TOUCH A STAR:

A TEACHER’S AID FOR THE STARLIGHT AND BREAKTHROUGH STARSHOT INTERSTELLAR TRAVEL INIATIVES

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The “Starlight” and “Breakthrough Starshot” programs are working to design a spacecraft capable of voyaging to a star. This Teacher’s Aid aims to enable science teachers at the high school level and beyond to introduce their students to these exciting projects. And it uses them as a context in which to introduce students to some of the most important principles of physics.

(1) INTRODUCTION

(A) Motivation: Why Pay Attention To Starlight and Breakthrough Starshot?

Interstellar travel has long been a source of endless fascination for writers of science fiction. The dream of reaching the stars has held perpetual sway for generations. But it has only been the stuff of science fiction and dreams -- because it has always been far beyond our reach.

Until now.

Starlight[1] and Breakthrough Starshot[2] are projects, underway at this very moment at research centers across the globe, to show that this is no longer the case. They aim to demonstrate that, for the first time in human history, interstellar travel is no longer the stuff of fantasy. While travel to the stars will demand a major improvement in technology, that improvement now appears to be doable. Young people today live in an age in which the dream of ages may become a reality within their lifetimes.

And it is because of these young visionaries that I wrote this Teacher's Aid. I have always felt that my primary challenge as a science teacher has been to motivate my students. In this regard, nothing is more potent than the lure of an unsolved problem. What can be more motivating for our students than to grapple with a vision that has gripped humanity for ages? What can be more thrilling for a young mind than the thought of achieving something that previous generations could only dream of? Once this is possibility is within their grasp, the challenge for the teacher is no longer to "effectively communicate the material." It is to harness an explosion of energy. It is to control a stampede.

In addition, one of the nice things about these projects is that they provide a perfect context in which to teach students some the most important principles of physics --

- Energy
- Momentum
- The great conservation laws of physics
- Geometrical thinking
- Quantitative reasoning

[1] http://web.deepspace.ucsb.edu/projects/starlight

[2] https://breakthroughinitiatives.org/initiative/3

(B) Prerequisites

And finally, another nice thing is the fact that only these concepts are required. Students need not understand advanced physics and mathematics. The only technical prerequisites for a full understanding of what follows are a working knowledge of

- exponential notation
- basic algebra
- elementary geometry

We use the MKS system (the Meter – Kilogram – Second system) throughout.

(C) Problems and Projects

I have suggested a number of exercises for the students to perform.

- *Problems* are short and can be done in one sitting.
- *Projects* are more extensive, and they are open-ended: perhaps it is best to think of them as small research projects. They have no well-defined “stop point.” They could well be worked on by several students working together as teams.

(2) A GUIDE TO THIS TEACHER’S AID

Here is a quick guide to the structure of this Teacher’s Aid and to the logic of its presentation.

(3) **WHAT ARE STARLIGHT AND BREAKTHROUGH STARSHOT?**

(A) The concept Here we introduce the basic concept, which is to push our spacecraft using an intense burst of light

(B) The Target Star: Proxima Centauri Proxima Centauri is the closest star to us: it possesses a planet which lies in the so-called “habitable zone” which might conceivably support life.

(C) The programs and their funding

(4) **TERMINOLOGY: THE ASTRONOMICAL UNIT AND THE LIGHT YEAR** We begin by introducing two new units of distance. The *astronomical unit* is a natural way to measure distances within the Solar System. Similarly, the *light year* is a natural way to measure distances among the stars. Throughout this Teacher’s Aid we will be using these units regularly.

(5) **INTERSTELLAR DISTANCES**. Interstellar travel is hard because the stars are far away – very much farther than the planets.

(A) Interstellar Travel in Context: The Voyager Mission To appreciate the extreme difficulties of interstellar travel, we place it in context by comparing it to humanity’s farthest push outwards into the cosmos so far.

(B) Scale Models of the Cosmos We make vivid the huge scale of the distances involved by building in our minds a scale model of the cosmos.

