavity is greatly increased. In a standard laser the mirror separation is $\sim 10^6$ times the wavelength, whereas in the laser elevator it is 10^{12}–10^{14} times the wavelength. Thus, the unique challenge of the laser elevator is to extend by a factor of 10^6–10^8 the conditions that allow for mode-locked propagation over distances much larger than the wavelength of light. One approach is to consider the ground-based lasing medium and laser mirrors as separate from the two mirrors in the laser elevator. The precise (fraction of a wavelength) optical alignments in a laser may not be compatible with launching one end of the laser into space. However, many bounces may still be possible between a ground-based mirror and a rising mirror/sail fed by a beam extracted from a ground-based lasing cavity. Figure 1 illustrates this concept, with beam divergence exaggerated. In this paper we examine the physics of laser elevators, characterize their loss mechanisms, and then analyze their effectiveness for achieving various objectives.

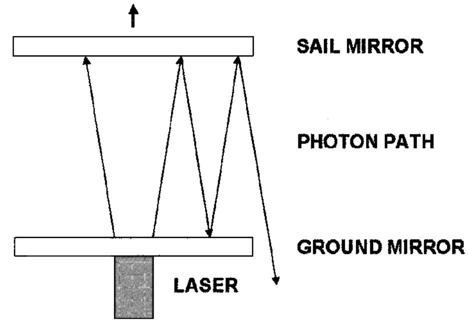

Fig. 1 Laser elevator; imperfections limit the number of useful bounces.

General Considerations

Rockets eject mass to provide thrust. In a chemical rocket the kinetic energy of the exhaust is derived from combustion of the propellant. There are also systems in which the propellant is inert and energy is supplied by external transmission as in laser thermal rockets. In either system the unspent propellant must be accelerated along with the payload, which severely inhibits rocket performance, particularly at high velocities. In the lightsail concept the force to propel the payload is derived from the momentum of a light beam supplied from an external source, so that no onboard propellant is required.

For the lightsail, the force F on the target mirror is proportional to the power P in the incident beam and depends on the reflectivity η and absorptivity α of the mirror[6]:

$$F = (2\eta + \alpha)(P/c) \tag{1}$$

The factor 2 on η owes to the fact that twice the photon momentum will be imparted to the sail if the photon is reflected as compared to if it is absorbed. If we assume there is no transmittance, then $\eta + \alpha = 1$, and so we can write Eq. (1) as

$$F = (1 + \eta)(P/c) \tag{2}$$

Here we have assumed that the reflectivity is mirrorlike and that the angle of incidence is close to 90 deg. We have neglected that mirrors that exhibit specular reflection also have a small diffusely scattered component usually expressed as the bidirectional reflectance distribution function (BRDF), which would need to be considered in a full engineering design. Typical commercial low-loss mirrors have a BRDF of 10^{-5}–10^{-6}, $\eta = 0.9997$, optical loss $\sim$50 ppm, and surface microroughness <1 Å rms.

For reasonable values of the parameters in Eq. (1) the power level is enormous; gigawatts are required to impart a 1-g acceleration to a 1-kg object. However, this power level is misleading in the sense that after the beam reflects off of the payload most of this power is still available to do useful work, if it can be redirected toward the target again. In the laser elevator concept the light beam is recycled, and thus, there is a potential for great savings in total energy required.

The average power in the laser elevator can be related to the total energy in the beam by noting that the time it takes for the beam to circulate once is given by $2z/c$, where z is the separation between the target mirror and the fixed mirror, and c is the speed of light. The average power is then the total energy divided by this round-trip time:

$$P = Ec/2z \tag{3}$$

For example, a laser elevator 1 m in length that contains a total energy of only 10 J gives a power level of 1.5 GW. Thus, if the light beam is redirected toward the target repeatedly, the amount of energy required to achieve gigawatt power levels is surprisingly low.

This counterintuitive result can be illuminated by the use of a simple example. If we consider the light coming from a 1-W flashlight for a total period of 10 s, both the power (1 W) and the total energy (10 J) are small and well within understandable parameters. However, that light beam exiting the flashlight is spread over 10 light seconds distance ($\sim 3 \times 10^9$ m). If the beam were to be compressed into a distance of 1 m the total energy would still be 10 J, but the power would now be 3 GW. Physically, it is the large value of the speed of light that results in these seemingly peculiar relations.

Another way to look at this is to consider the nonrelativistic ratio of energy to momentum for a particle:

$$\frac{\text{energy}}{\text{momentum}} = \frac{\frac{1}{2}mv^2}{mv} \propto v \tag{4}$$

Hence, the ratio of energy required to impart a certain momentum scales as the velocity of the particle. More specifically, for an elevator concept as discussed here, the energy required to support a payload with any type of recirculating particles, even massive ones, is related to the particle velocity and the length of the elevator. In practice, of course, a gigawatt light beam circulating between two mirrors separated by 1 m will be rapidly dissipated due to system losses. In fact, in a laser elevator system the power required to levitate or accelerate a payload is virtually all due to the losses in the system. In general these losses occur principally as a result of three processes: nonperfect reflectors, atmospheric extinction, and diffraction. These will be analyzed in the next section.

Basic Equations

The efficiency with which an incident laser beam imparts energy to the payload can be determined by considering the impact process for a single photon. Initially, a photon moving toward the payload has a given momentum $h\nu/c$. After reflection from the payload, the photon now has momentum in the reverse direction of magnitude $h\nu'/c$, and the payload has gained a velocity increment Δv. The initial and final states of a photon collision with the payload are shown in Fig. 2, resulting in a small change in momentum of the photon.

