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Riding a Beam of Light

The single most important characteristic of a solar sail is its power source—the Sun. The Sun supplies a continuous source of sunlight, providing the gentle push that makes a solar sail such a useful propulsion system. Unfortunately, the Sun is also the limiting factor in the overall usefulness of a solar sail. When a spacecraft gets far from the Sun, there is simply not enough light available to provide additional propulsion. Recall the "inverse square law" discussed previously. In deep space, the Sun is essentially a point source, with sunlight radiating away from it in all directions forming an ever-expanding sphere of light. Since the total amount of light from the Sun is the same when the expanding light sphere reaches the orbit of Mercury, Venus or Earth, we are not "losing" sunlight. What we are doing, however, is reducing its intensity. The amount of sunlight may be the same, but the surface area of the sphere is much larger the farther you get from the Sun. The only way that the amount of sunlight can remain constant (which we intuitively know it must), yet cover a much larger area, is for the amount of sunlight per unit area to decrease. And decrease it does; as the distance from the Sun doubles, the amount of sunlight falling on a 1 m^2 area on that sphere drops to one fourth of its previous value. The distance is doubled, and the amount of light is reduced by a factor of four. Since $4 = 2^2$, this predictable decline in sunlight is governed by the inverse square law and holds true no matter how far away from the Sun the sphere of light travels. If you measure the total amount of light falling on a 1 m^2 area of sail and then quadruple the distance, the amount of sunlight falling on that same sail drops to 1/16 of its previous value: $4^2 = 16$. As we move away from the Sun, the push our sailcraft receives drops rapidly.

Thanks to Newton, we understand that a sailcraft won't slow down when the sunlight dims. It will continue moving with whatever velocity it achieved during its acceleration phase until some outside force acts upon it. For a sailcraft targeted to deep space, this might mean that the sail continues on its journey for thousands or millions of years. Without light, it will not continue to accelerate and move with an ever-increasing velocity. If we want to use a sail to reach the stars in a reasonable amount of time (from a human perspective), this simply will not do. Using sunlight alone, with the largest, thinnest sail we can imagine, and with a very close solar approach, a sailcraft will take at least one thousand years to reach the nearest star.

G. Vulpetti et al., *Solar Sails*, Springer Praxis Books,
DOI 10.1007/978-1-4939-0941-4_10

Clearly, we must find a way to change the rules of the game and make sure our sailcraft has an ever-constant beam of sunlight available so that it can continue to accelerate to higher and higher velocities—making journeys into interstellar space possible with a trip time of less than a thousand years! Fortunately, nature provided us with ways in which this might actually be achieved.

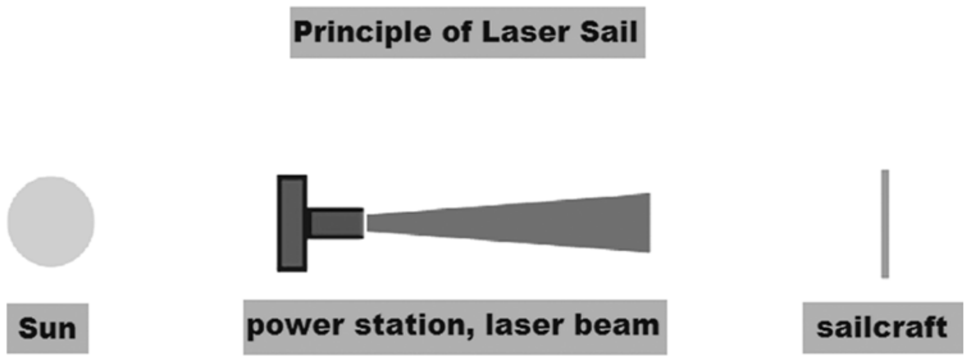
LASER SAILING

Enter the laser, a word that originated as an acronym for light amplification by stimulated emission of radiation. It is a science fiction-like invention of the 1950s that may provide an alternative to sunlight for providing the thrust a solar sail needs when it is far from the Sun. An ideal laser emits light at one wavelength, or color, in a narrow beam. Unlike light emitted from the Sun or a light bulb, ideal laser light is highly directional and does not spread out in all directions—meaning that the inverse square law does not apply. Such a laser can theoretically push our solar sail even when it is very far from the Sun. Unfortunately, we cannot build an "ideal" laser, and even the best laser beam will spread out somewhat as it moves away from its source. This is due to a process called diffraction, which the interested technical reader can learn more about by referencing a good physics textbook. That said, a laser-driven sail is still an exciting possibility, as the diffraction-limit doesn't appreciably impact the performance of a sailcraft until distances much, much greater than those limiting solar sails are surpassed.