Our conclusion is that, in order to reach Proxima Centauri in a reasonable amount of time, our spacecraft will have to travel at enormous velocities – very much faster than anything we have achieved so far.

(6) **HOW MUCH FUEL WOULD A CONVENTIONAL ROCKET NEED? THE ROCKET EQUATION.** Here we show that the amount of fuel required to reach such velocities is impossibly great. No conventional technology involving rockets is capable of reaching the great speeds that interstellar travel requires. This is the central problem facing interstellar travel.

(7) **THE NEW IDEA: PUSH THE SPACECRAFT WITH LIGHT**.

(A) The Basic Idea In normal experience we never notice that light exerts a force. But this is because in normal experience light is relatively faint. A brilliant light, on the other hand, can exert a force great enough to send our mission on its way. In this section we will analyze just how bright the light must be.

(B) The Energy of Light The force of light depends on the light’s energy. So this is where we begin.

(C) The Momentum of Light Here we analyze the push delivered by light: the force it exerts.

(D) Push the Spacecraft by Bouncing Light off of it Here we develop a formula which tells us the energy our laser must emit if it is to accelerate our payload to the desired velocity.

(E) Try a Few Numbers: 1/5 the Velocity of Light Here we plug some numbers into our formula. We find that the energy required to send a conventional payload to the stars is impossibly great. But if we send a “starchip” instead, the energy required is not so great. Perhaps we have found a feasible way to reach the stars!

(8) **THE LAUNCH: HOW POWERFUL A LASER DO WE NEED?**

(A) For How Long Must We Fire Our Laser? Only a certain amount of time is available.

(B) Laser Power The shorter the time, the more powerful the laser must be. Our conclusion is that we already posses lasers of sufficient power, but that they do not at present fire for sufficiently long periods of time.

(9) **DESIGN THE LIGHT SAILS**

(A) How Big A Mirror Do We Need? The beam of light from the laser will form a cone. We need our mirror to be big enough to catch all the light within that cone. So the farther up we place our starchips, the larger the mirror will need to be.

(B) Protect The Mirror The launch process will be cataclysmic. We need to make sure the mirrors and spacecraft are not damaged.

(10) WHERE SHALL WE PUT OUR LASER? The target star lies in the southern hemisphere. Therefore that is where we will have to situate our laser. This raises some political problems.

(11) **DANGER!** The laser will be very powerful, and the light it emits will be very intense.

(A) A Long Thin Atomic Bomb Indeed, the launch will be more like a catastrophe than the mere turning on of a light. We need to think carefully about the environmental and political issues involved.

(B) The Reflected Light will be sent back towards us – and it could pose a great danger.

OK – THAT’S ENOUGH. HERE WE GO!

(3) WHAT ARE STARLIGHT AND BREAKTHROUGH STARSHOT?

(A) The Concept

The Starlight and Breakthrough Starshot programs are working to design a spacecraft capable of voyaging to a star.

Plans call for a voyage lasting twenty years. Once it has arrived at its destination, the spacecraft will send back a message announcing its achievement. That message will take four more years to reach us. So if all goes well, twenty-four years after having sent forth our voyager, we will receive confirmation that the project has succeeded.

Twenty-four years: that is how long Marco Polo took for his voyage.

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The stars are very far away – incomparably farther than the planets of our Solar System. The distance the proposed voyager will have to traverse is overwhelmingly greater than distances to the planets. So the spaceship will have to go fast – very fast, faster than any man-made object has ever gone. The plan is for it to travel at 1/5 the velocity of light.

No foreseeable technology involving rockets that we might develop, now or in the future, is remotely capable of reaching such great speeds. As a consequence, the technology we have developed to explore inter<u>planetary</u> space is utterly insufficient to explore inter<u>stellar</u> reaches. New technology is the only answer. And in fact, propelling the interstellar voyager on its way will not be a conventional rocket engine at all. It will be pure, unadulterated radiance. Light exerts a force: the only reason we do not experience this force in daily life is that the light we normally experience is relatively weak. But the more intense the light the greater the force it exerts. Starlight and Breakthrough Starshot aim to develop a laser of unpatrolled intensity to speed the interstellar voyager on its way.