If the target mirror is initially moving at velocity v, then the frequency drop due to the motion of the target can be computed using conservation of momentum

$$h\nu/c + mv = -(h\nu'/c) + m(v + \Delta v) \tag{5}$$

and conservation of energy

$$h\nu + \tfrac{1}{2}mv^2 = h\nu' + \tfrac{1}{2}m(v + \Delta v)^2 \tag{6}$$

We solve for Δv in Eq. (5) and substitute into Eq. (6). Defining $\bar{\nu} = (\nu + \nu')/2$ and $\Delta\nu = \nu' - \nu$, we obtain

$$\Delta\nu/\bar{\nu} = -2v/c + -2h\bar{\nu}/mc^2 \simeq -2v/c \tag{7}$$

The validity of the approximation stems from the rest mass energy of the vehicle mc^2 being vastly greater than the energy of the photon $h\nu$.

Because the energy in the beam is proportional to ν, the energy loss due to the impact is given by

$$\Delta E/E = \Delta\nu/\nu = -2v/c \tag{8}$$

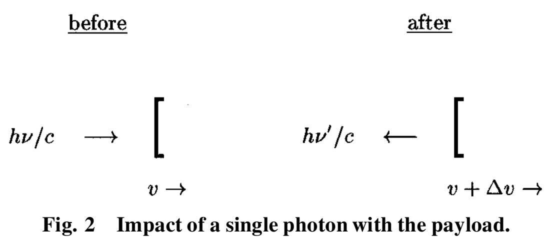

Fig. 2 Impact of a single photon with the payload.

This reduction in the energy of the reflected laser beam is the result of the energy that was imparted to the payload. This reduction represents the useful work done by these photons. An alternate derivation of Eq. (8) could be obtained from considering the force experienced by the payload and computing the work done on the payload divided by the energy in the laser beam. As ΔE becomes larger, approaching E, the more efficient is the transfer of energy from the laser beam to the payload. Clearly, for velocities less than the speed of light, $\Delta E \ll E$. Thus, a laser lightsail has the interesting property that the faster it goes compared with the speed of light, the more efficient it becomes.

In an actual laser elevator there would be a large number of photons continually moving between the payload mirror and the mirror at the source. It is, therefore, more convenient to cast the momentum and energy equations in continuum form. We consider the basic equations that describe the motion of the payload and the energy balance of the laser elevator in a gravitational field in the nonrelativistic limit. The momentum equation can be expressed as follows:

$$(2\eta + \alpha)E/2z - mg = ma \tag{9}$$

Physically, Eq. (9) states that the force of the laser light in the cavity, less the force of gravity, results in an acceleration of the payload. The conservation of energy equation can be expressed in terms of the change in energy in the beam between time t and the initial time. This change is balanced by the integrated source and loss rates of energy over time and changes in the kinetic and potential energy of the payload:

$$E(t) - E_0 = \int_0^t P_i(t)\,\mathrm{d}t - \int_0^t L(t)\,\mathrm{d}t - \frac{1}{2}m\left(v^2 - v_0^2\right) - mg(z - z_0) \tag{10}$$

A more useful form of Eq. (10) can be derived by differentiating and solving for the input power:

$$P_i = \frac{\mathrm{d}E}{\mathrm{d}t} + L + mav + mgv \tag{11}$$

Remember that P_i is the total power added to the laser beam and E is the total optical energy of the beam and does not include the energy of the payload. L is the total dissipative loss rate of radiative energy from the laser beam including absorption and diffraction. The L term does not include the diminution of the optical energy in the laser beam due to energy imparted to the payload by reflected photons. The last two terms in the equation represent the energy transferred into the kinetic and potential energy of the payload, respectively. Physically, Eq. (11) states that the power that must be supplied to the beam must compensate for increases in the energy stored in the beam, any optical losses, plus increases in the kinetic and potential energy of the payload.

Dissipative Loss Terms

The dissipative losses in beam energy result principally from absorption and diffraction. We consider these losses here in a simplified heuristic discussion in which we first treat the beam as a discrete packet bouncing between two mirrors that are moving very slowly compared to the speed of light and then consider these loss terms in the continuum equations.

There are three types of losses to be analyzed: 1) reflectance loss resulting from less than perfect reflectance, 2) absorption and scattering in the optical path between the two mirrors, and 3) diffraction loss due to spreading of the beam.

When the losses are analyzed, it is useful to keep in mind the potential situations in which the laser elevator might operate. Two potential applications are 1) launching of payloads from the surface of the Earth to low Earth orbit and 2) injection of payloads from Earth orbit into higher (stationary) orbits or into interplanetary trajectories. In the first case the distances between the mirrors are fairly small and the losses are dominated by absorption in the mirrors and atmospheric extinction. In the second case, there is no absorbing medium, and the path lengths are sufficiently long that diffraction rapidly dominates the loss rate.

Reflectance Loss

Loss due to imperfect reflectance at the mirrored surfaces is a major loss term, particularly at small distances when atmospheric extinction and diffraction are negligible. It is useful to consider the decay of an initial beam due to the reflectance loss at the mirrors by treating the beam as a discrete packet of photons. Because of the finite absorption of each mirror, on each reflection the number of photons in the packet is reduced to η times its earlier value. Not all of the energy reflected off the mirror η remains in the resonant cavity. Because of small imperfections in the mirror surface some component of the reflected light will be reflected with a sufficient angle to remove the light from the axial beam after being propagated over the distance between the mirrors. For this reason, we let η be composed of two components:

$$\eta = \eta_\perp + \eta_s$$

where $\eta_\perp$ is the fraction of the incident light that is retained in the axial beam and that continues to circulate between the mirrors and η_s is the fraction of the reflected light that is scattered out of the axial direction. Note that $\eta_\perp$ will decrease as the separation between mirrors increases because small angular scattering will result in increasingly larger lateral offsets as the distance increases. In the following discussion, we treat $\eta_\perp$ as constant.