We discussed how sunlight could push a solar sail when the sailcraft is near the Sun and propel it outward into the solar system until it reaches approximately the orbit of Jupiter. We've also determined that we can use a laser to continue pushing the sail when sunlight is no longer available. So where do we put this laser (knowing that it will require a lot of energy to produce a beam powerful enough to cross the gulf of space and still provide the sailcraft with enough light for propulsion)?

If the laser were built on Earth, the power problem would certainly be easily solved. Many industrial nations have a power infrastructure that could easily sustain the operation of the laser required for deep-space or interstellar flight. But Earth is not a good location, for many reasons. First, the laser would be travelling through our dense atmosphere, which would immediately produce not only significant degradation of the beam's intensity (lots of light would be lost during the beam's passage through the atmosphere), but it would also cause the beam to diverge, or spread out, much sooner than would otherwise be the case for a comparable beam generated in vacuum. Second, Earth rotates about its axis once every 24 h. That means it would be impossible to point a laser toward a specific point in space for more than a few hours at a time and even this would require a complex pointing system as it would have to moving constantly to maintain its aim point as the Earth rotates. And don't forget that Earth is in orbit around the Sun, adding additional motion for which a pointing system must compensate. Lastly are the politics of basing the laser on Earth. If a country builds a laser powerful enough to propel a spacecraft through deep space, then it would have a laser powerful enough to knock down another country's aircraft, missiles and even their orbiting satellites. Such a laser could be used as a weapon.

What about putting the laser in Earth orbit? The political problem would still remain. A large, powerful, space-based laser could threaten not only aircraft, missiles and



10.1 A laser-driven sailcraft could be accelerated significantly

spacecraft, but anything on the ground (provided that Earth's atmosphere was transparent to the laser's wavelength). Pointing would also still be an issue. Recall that a spacecraft in orbit is not stationary—it is moving at very high speeds so that it can remain in orbit and not fall back to Earth. A craft in low Earth orbit (up to about 1,000 km), circles the globe approximately once every 90 min. Instead of sweeping across the sky once every 24 h, the laser is now forced to do so every 1.5 h! And the motion of Earth around the Sun is still a factor to be considered. Tracking and pointing may be much more difficult for an orbiting space-based laser than one located on the ground.

What about power? Without a power grid to tap into, an Earth-orbiting laser would be required to generate its own power. Extremely large solar arrays or onboard nuclear reactors would be required to produce the energy needed to drive the laser. Though the atmosphere is no longer a problem, moving the laser from the surface of Earth to Earth orbit does not appear viable.

Where, then, can we find abundant power, no atmosphere to attenuate the beam, relatively stable pointing (so the laser can push on the sail for a long period of time with minimal active pointing required) and no fear of the laser being considered a military threat?

One option would be to place the laser in orbit around the Sun, as shown in Fig. 10.1. If the laser station is relatively close to the Sun, then the inverse-square law works in our favor by making solar array panels capable of producing much more power. If we locate at one-half the Earth-to-Sun distance, the arrays will theoretically generate four times more power from the greater intensity sunlight falling upon them. There is no atmosphere, so there will be no immediate laser beam loss or added divergence. Pointing is still an issue, but it should be easier to steer and point the beam at our sailcraft from a laser in solar orbit because there is no longer planetary or planet-centric orbital motion that must be considered. Only the motion of the laser around the Sun must be accounted for. To compensate for the times when the laser is on the opposite side of the Sun from our sailcraft, two or three laser stations could be placed in solar orbit, with at least one of them always being in line-of-sight with the sailcraft, thereby providing propulsion.

A laser station closely orbiting the Sun is potentially not the best solution to the problem, however. Recall that we are concerned about not having enough light falling on the sail to allow it to continue thrusting once it passes Jupiter. If lasers didn't suffer from diffraction causing divergence, our problem would be solved. We could place our laser virtually anywhere and point it where we want it, without regard to distance. But lasers are diffraction-limited and they do diverge. Placing a laser close to the Sun only serves to reduce the maximum distance from Earth at which the laser light is still sufficiently intense to produce thrust on the sail. Ideally, we would place our laser at or near Jupiter so it can begin pushing the sail when the Sun completes its part of the job. Fortunately, Jupiter might be a great place for our laser.