Of course, the bigger the spacecraft the harder to propel it up to the requisite great speed. So the voyager will have to be tiny. Not a space ship, large enough to house astronauts Not even a robot such as those we have sent throughout the Solar System. Instead, the projects propose to send a voyager such as illustrated in Figure 3.1

Figure 3.1 <u>The Interstellar Voyager</u> must be very small.

It looks like a chip -- an integrated chip, the sort of thing you would find if you were to pry open your computer and look inside. So that’s what the Breakthrough Starshot people call it: not a “starship” but a “starchip.” In the Starlight program people call it a “wafer-sat.”

Such a tiny voyager will not just be small. It will also be fragile. Weight is the main enemy, and adding a protective armor about the miro-craft would increase its weight unacceptably. So it will have to travel unprotected. And while underway it will be exposed to all the rigors of interstellar space -- cosmic rays, ultraviolet radiation, interstellar grains -- through which it will rush at breakneck speed.

There is, therefore, only a slight chance that such a fragile device will survive. Most likely it will be destroyed en route. So the plan is to take refuge in numbers. Don’t send just one – send many. An entire flotilla of voyagers will set forth, in the hope that a few will survive the journey and remain functional when they arrive at their destination.

The plan we will analyze in this Teacher’s Aid calls for a conventional rocket to place the flotilla of starchips / wafer-sats into an orbit about the Earth. As they circle the planet, each will be attached to a mirror composed of some highly reflecting material. The mirrors, known as “light sails,” will orient themselves so that their reflecting surfaces face the ground below. The flotilla, spacecraft and light sails, will be orbiting the Earth at 17,000 miles per hour.

Down below on the ground, will sit a gigantic laser. It is pointing directly upwards.

Now the orbiting flotilla appears over the horizon. The laser waits. And at a precise moment, just as the flotilla passes overhead, the laser fires. It emits an intense burst of light (Figure 3.2).

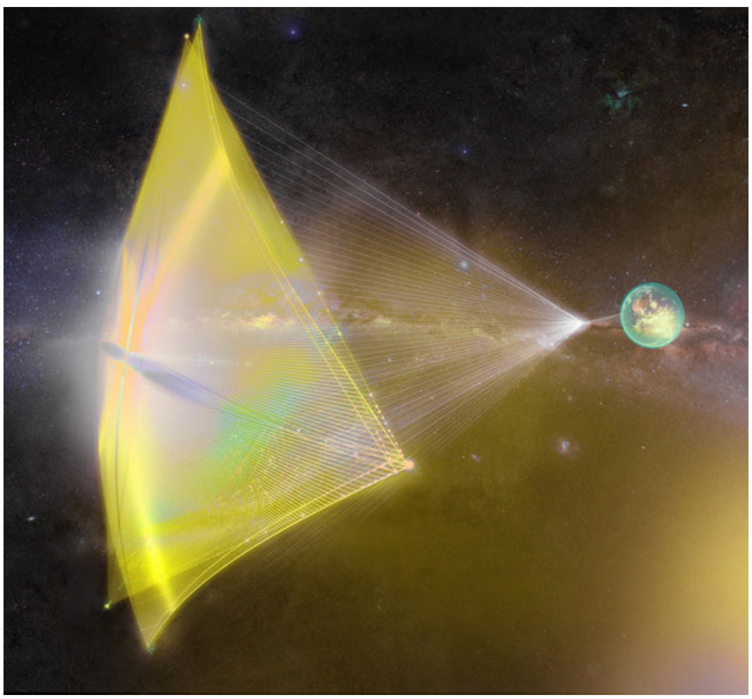

Figure 3.2 The Laser Fires propelling the flotilla on its way.

So intense is the light that it will exert a mighty acceleration on the light sails. They will be violently shoved outwards. Suddenly the spacecraft will be no longer travelling at 17,000 miles per hour, but at 37,000 miles per second. In a matter of moments they will have rushed past the Moon (the Apollo astronauts took 3 days to get there). In a matter of hours they will have rushed past the orbit of Neptune, outermost planet of the Solar System (the only spacecraft to have visited it, Voyager 2, took 12 years to get there).