After each round trip hitting two mirrors, the beam power is reduced by $\eta_\perp^2$. The mirror absorptions are assumed to be identical. After another round trip the beam is reduced by the factor $\eta_\perp^4$, and so on. Summing the contribution from each subsequent impact of the laser beam on the payload, we can write

$$F = (2\eta + \alpha)(P/c)\left[1 + \eta_\perp^2 + \eta_\perp^4 + \eta_\perp^6 + \cdots\right] \tag{12}$$

where F is the total force on the payload and the term $(2\eta + \alpha)P/c$ is the force due to the first reflection as given in Eq. (1). This series can be summed analytically to give

$$F = \frac{(2\eta + \alpha)P/c}{1 - \eta_\perp^2} \tag{13}$$

For a value of $\eta_\perp = 0.99$, the increase in momentum transfer of the recycled beam over the single impact is ~50; for $\eta_\perp = 0.9999$, the increase is 5000.

In the continuum form of the energy equations, the loss term due to reflection L_r is determined by the fraction $1 - \eta_\perp$ of the power that is lost from the axial beam at each mirror. Thus,

$$L_r = 2(1 - \eta_\perp)P = (1 - \eta_\perp)(Ec/z) \tag{14}$$

where the final equality is obtained by use of Eq. (3).

Atmospheric Loss

Atmospheric extinction is due to absorption and scattering of photons during the transmission of the laser beam through the Earth's atmosphere. It can be minimized by selection of suitable wavelengths. The atmosphere has significant windows in the visible and near infrared (0.3 − 10 μm) (Ref. 15). In general the reduction due to atmospheric extinction in a one-way trip between the two mirrors is given by e^{-kz}, where k is the average extinction coefficient of the atmosphere at the wavelength of the laser beam. As before, it is useful to consider the decay of an initial beam by treating the beam as a discrete packet of photons. Now, if we include atmospheric extinction in addition to the finite absorption of each mirror, on each reflection the beam becomes $\eta_\perp e^{-kz}$ times its earlier value. Thus, after each round trip hitting two mirrors, the beam power is reduced to $\eta_\perp^2 e^{-2kz}$ of its earlier value.

As in Eq. (13), the result of the summation of the contribution from each round trip can be written as an infinite series and summed analytically to give

$$F = \frac{e^{-kz}(2\eta + \alpha)P/c}{1 - \eta_\perp^2 e^{-2kz}} \tag{15}$$

In terms of the continuum equations the losses due to atmospheric extinction can be represented as

$$L_a = 2kzP = kEc \tag{16}$$

The larger the separation between the payload and the mirror, the larger are the losses due to atmospheric extinction. The path length through the entire atmosphere is simply the atmospheric scale height ($z \simeq 8$ km) with a correction factor due to the zenith angle, θ ($\simeq \cos\theta$). The term $2kz$ that scales the atmospheric extinction to the incident power can be compared directly with the corresponding term for losses due to absorption at the mirrors, $2(1 - \eta_\perp)$ in Eq. (14). Because their combined effect is the sum of the two terms, the gain of the laser elevator over a conventional lightsail is limited by the dominating loss factor.

Diffraction Loss

Diffraction is a potentially serious loss term for the laser elevator and, in fact, is the dominant loss term in conventional laser systems. For a diffraction-limited spatially coherent beam the divergence θ_d of the wave can be written as

$$\theta_d = \beta(\lambda/D) \tag{17}$$

where β is a numerical factor of order unity that depends on the shape of the wave. For a plane wave emerging from a circular aperture an Airy pattern is produced, with $\beta = 1.22$. The Airy pattern consists of concentric bright and dark rings. The value 1.22 comes from the assumption that the beam spread is determined by the first dark ring in the Airy pattern. For a Gaussian beam, that can be produced with a confocal resonator, $\beta = 2/\pi$. Such a beam has the minimum possible divergence for diffraction-limited beams, about half that of a plane beam.[14]

To compute the diffraction losses in the laser elevator we assume that after repeated bounces, the light beam behaves as if it had propagated in a straight line over an equivalent distance of space. In other words, on the second bounce (the light has traversed the cavity three times) the diffraction pattern is that which corresponds to the distance of $3z$. In this case the contribution from repeated bounces can be expressed analytically to give the force on the sail at a distance z from the laser:

$$F = e^{-kz}(2\eta + \alpha)(P/c)\left[\mathcal{F}(z) + \eta_\perp^2 e^{-2kz}\mathcal{F}(3z) + \eta_\perp^4 e^{-4kz}\mathcal{F}(5z) + \eta_\perp^6 e^{-6kz}\mathcal{F}(7z) + \cdots\right] \tag{18}$$

where $\mathcal{F}(z)$ is the fraction of the beam still retained within the mirror after diffraction losses over a distance z. The term in brackets corresponds to the losses due to diffraction and the enhancement of the basic force term due to repeated bounces.

For a wave spreading at a divergence angle θ_d, the beam will fill the target mirror after it has traversed the diffraction distance S_d given by

$$S_d = Dd/2\beta\lambda \tag{19}$$

With further separation, the fraction of the beam that is intercepted by the mirrors drops off as the square:

$$\mathcal{F}(z) = [S_d/z]^2, \qquad z > S_d \tag{20}$$

Equation (20) represents a geometric approximation to the spreading of a diffraction-limited beam. For example, in the exact Airy pattern solution for a plane wave emerging from a circular aperture, $\mathcal{F}$ is given by the equation[16]

$$\mathcal{F}(z) = 1 - J_0^2(\pi Dd/2\lambda z) - J_1^2(\pi Dd/2\lambda z) \tag{21}$$

where J_0 and J_1 are Bessel functions. A sail enclosing the first, second, and third dark rings of the original Airy pattern would encircle 84, 91, and 94%, respectively, of the available beam energy. For a Gaussian beam Eq. (20) is correct in the limit that the distance z is much larger than the initial size of the beam (the spot size at the beam waist; see, for example, Svelto and Hanna).[14]

When the separation between the mirrors is equal to or greater than the diffraction distance ($z \geq S_d$), the beam is severely attenuated by diffraction on each pass, falling off as the square of the total distance covered. The energy returned from the first reflection off of the target is proportional to $(S_d/z)^2$. The energy returned from the first reflection from the fixed mirror at the laser redirected back toward the target is $(S_d/2z)^2$. The energy after the beam has a second reflection at the target is proportional to $(S_d/3z)^2$, and so on.