At first glance, Jovian orbit seems to have nearly all the benefits of a solar-orbiting locale for basing the laser—except for power. The laser would not be located on a planetary surface, so there is not an atmosphere to contend with, nor is anyone nearby who might construe the laser to be a military threat. The motion of Jupiter around the Sun, and the commensurate viewing and pointing considerations, can be compensated for, as Jupiter orbits the Sun only once in 12 years. If the laser station is in a polar orbit around Jupiter, it could have a clear line-of-sight to our sailcraft for a decade at a time—taking into account only the orbit of the planet around the Sun.

But what about power? Jupiter is far from the Sun, so solar power is not a good candidate. As discussed earlier, the laser station might be nuclear powered. Alternatively, the energy contained in the Jovian magnetic field might be harnessed with a long, conducting wire, or tether, deployed from the laser platform deep into the Jovian magnetosphere. The tether, due to its motion through the planet's magnetic field, would generate a potential difference across its length. This potential difference, or voltage drop, would result in the collection of electrons from the Jovian magnetosphere, thus producing a flow of electricity through the wire. The principle is the same as that which is seen when an electric generator produces electricity in a terrestrial power plant. On Earth, we produce electricity by moving wires through intense magnetic fields. Jupiter has the second most power magnetic field in the solar system, only behind the Sun. Our tether, moving through this field, can produce megawatts of power to drive the laser.

This is by no means the only scenario in which lasers might be used to push our sails. But it is certainly a likely one. A mission might proceed something like this: A sailcraft departs from Earth on a sunward bound trajectory. The craft falls toward the Sun and orients its sail to maximize solar thrust at perihelion, giving it an incredible boost toward the outer solar system. Sunlight continues to push on the sail until it reaches the orbit of Jupiter, at which point our tether-driven laser sends a beam of light to reflect from the sail, picking up from where the now feeble sunlight leaves off. The laser maintains its aim point on the sail, providing continuous additional thrust, until the diffraction limit of the laser results in no net thrust being applied to the sail—somewhere in deep space. In this way, we can effectively extend the useful range of solar sails two- to fivefold.

MICROWAVE SAILING

The laser is a powerful technology and it certainly represents one option to increase the effective range of a solar sail. But it is not ideal.

One problem of the laser is cost. Low-power lasers are fairly economical. One has to look no further than the ubiquitous compact disc or DVD player to realize that mass produced lasers can be manufactured cheaply. Unfortunately, high-power lasers, with far fewer commercial applications, are much more expensive to produce.

Happily, there is a far less expensive beamed-power alternative to the laser, although it too has its disadvantages. That alternative is the so-called “maser,” or microwave laser. And high-power masers may be much less expensive to produce than their laser cousins.

There is no intrinsic reason why microwave-energy generators should be less expensive than lasers. The reasons for this cost disparity are tied in with military history and, as you might have guessed, mass production.

Large-scale generation of microwave power was pioneered during World War II by many of the belligerent powers. Radar, which uses microwaves, was developed in that era both to detect enemy aircraft at great distances by radar-beam reflection and to serve as a navigational aid. The enormous cost of developing high-power microwave generators was therefore born by the military establishments.

Besides cost, as with many technologies that appear magical at first glance, there is a catch. The wavelength of a microwave is generally in the millimeter-to-centimeter range. The wavelength of a near-infrared laser is about one ten-thousandth of a centimeter. By a mathematical principle called Rayleigh’s criterion, the beam-spread or divergence of even a perfect laser depends upon the laser’s wavelength.

You can get some idea of what this wavelength-dependent beam divergence means in practice by considering the following example. Let’s say that you design an interstellar expedition to be accelerated by a near-infrared laser. To intercept all beamed energy at the extreme range of the laser, you estimate that the sail diameter is a large, but at least imaginable, 500 km. But if you desire to save money on the propulsion mechanism and replace your laser with a 1 cm wavelength microwave transmitter of equal power and still have your sail intercept all transmitted radiation, your sail size must increase to a gargantuan 5 million km, about three times the diameter of the Sun!

Clearly, something must be done or microwave-beamed propulsion becomes absurd. One possibility, as presented by Robert Forward, is to insert a thin-film focusing lens into the microwave beam between the transmitter and the sailcraft. Although such an approach, in principle, can deliver a lot more beamed energy to the sail, you must now contend with the problem of another large optical component that must be very accurately positioned in the depths of interstellar space.