And then they will be on their way to the stars.

(B) The Target Star:
Proxima Centauri

To which star?

To the naked eye Alpha Centauri is the third brightest star in the sky. But a surprise is in store if you look at it through a small telescope: what appears to be a single star is actually two. Known as Alpha Centauri A and Alpha Centauri B, each is pretty similar to our Sun. One is a little brighter, the other a little dimmer. They swing about one another in an orbit lasting 80 years.

It takes a far more powerful telescope to discover that Alpha Centauri is not just a double star -- it is a triple. In 1915 the astronomer Robert Innes spotted a third star, orbiting quite far away from the other two. It is very much smaller and fainter then they (Figure 3.3).

This object, known as Proxima Centauri, swings about the others in an orbit requiring hundreds of thousands of years. Currently Proxima Centauri is the closest known star. It is 4.24 light years away. In 2016 a planet was discovered orbiting about it, a planet roughly the size of the Earth. This planet lies in the so-called “habitable zone” about the star – the region where it is not so hot that water boils, and not so cold that water freezes. The region where liquid water can exist. The region in which a planet just might conceivably support life.

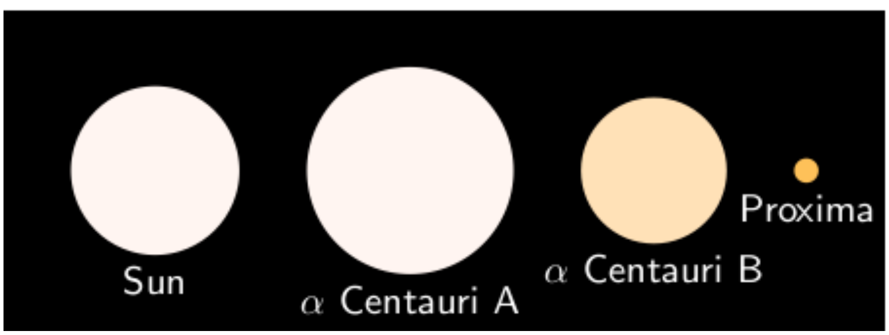

Figure 3.3 The Target Star System is Alpha Centauri. Specifically, Breakthrough Starshot will aim towards Proxima Centauri, the closest star to us.

That is where the spacecraft will go. The goal is for it to study that planet and radio back to us what it found.

When it gets there, if it were to take a look around it would find that the view of the universe from Proxima Centauri is pretty much the same as it is from Earth. By and large, the constellations will look as they do from here. There is one difference, though: an alteration of the constellation Cassiopeia. As seen from Proxima Centauri there is an extra star in Cassiopeia, shining brightly.

That star is us – our own Sun.

(C) The Programs and Their Funding

Two programs are currently underway to explore this new way to reach the stars:

The Starlight Program, based at the University of California Santa Barbara, is a program of the UCSB Experimental Cosmology Group. Directed by Philip Lubin, it is primarily funded by NASA.

It was Lubin who first pioneered the concept of powering interstellar spacecraft by light.[3]

Breakthrough Starshot, a more widely-spread program, is unusual in that it is funded by a single person: Yuri Milner. Milner is an Israeli-Russian entrepreneur, venture capitalist and physicist. In 2016 he announced the founding of Breakthrough Starshot, setting aside $100 million of his own money over a decade for the project.

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[3] http://arxiv.org/abs/1604.01356

(4) TERMINOLOGY:
THE ASTRONOMICAL UNIT AND THE LIGHT YEAR

Before we start, it will be helpful to introduce two units by which astronomers measure distances: the astronomical unit and the light year.

First, the astronomical unit:

The astronomical unit
The distance from the Earth to the Sun
1.50×10^{11} meters

The astronomical unit is the natural unit of distance within the Solar System. For instance Mercury, the closest planet to the Sun, has a mean distance from the Sun of just over 1/3 of an astronomical unit. Neptune, the farthest, has a mean distance from the Sun of slightly over 30 astronomical units.