Thus, the net impulse transferred to the payload is (neglecting the reflection losses that are trivial by comparison)

$$\Delta v = \Delta v_1 \left(1 + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \cdots\right) = \Delta v_1 \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \tag{22}$$

This series converges to give a total momentum enhancement of

$$\Delta v = \Delta v_1 \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} = 1.23 \Delta v_1 \tag{23}$$

In this far limit, diffraction truncates the beam so rapidly (multiple returns only add 23% to the initial one-shot result) that attenuation due to other processes is negligible. Equation (22) utilizes the geometric approximation to the diffraction-limited beam, however, the numerical results for plane and Gaussian wave also give 1.23 as the net enhancement factor for separations larger than the diffraction distance.

Figure 3 shows the acceleration that is achievable when reflection losses and diffraction losses, but not atmospheric losses, are in effect. Mathematically this is given by Eq. (18) with k set to zero. The acceleration multiplier, plotted on the ordinate, is the acceleration achieved by the sail divided by the equivalent one-bounce acceleration. The abscissa is the distance between the laser and the sail in units of the diffraction distance. For distances well below the diffraction limit the acceleration multiplier is constant and limited by the reflectivity of the mirror. However, as the distance approaches a value equal to the diffraction distance divided by the number of bounces as set by the reflectivity of the mirror, diffraction becomes the dominant loss mechanism and the acceleration multiplier becomes limited by diffraction only, independent of the mirror reflectivity.

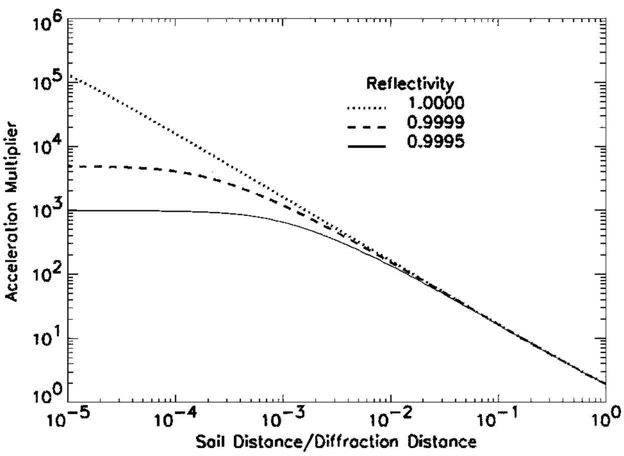

Fig. 3 Acceleration multiplier (effective bounces).

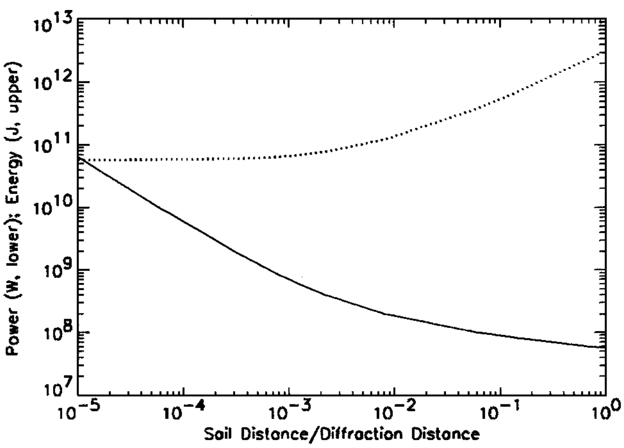

Fig. 4 Power and energy required to achieve a velocity of 20 km/s as a function of laser turnoff distance.

Table 1 Examples of parameters to reach 20 km/s

Parameter	Case 1	Case 2	Case 3
Sail diameter, m	50	50	80
Areal density, g/m^2	10	10	10
Sail mass, kg	20	20	50
Wavelength, μm	1	1	1
Reflectivity	0.9995	0.9995	0.9995
Effective bounces	1000	1000	1000
Damage threshold, W/cm^2	9240	4350	3600
Lightsail temperature, K	950	787	751
Laser power, MW	181	85	181
Operating time, h	0.284	2.84	0.73
Distance to cutoff, z/S_d	0.01	0.1	0.01
Energy expended, MW · h	51	241	132
Velocity increment, km/s	20	20	20

Figure 4 shows the loss in efficiency that results when the laser is operated at distances where the diffraction losses become important. The laser power and total energy required to achieve a velocity of 20 km/s is shown as a function of laser turnoff distance expressed in units of z/S_d. The assumed parameters for this plot are the first six entries for case 1 in Table 1. As shown in Fig. 4, the laser power required steadily decreases as the laser turnoff distance increases; however, this decrease is attenuated and the total energy grows rapidly once the diffraction losses become dominant. Optimal power and energy efficiencies are achieved when the laser turnoff distance is approximately equal to the diffraction distance divided by the effective number of bounces due to the reflectivity. The total energy used (upper curve in Fig. 4) to reach a velocity of 20 km/s divided by the corresponding laser output power (lower curve) yields the time required to reach 20 km/s.

Diffractionless beams have been produced in the laboratory utilizing a zero-order Bessel function beam.[17,18] Although currently such beams are not practical for propagating power over large distances, diffractionless beams may point the direction toward future significant advances in beam geometry manipulation that may help reduce the losses due to diffraction.