During the early years of the twenty-first century, a NASA-funded team led by physicist Jim Benford and his author and brother Greg Benford further investigated the problems and possibilities posed by microwave sailing. They concluded that microwave sailing might be best employed over short distances—such as accelerating a sailcraft from low Earth orbit to Earth escape velocity using ground-transmitted microwave beams (a real possibility since the atmosphere is transparent to most microwaves, and existing radio telescopes can be used as transmitters).

The Benfords also employed a phenomenon called desorption that increases the efficiency of a microwave sailcraft. As well as pushing the sail by radiation pressure, microwave heating can evaporate gas molecules trapped in the sail during its manufacture, which can increase sail velocity. A small boost perhaps, but a boost nonetheless!

PARTICLE-BEAM SAIL PROPULSION

One disadvantage of radiation-pressure propulsion—of the solar, laser or microwave variety—is the very small momentum of a photon. But what if we could construct a huge version of a nuclear accelerator to accelerate particles of matter to high velocity and impinge them against some form of sail? Just as in a solar sail, the reflected particles would impart some of their momentum and energy to the sail providing thrust.

Ground-based particle accelerators have been in use for decades in physics research. Currently, there are three very big accelerators in the world: Fermilab (Chicago, US), CERN (Geneva, Switzerland) and KEK[1] (Tsukuba, Japan). The next generation of gargantuan accelerators should include the International Linear Collider (ILC). Charged particles are accelerated in many mile-long paths, literally, and slammed into targets, or other accelerated beams of particles in order to study the very deep essence of the universal physical interactions at particle energies that occur in nature very close to black holes, or existed in the Universe state a long, long time ago, before the birth of galaxies.

Charged particles like protons are used because we know how to make them move (accelerate). A charged particle in an electric or magnetic field will experience a force due to that field, making it move. By properly aligning the fields, these charged particles can be accelerated to very high speeds—close to the speed of light. If such a particle beam were to strike a sail in the vacuum of space, the sail would move and continue to gain speed as long as the beam impacts it.

Charged particle beams have one very serious flaw in their potential application to space travel—divergence. Unlike divergence in laser or maser sails, the divergence of a particle beam is caused by the accelerated particles themselves. The simple axiom, "like charges repel; opposite charges attract," dooms a charged particle beam sail from being useful at any significant distance from its source. As the beam of charged particles emerges from whatever accelerator created it, the very atoms within the beam, typically protons (with a positive charge), begin to push away from each other, until the beam spreads and becomes too diffuse to be useful.

In the heyday of the US's Strategic Defense Initiative (SDI), space-based particle beam weapons were being seriously considered as a method for shooting down or disabling missiles. To circumvent the beam-divergence problem inherent with their operation, engineers and scientists began developing neutral particle beam systems—neutral particles don't repel one another, thereby reducing or eliminating the problem of beam divergence.

The first step in producing a neutral particle beam is making a charged particle beam. Neutral atoms cannot be accelerated in an electric or magnetic field because they carry no net charge. Therefore, a beam of charged particles, typically protons, is first produced and accelerated to high velocities. Passing it through a very thin film or plasma cloud then neutralizes the beam. (To "neutralize" a proton means to simply provide it with an electron so that it becomes charge neutral, therefore not susceptible to charged-particle self-repulsion.) The charge-neutral beam can then propagate through space unimpeded to

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[1] KEK is the Japanese acronym standing for High Energy Accelerator Research Organization (Japan), also employed for referring to the accelerator complex.

the target, or in our case, to the sail. As with most engineering solutions, the charge neutralization process is not without problems. It, too, induces beam divergence that causes the beam to spread out over long distances. This divergence is caused by the atoms of the beam colliding with atoms in the film or plasma cloud and reflecting from them as they "pick up" an electron.

Putting large, high-power neutral particle beam accelerators in space to propel starships may indeed be possible. We don't yet know how to engineer a system large enough, powerful enough or with sufficiently low divergence, but there appears to be no physical reason we cannot. As with high-power lasers, the politics may prevent us from developing them: a high-power neutral particle beam system in Earth orbit could easily be used as a weapon.

FURTHER READING

Principles of beamed propulsion are reviewed in E. Mallove and G. Matloff, *The Starflight Handbook,* Wiley, NY, 1989. For a more up-to-date technical treatment and review, see G. L. Matloff, *Deep-Space Probes,* 2nd ed., Springer-Praxis, Chichester, UK, 2005.

AIP Conference Proceedings 664: First International symposium on Beamed-energy Propulsion, May 2003, American Institute of Physics.