And next the light year:

The light year
The distance light travels in a year
9.46×10^{15} meters

The light year is the natural unit of distance among the stars. For instance Alpha Centauri, the closest star visible to the naked eye, lies 4.37 light years away. Proxima Centauri is 4.24 light years away. Many stars visible to the naked eye lie hundreds or even thousands of light years away.

(Be careful here, because there is a potential for confusion. The very name “light year” brings to mind the concept of time. But the light year is not measure of time: it is a measure of distance. It is like saying that a highway hour is 65 miles.)

Notice that light travels at the speed of one light year per year. So, when we look at Alpha Centauri, which is 4.37 light years away, we are seeing it as it was 4.37 years ago. And if a race of alien astronomers exists several hundred light years away, when they look at us through their telescopes they are seeing us as we were several centuries ago.

Problem how many miles are there in a highway minute?

Problem How many meters are there in a light week? (The speed of light “C” is $C = 3.00 \times 10^8$ meters / second)

Problem the Moon’s orbit about the Earth is a circle of radius 3.84×10^8 meters. When the Apollo astronauts were walking on the Moon and conversing with flight controllers back in mission control, how much time elapsed between an astronaut speaking and receiving a reply? (Radio signals travel at the speed of light.)

<u>Problem</u> If the Sun were suddenly to stop shining, how long would it take us to notice the fact? (Don't panic: it's not going to happen!)

<u>Problem</u> Since light takes a certain amount it time to travel interstellar distances, an alien astronomer surveying the Earth with a telescope is seeing the Earth as it was some time ago. Find an online catalog of nearby stars, and identify one upon which such an astronomer would be able to watch you when you were a baby. Does there happen to be a star from which the astronomer could watch you being born?

<u>Aiming the mission</u> Our proposed flotilla will have to pass fairly close to that planet orbiting Proxima Centauri when it gets there – otherwise the spacecraft would be unable to study it! So we need to aim it pretty carefully. How carefully? Let us say that we want a spacecraft to pass within one astronomical unit of the planet. How difficult will this be to arrange? To get a feel for this, let us think of it as hitting a bull's eye at some distance.

Suppose our bull's eye is a dime. How far away must that dime be in order for the task of hitting it to be similar to the task of coming within one astronomical unit of Proxima Centauri's planet? We can think in terms of a proportion:

(Dime distance) / (dime diameter) = (Proxima Centauri distance) / ("bull's eye" diameter)

I measured a dime and found it to be around 11/16 of an inch across, which is 1.75×10^{-2} meters. Similarly,

distance to Proxima Centauri = 4.24 light years
= $(4.24)(9.46 \times 10^{15}$ meters)
= 4.01×10^{16} meters

"bull's eye" diameter = 2 astronomical units *Careful! Why the "2?"*
= $(2)(1.5 \times 10^{11}$ meters)
= 3.0×10^{11} meters

So our proportion tells us

(Dime distance) / (1.75×10^{-2} meters) = (4.01×10^{16} meters) / (3.0×10^{11} meters)

Which we solve to find

Dime distance = 2.34×10^{3} meters = 1.45 miles

So the task of aiming our flotilla correctly is like the task of hitting a dime a mile and a half away.

<u>Project</u> Research some recent space missions. How close to their intended target did they come? Compare the "aim" they achieved with what our flotilla will have to achieve.

(5) **INTERSTELLAR DISTANCES**

(A) Interstellar Travel in Context:
The Voyager Mission

To appreciate the extreme difficulties of interstellar travel, let us place it in context. Let us take the best we have been able to achieve so far, and compare it to what is needed to reach a star.