Cavity Q

A useful criterion for determining the importance of losses in the cavity is the Q value. Q is defined to be 2π times the ratio of the time-averaged energy stored in the cavity to the energy loss per cycle[19]:

$$Q = \omega_0 \frac{\text{stored energy}}{\text{power loss}} \tag{24}$$

By the use of Eq. (9), its derivative, and the loss term for atmospheric extinction and mirror absorption only, Q can be expressed as

$$Q = \pi/(1 - \eta_\perp + kz) \tag{25}$$

For $k = 0$ and $\eta_\perp = 0.99$, Q is approximately 300. The Q corresponding to a value of $\eta_\perp = 0.9999$ is 30,000. In effect, $Q/2\pi$ represents the number of round trips that a photon makes between the two mirrors. It is essentially equal to the momentum enhancement factor discussed earlier with respect to Eq. (13) and implied with respect to Eq. (15).

Comparison of Rockets with the Laser Elevator

In this section we present a general argument, adapted from Meyer et al.,[6] showing that very rapid delivery of payloads is better achieved with the laser elevator system than with rockets. By rocket we mean any type of craft that achieves acceleration by the exhaust of onboard propellant. By contrast, a laser lightsail is driven by the transfer of momentum from the laser beam to the sail, where the laser and its power supply is external to the lightsail vehicle. The governing physical difference between these two methods is that when the fuel or propellant is carried by the spacecraft, as is the case in conventional rockets or laser thermal rockets, the performance is limited by the rocket equation. In the case of the lightsail, although there is not much momentum in photons, performance is not limited by the rocket equation. To give a quantitative illustration of this difference we have calculated the energy E required to propel a mass m_f to a velocity Δv in the absence of a gravitational field for both a rocket and a lightsail.

For the purposes of this calculation we assume that the lightsail is perfectly reflecting, massless, and is always larger than the beam size of the laser; the laser is 100% efficient; and, for the rocket, we assume that all mass that is not payload is fuel (note that in real rockets this is approximated by multiple staging) and that the production of thrust from fuel thermal efficiency is 100% efficient. For the case of a rocket we calculate the energy E_R required to accelerate a payload m_f to a velocity Δv, exhausting a propellant at a jet velocity u, at a mass flow rate of $\mathrm{d}m/\mathrm{d}t$. Because the fuel is carried in the vehicle, the rocket equation applies and the launch weight is exponentially related to the required Δv:

$$m_0 = m_f e^{\Delta v/u} \tag{26}$$

where m_0 is the launch weight.

In the idealization considered here, the energy expended is only the energy associated with the jet velocity of the exhaust and is, therefore, given by

$$E_R = \int_0^t \frac{1}{2}\frac{\mathrm{d}m}{\mathrm{d}t}u^2\,\mathrm{d}t = \frac{1}{2}(m_0 - m_f)u^2 \tag{27}$$

where we have assumed that u is constant to do the integration. Substituting from Eq. (26) to eliminate m_0 gives

$$E_R = \tfrac{1}{2}m_f u^2(e^{\Delta v/u} - 1) \tag{28}$$

This equation gives the energy for an idealized rocket to achieve a velocity Δv.

We now calculate for the case of a lightsail the energy E_S required to accelerate a payload m_f to a velocity Δv. When a photon reflects from the lightsail, its momentum vector has changed direction. From conservation of momentum, the sail must have acquired a total momentum equal to twice the photon momentum. Hence, the Δv imparted to a vehicle of mass m_f due to a beam with time-integrated output power, or energy, E_s is given as

$$m_f \Delta v = 2E_S/c \tag{29}$$

where we have made use of the energy in the light beam being equal to the momentum times the speed of light c. This can be rewritten as

$$E_S = \tfrac{1}{2}m_f \Delta v c \tag{30}$$

This equation gives the energy required for an idealized lightsail to achieve a velocity of Δv.

We can use Eqs. (28) and (30) to compare, for a given delivered vehicle mass m_f, the energy required to achieve a given Δv for the two methods. Defining N as the ratio E_R/E_S, we can then write

$$N = (u^2/\Delta v c)(e^{\Delta v/u} - 1) \tag{31}$$

We first consider the case in which the Δv required is much less than the jet velocity u. Clearly, if $\Delta v/u \ll 1$, then N becomes very small as can be seen from a Taylor expansion of the exponential term ($e^{\Delta v/u} = 1 + \Delta v/u + \cdots$). If we retain only first-order terms in $\Delta v/u$, then N can be written approximately as

$$N = (u^2/\Delta v c)(1 + \Delta v/u + \cdots - 1) = u/c \tag{32}$$

which is clearly much less than one. This analysis implies that the rocket requires much less energy than the lightsail to reach a given Δv, for small Δv.

We now consider the case in which Δv is much larger than the jet velocity. If $\Delta v/u \gg 1$, then the exponential term in Eq. (31) dominates and can be approximately expressed as

$$N = \frac{u^2 e^{\Delta v/u}}{\Delta v c} \tag{33}$$

which becomes large exponentially. This analysis implies that the lightsail requires less energy than the rocket to reach a given Δv, for large Δv.

To quantify this we have plotted (Fig. 5) the specific energy, defined to be the energy required per unit payload mass to reach δv from rest, given by

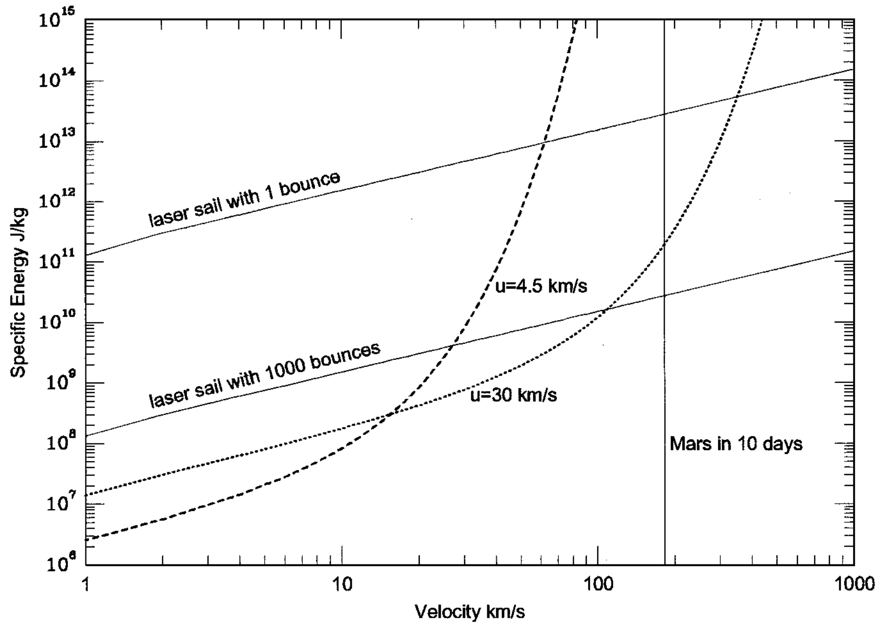

Fig. 5 Plot comparing the specific energy required for an idealized rocket e_R and lightsail e_S to achieve a given velocity change Δv, based on Eqs. (28) and (30).

$$e_R = E_R/m_f = \tfrac{1}{2}u^2(e^{\Delta v/u} - 1) \tag{34}$$

$$e_S = E_S/m_f = \tfrac{1}{2}\Delta v c \tag{35}$$

as a function of Δv for a choice of jet velocity u characteristic of the space shuttle ($u = 4.5$ km/s).

Note that e_R has an exponential dependence on Δv, whereas e_S has a linear dependence.

We define Δv_c, the crossover point of the two plots, as the point at which the lightsail method becomes more efficient than the rocket method for achieving high Δv. This can be calculated by equating e_R and e_S and is given by the solution of the equation

$$(u/\Delta v_c)(e^{\Delta v_c/u} - 1) = c/u \tag{36}$$

We note that, for a single bounce from the sail, Δv_c is 61.8 km/s (assuming a u of 4.5 km/s characteristic of a current high-performance chemical rocket). For a more speculative high-performance nuclear rocket with u of 30 km/s, the crossover point is 350 km/s for a single-bounce sail, or 108 km/s for a 1000-bounce laser elevator. The velocity changes that characterize current interplanetary coast missions using chemical rockets are less than 20 km/s, hence, the single photon bounce lightsail method is clearly less efficient. However, the same value illustrates that, if a laser elevator can achieve the equivalent momentum transfer of 5000 bounces per photon, the crossover velocity favors the laser elevator for speeds above 20 km/s. For missions requiring very fast transit times in the solar system or for interstellar flights, where the velocity is in excess of Δv_c, vehicles that carry their own propellant become extremely inefficient, and, hence, the laser elevator method becomes very attractive.

Cases of Interest

The primary indicator of the performance of the system is the power that must be supplied to levitate or accelerate a payload. We can obtain a general expression for the power from our basic equations. By differentiating the momentum balance equation, Eq. (9), and substituting for $\mathrm{d}E/\mathrm{d}t$ from Eq. (11), we obtain the following equation for the power:

$$P_i = (mav + mgv)\left[1 + \frac{2}{2\eta + \alpha}\right] + L + \frac{2mz}{2\eta + \alpha}\frac{\mathrm{d}a}{\mathrm{d}t} \tag{37}$$

If we consider sufficiently small mirror separations so that diffraction is not important and the losses are entirely determined by absorption by the mirrors, Eq. (14), and by atmospheric extinction, Eq. (16), we obtain on substituting for L in Eq. (37)

$$P_i = (mav + mgv)\left[1 + \frac{2}{2\eta + \alpha}\right] + (ma + mg)\frac{2c(1 - \eta_\perp + kz)}{2\eta + \alpha} + \frac{2mz}{2\eta + \alpha}\frac{\mathrm{d}a}{\mathrm{d}t} \tag{38}$$

Levitation

As a first application of Eq. (38) we consider the power required to suspend an object against gravity, neglecting atmospheric extinction and diffraction. In this case, the velocity is zero and the power required is given by

$$P_i = \frac{2mgc(1 - \eta_\perp)}{2\eta + \alpha} \tag{39}$$

Clearly, as the efficiency of the mirror approaches unity the power required approaches zero. For perfectly reflecting mirrors with no other losses, the energy needed to suspend an object is determined simply from Eqs. (1) and (3) to be

$$E = mgz \tag{40}$$

In a lossless system, this energy would not need to be replenished, and, hence, no power is required to levitate the object. A plot of the power required to levitate a 1-kg object as a function of the reflectance $\eta_\perp$ is shown in Fig. 6. A reflectance value of zero corresponds to a perfectly absorbing surface. For a typically available

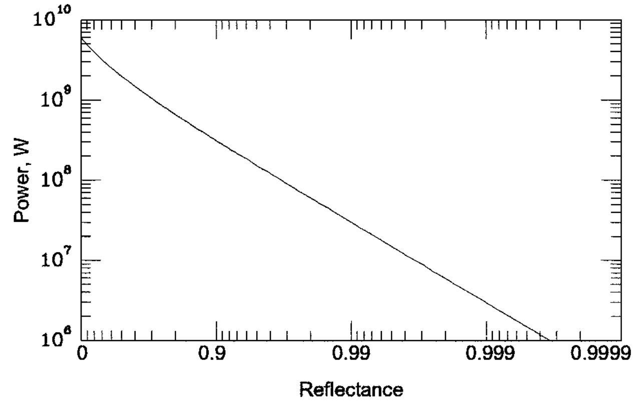

Fig. 6 Power required to levitate a 1-kg object using the recirculating laser beam of a laser elevator plotted as a function of the reflectance of the mirrors.

laser mirror with a value of $\eta_\perp = 0.999$ the power required to levitate an object is only 3×10^6 W $\cdot$ kg^{-1}. Readily available commercial lasers with continuous power levels in the range of ~10 kW could, therefore, be used for small-scale demonstrations with 3-g mirrors.