The Voyager mission represents humanity’s farthest push outwards into the cosmos[4]. Two identical spacecraft were launched in September 1977: their goal was to explore the outer Solar System. One of these, Voyager 1, is currently the most distant man-made object in existence. Nothing has traveled farther. As of January 1, 2019 it was far beyond the outermost planet Neptune, at a distance from the Earth of

Distance to Voyager 1 = 145 astronomical units
= (145 astronomical units)(1.50 X 10^{11} meters / astronomical unit)
= 2.17 x 10^{13} meters

<u>Problem</u> *To get an intuitive feel for it, translate this result into miles*

Voyager 1 is so distant that nearly a day is required for its radio transmissions to reach us.

<u>Problem</u> *Find the exact signal travel time from Voyager to us (to repeat -- radio signals travel at the speed of light).*

To get a feeling for how difficult it is to send a mission to the stars, let us ask how long this spacecraft would take to reach the closest star.

We can use proportions. If we denote

$\mathscr{g}$ = (distance to Proxima Centauri) / (distance to Voyager 1)

Then we know that, if Voyager keeps travelling at the same speed

(time to reach Proxima Centauri) / (time Voyager 1 has been travelling) = $\mathscr{g}$

The time Voyager has been travelling is the time between launch and January 1, 2019: this is 41.3 years. So we calculate

Distance to Proxima Centauri = 4.24 light years
= (9.46 X 10^{15} meters / light year)(4.24 light years)
= 4.01 X 10^{16} meters

[4] https://voyager.jpl.nasa.gov/mission/

Distance to Voyager 1 = 2.17×10^{13} meters

so that $\mathcal{J} = 4.01 \text{ X } 10^{16}$ meters / 2.17×10^{13} meters = 1.85×10^{3}

And we find our answer

Time to reach Proxima Centauri = ($\mathcal{J}$) (41.3 years) = **76,400 years**

<u>Problem</u> There’s another way to do this. First find the average velocity of the spacecraft by dividing the distance it travelled by the time it took to do so: then find out how long it would take to travel the required distance. Make sure you get the same answer! As an added fillip, translate your answer for Voyager’s average velocity into miles per hour – when I did it, I was surprised.

A note of caution: our calculation is not exact. There are three reasons

1. Voyager did not take a straight-line path to its current location. Indeed, in space nothing follows a straight-line path: things follow orbits. Within the Solar System these are ellipses with one focus at the Sun. And in interstellar space, objects follow orbits within the Galaxy.

2. Voyager did not leave from the Sun: it left from the Earth.

3. Voyager is not aimed at Proxima Centauri. Indeed, it is not aimed at any particular star.

Nevertheless our general conclusion is certain: the stars are enormously distant. And this makes travel to them enormously hard.

<u>Problem</u>: The Apollo astronauts took 3 days to reach the Moon. At this speed, how long would they have taken to reach Proxima Centauri?

(B) Scale Models of the Cosmos

Let continue with our effort to get an intuitive feeling for the magnitude of distances in the cosmos. Let us build in our minds a scale model.

Imagine that in this model we represent the Earth by a marble one inch across, so that its radius would be ½ inch, or $1.27 \text{ X } 10^{-2}$ meters. Since the Earth’s true radius is $6.38 \text{ X } 10^{6}$ meters, in our model distances are shrunk by the factor $\mathcal{R}$ --

$\mathcal{R}$ = (Earth’s radius in the scale model) / (Earth’s radius in reality)

$\mathcal{R} = (1.27 \text{ X} 10^{-2}$ meters) / ($6.38 \text{ X } 10^{6}$ meters) = $1.99 \text{ X } 10^{-9}$

Now consider Neptune – the outermost planet in the Solar System. How far away would it be in our scale model?

Neptune’s orbit has a mean distance from the Sun of 30.1 astronomical units. Since our orbit has a mean distance from the Sun of 1 astronomical unit, at closest approach Neptune lies 29.1 astronomical units from Earth, or

Distance to Neptune at closest approach = 4.37×10^{12} meters

Since distances are shrunk by the factor $\mathcal{R}$ we find

<u>The distance to **Neptune** in the model</u> = ($\mathcal{R}$)(4.37×10^{12} meters) = 8.70×10^{3} meters = **5.4 miles**

In contrast, <u>the distance to **Proxima Centauri** in our model</u> would be

($\mathcal{R}$)($4.01 \text{ X } 10^{16}$ meters) = $7.98 \text{ X } 10^{7}$ meters = **49,600 miles**

which gives us an idea of how distant the stars lie from us.