Lifting

If, in addition to levitating the object, it is raised upward at a constant velocity, the power required would be given by, again neglecting diffraction,

$$P_i = (mav + mgv)\left[1 + \frac{2}{2\eta + \alpha}\right] + \frac{2mgc(1 - \eta_\perp + kz)}{2\eta + \alpha} \tag{41}$$

For an ideal mirror, $\eta_\perp = 1$, and for a lossless transmission path, $k = 0$, the power required to raise an object, is given by

$$P_i = 2mgv \tag{42}$$

The power is double the value one might expect, and the factor of two is due to the requirement that the energy supplied not only provide the potential energy of the object being raised but also provide the photons for filling the ever-expanding optical cavity as the payload mirror moves away from the source mirror. Thus, the optical energy in the cavity is equal to the potential energy of the payload, for the case of perfect mirrors and no acceleration, as is shown in Eq. (9). In a real system, the work done on the payload is small compared to the losses.

Launch to Orbit

One of the important applications of any new propulsion system would be to launch payloads to low Earth orbit. For a laser elevator system this is difficult because the thrust of the system is always along the line connecting the payload and the source mirror. It is, therefore, difficult to obtain the tangential velocity component required for orbital insertion. A novel approach to this problem, shown in Fig. 7, was published in Ref. 4.

In this method a vehicle is launched on a suborbital parabolic path and allowed to coast until it has considerable downrange velocity. The craft then receives a second boost from the laser system or alternatively from another laser system downrange. This second boost cancels the downward component of the velocity and provides the additional tangential velocity increment to achieve a stable orbit.

The theoretical energy requirement to place a 1-kg object into low Earth orbit is about 9 kW $\cdot$ h kg^{-1}. We can use this value, combined with a rough estimate of the energy efficiency of a laser elevator, to calculate the energy required to place an object in orbit with this system. In considering the launch to low Earth orbit, we ignore diffraction effects because the distances involved are much smaller than the diffraction distance. For a 10-m aperture laser and a 10-m reflector on the spacecraft, the diffraction distance is about 40,000 km.

The efficiency of the laser elevator ε can be approximately represented as the rate of work done on the payload vF divided by the

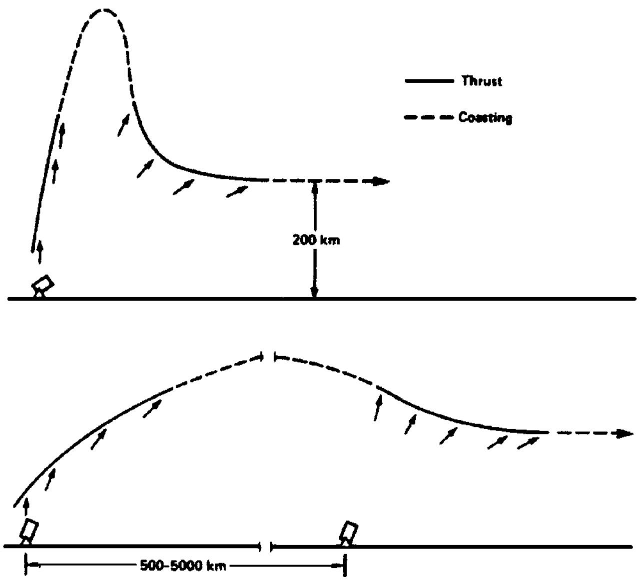

Fig. 7 Two methods for launching to orbit using variously one or two laser sites, adapted from Kare.[4]

power applied to the system P_i, which, from Eqs. (1) and (38), can be expressed, neglecting a term proportional to the derivative of the acceleration, as

$$\varepsilon = \frac{vF}{P_i} = \frac{2\eta + \alpha}{(2 + 2\eta + \alpha) + 2(1 - \eta_\perp + kz)c/v} \tag{43}$$

The maximum efficiency ε of the system is 0.5, and it is reached when $\eta_\perp$ approaches unity. This was seen earlier in the lifting example. For launch to orbit kz is the total optical depth of the atmosphere. In certain parts of the infrared region of the spectrum ($\sim$1–10 μm) the transmission approaches values of 99%. This corresponds to an optical depth of 0.01. For a typical average velocity of 5 km s^{-1}, and assuming $kz = 0.01$, and choosing the reflectance of the mirrors to be $\eta_\perp = 0.99$, then the value of ε is 0.08%. When the same efficiency assumptions made by Kare[4] are used, if the efficiency of the laser as an energy source is 0.2 and the efficiency of the orbital injection maneuvers is also 0.2, then the total energy requirement is 270,000 kW · h kg^{-1}. At a year 2000 energy price of \$0.06 per kW · h this implies an energy cost of \$16,200 per kilogram.

If the system efficiency ε is 0.25, half of its theoretical maximum value, this could correspond to no atmospheric extinction and a mirror reflectance increased to 0.999967. The corresponding energy costs are, using Eq. (43), 900 kW · h kg^{-1}, only \$54 per kilogram. These examples illustrate the importance of high reflectivity for a laser elevator.

Elevator mirrors may use dielectric multilayers because these can be made extremely low loss over a specified range of wavelengths (10–15 μm in the following reference) and scattering angles.[10,20] Mirrors being produced for the Laser Interferometer Gravitational-Wave Observatory (LIGO) are made of fused silica coated by a multilayer dielectric. They are designed to have absorption and scattering losses not exceeding a few parts per million.[21] These mirrors will permit laser beam storage in multibounce cavities for about 1 ms. Applying similar mirrors to a laser elevator system will provide a great advantage over a one-bounce laser sail; however, at this level of reflectivity, diffraction dominates the loss terms.

The use of ultrahigh reflectivity mirrors in the Earth's atmosphere is potentially problematic because the likelihood of contamination of the surface is great. The most practical regime for launch applications for this technology is likely to be from the surface of the moon or other airless bodies.