<u>Problem</u> Recall that the Moon’s orbit about the Earth is a circle of radius $3.84 \text{ X } 10^{8}$ meters. How distant would it be in our model?

<u>Problem</u> Suppose we have a model in which Neptune is one mile away. How far would it be in this model to Proxima Centauri?

<u>Problem</u> Suppose we have a model in which the Earth is one foot across. How far would it be in this model to Proxima Centauri?

<u>Problem</u> Suppose we have a model in which Proxima Centauri is 1,000 miles away. In this model is the Earth big enough to see with your naked eye?

Now we are beginning to understand why interstellar travel is so hard. One way to achieve it is to imagine a spacecraft capable of travelling for great amounts of time – centuries, thousands of years. But if we want to reach the stars in a shorter amount of time, we will need to travel fast – very fast, far faster than any rocket has ever travelled before. But, as we will now see, using conventional technology this is impossible. It requires too much fuel.

(6) HOW MUCH FUEL WOULD A CONVENTIONAL ROCKET NEED?

THE ROCKET EQUATION

The launch of the Voyager mission was a spectacular and cataclysmic event:

Figure 6.1 Launch Of The Voyager Mission was like lifting a skyscraper into the sky.

The launch vehicle, a Titan / Centaur rocket, stood 160 feet high: that's the size of a 16-storey skyscraper. It weighed 1,395,460 pounds – nearly 700 tons. The Voyager spacecraft it carried, in contrast, was positively puny. Below is a schematic diagram: you can see how small Voyager was in contrast to the rocket that launched it.

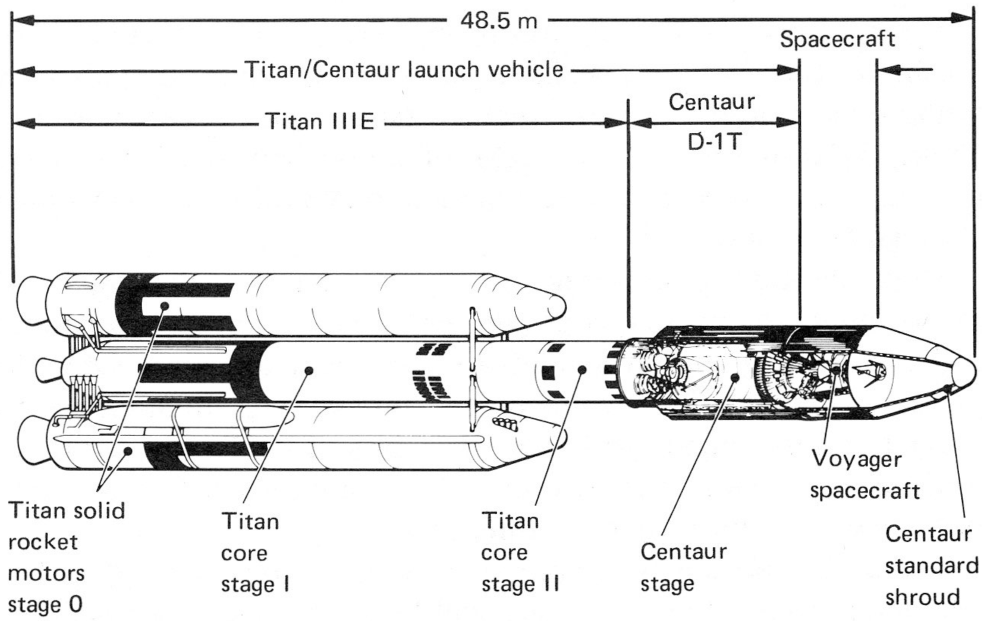

Figure 6.2 *<u>The Vehicle That Launched Voyager</u>* *was very much larger than the spacecraft itself.*

But the point is not that Voyager was small. The point is that the rocket that launched it was big. Most of what so spectacularly lifted off from Cape Canaveral that climactic day never made it to the outer Solar System. Indeed, it never even made it into space! Rather it was used on the way up. Almost all of what those thundering engines were lifting upwards that day was not the spacecraft at all. It was fuel – fuel that was going to be needed just a few minutes later.