The laser elevator technology presents significant engineering challenges that must be solved before practical applications are feasible. Among the advances needed are more powerful lasers, improved mirror reflectivity, surface quality, and damage thresholds and methods for reducing mirror mass. In the near term the most easily achievable applications of the laser elevator are likely to be missions requiring minimal payloads launched in space where the environment is clean and competing gravitational forces are minimal.

Rapid Delivery

One of the interesting applications proposed for lightsails is the rapid delivery of small payloads across the solar system, for example, to Mars.[6] In this application, a laser system is used to propel the payload at a high acceleration until the distance to the payload is large enough that diffraction losses curtail the efficient transfer of energy. Optimization of the rapid delivery problem discussed by Meyer et al.[6] for a laser elevator would benefit from the increased efficiency of the laser elevator over the conventional laser lightsail at distances small compared to the diffraction limit. The net result would be to enable higher accelerations at smaller distances, achieving the necessary cruise velocity more rapidly for a given power level. In addition, there would be an increase in overall energy efficiency by a factor proportional to the number of photon bounces.

In a plausible scenario for the realization of such a rapid delivery system, the limiting factors would be the stored energy (presumably accumulated over time before the launch) and the maximum tolerable acceleration or thermal load on the mirrors. In this case the initial laser power would be set to the maximum allowable at close range and then increased to compensate for diffraction losses as they grow with increasing separation between the mirrors. Once that separation were comparable to the diffraction distance divided by the effective number of bounces, it would become increasingly impractical to apply power.

Many useful missions can be performed by spacecraft moving rapidly enough to reach the outer solar system. For example, we consider a mission to Pluto, reaching that planet in six and a half years, less than half the trip time achievable with current technology. We consider a light sail 50 m in diameter, with an areal density of 10 g/m^2, and with a damage threshold of 9240 W/cm^2. The mirror reflectivity is assumed to be 0.9995, equivalent to 1000 effective bounces (solid line in Fig. 3). This allows a laser power of 181 MW. Assuming an emissivity of 0.5, the lightsail temperature would be 950 K. As seen in Fig. 3, it is sufficient to operate the laser only until the sail reaches 0.01 times the diffraction distance. In this case the total power expended is 51 MW · h and the laser operates for 0.284 h. The payload achieves a velocity increment of 20 km/s, which, when added to the Earth orbital velocity, implies a transit time to 40 AU of about 6.5 years. Were the laser to be operated until the craft reached 0.1 times the diffraction distance, the laser power and mirror damage threshold requirements would be lowered, but at a cost of about five times the energy. These results are listed as cases 1 and 2 in Table 1.

Although some of the requirements in these examples are beyond the current state of the art, they are not very far beyond the range of foreseeable technology. Extrapolation of trends in the U.S. Air Force Airborne Laser program suggests that 100-MW class lasers or the use of multiple lasers in tandem will be feasible. NASA's long-range goal is to reduce the areal density of space-based optics to around 0.1 kg/m^2, and the astronomical community is already aspiring to build 100-M class mirrors for telescopes to image extraterrestrial planets. Possible approaches for making mirrors with very low areal density could include the use of polymer membranes or thin films supported on ultralightweight substrates, possibly made from foamed silicon, aerogel, or carbon fibers. The latter would have the potential for high-temperature operation. Mirrors with sufficiently high reflectivity for the laser elevator are already in use in space, but maintaining adequate smoothness and Strehl ratios on large-scale lightweight structures will be a serious challenge, albeit one that may also be addressed by the astronomical community. These difficulties might be reduced by manufacturing lightsails and mirrors in space where size is unconstrained and potential microgravity and vacuum benefits are available.

For the laser elevator to achieve high velocities with high efficiency, lightsail mirrors having high-reflectivity, high damage threshold, and low areal density are required. Typical high-reflectivity laser mirrors available today have damage thresholds in the range of 1–3 kW/cm^2 CW, limited mainly by the allowable temperature of the materials. Were mirrors with higher damage thresholds available, this could translate into significantly improved performance by allowing smaller lightsails and greater energy efficiency. Whereas efforts to increase damage thresholds is the subject of ongoing research, this requirement can also be reduced by tradeoffs with other parameters. Case 3 in Table 1 shows the reduction in damage threshold when the mirror diameter is increased to 80 m compared to 50 m for case 1. With the increased mirror mass, the total laser energy expended is increased proportionately, and the required damage threshold is lowered by nearly a factor of five. Performance of the laser elevator could be further enhanced by using confocal mirrors and variable power lasers.

The laser elevator has the advantage that much of the required technology could be developed by other interests. High-power lasers, high damage threshold optics, and precision pointing technology may be developed for defense uses, and large-scale ultralightweight mirrors are of growing interest for space-based astronomy. Once the laser boost facility has been built and the laser sail technology has been developed, multiple laser lightsails can be launched comparatively cheaply.

Conclusions

By recirculating the laser energy, the laser elevator system offers a potentially much higher efficiency over the conventional laser lightsail system. Mirrors with 0.9995 reflectivity would offer a factor of 1000 increase in efficiency. The laser elevator's most efficient operation occurs at distances shorter than the diffraction distance divided by the effective number of bounces as determined by the reflectivity of its mirrors. Beyond this point the efficiency of the laser elevator decreases at a rate inversely proportional to distance and falls to a value close to that of a single-bounce system when the lightsail reaches the diffraction distance. Because the laser elevator does not need to carry propellant, it has advantages over rockets for sustained operations such as levitation and for reaching high terminal velocities. We have considered potential applications that include launch to orbit and rapid delivery to Mars and Pluto.

The laser elevator has the potential to become an important new launch system, particularly for small payloads. Future work on the laser elevator concept could focus on 1) a detailed engineering design of the laser and the vehicle configuration, 2) laboratory demonstration of levitation on a small scale, and 3) mirror technology including high reflectance, high damage threshold, low mass, and self-pointing phase conjugate mirrors.

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A. C. Tribble
Associate Editor