Maybe an analogy will be helpful. Imagine that we are planning to drive off on a trip – a long trip, very long: all the way across the country perhaps. How much fuel will we need? Well, we know how far we are planning to drive and we know how many miles per gallon our car gets, so we might think that the calculation is simple. Just divide miles by miles per gallon.

But suddenly we realize that things are more complicated than that – because we just happen to know that there are no gas stations along the way. So we will have to carry along with us all the gas that we are ever going to need from the very start. Of course, the car's fuel tank isn't big enough for all that gas. So we'll have to tow a trailer-full of the stuff along behind.

But then we realize that all this fuel weighs something! And then we realize something more: that, hauling such a heavy load, our car doesn't get its usual mileage. Now its mileage is worse. We're going to need even more gas than we thought if we'll be dragging along that extra weight. So our initial calculation of how much fuel we need was too low.

And so we realize that we will need an even bigger trailer than we had thought, all filled with even more fuel than we had thought. But then we realize that our car's mileage is even worse than we had thought.

And so on and so on.

This is the problem with conventional rocketry. Huge quantities of fuel are required. And the faster we need our rocket to go, the worse the problem grows.

This circular, worm–eating–its–tail situation is neatly summed up in the rocket equation: a formula which tells us how much fuel we need[5]. If the velocity we wish our spacecraft to achieve is V and its mass is M, then the mass of fuel M_{fuel} required is

$$M_{fuel} = M\,[10^{(V/2.30 \text{ x } V_{exhaust})} - 1]$$

Here $V_{exhaust}$ is the exhaust velocity of our rocket engine – the velocity with which the engine expels its gasses.

Let us use this formula to get an idea of how difficult it would be to reach the stars using this sort of conventional rocketry. Suppose for the sake of argument that our rocket engine is the main engine of the Space Shuttle, for which

$$V_{exhaust} = 4.4 \text{ kilometers / second} = 4.4 \text{ X } 10^{3} \text{ meters / second}$$

Since we want send off our spacecraft at V = 1/5 the velocity of light

$$\begin{aligned} V / (2.30 \text{ x } V_{exhaust}) &= C / (5 \text{ x } 2.30 \text{ x } V_{exhaust}) \\ &= (3.00 \text{ X } 10^{8} \text{ meters / sec}) / (5 \text{ x } 2.30 \text{ x } 4.4 \text{ X } 10^{3} \text{ meters / second}) \\ &= 5{,}930 \end{aligned}$$

So the rocket equation tells us that the mass of fuel required is

$$M_{fuel} = M\,[10^{5{,}930} - 1]$$

How big a payload do we wish to send off to Proxima Centauri? Suppose the payload has the mass of a person, for which M is perhaps 70 kilograms.

Problem What is your mass in kilograms?

Then the mass of fuel required is

$$M_{fuel} = [70]\,[10^{5{,}930} - 1] \text{ kilograms}$$

[5] The derivation of this formula requires calculus. If your students are familiar with this subject, a good reference is given in https://en.wikipedia.org/wiki/Tsiolkovsky_rocket_equation

But this is an impossibly great amount of fuel. The factor in square brackets is a one followed by 5,930 zeroes. So the mass of fuel required is incomparably greater then the mass of the entire planet Earth!

Let us turn the problem around. Let us take the maximum quantity of fuel that we could possibly imagine, and ask what sort of payload it would be capable of accelerating to 1/5 the velocity of light. As an extreme case, let us imagine that we were to use the total oil reserves of our entire planet – surely that is a rigorous upper limit! I went roaming through the internet and found a very rough estimate:

$M_{\text{total oil}} = 2 \times 10^{14}$ kilograms

Using this as our M_{fuel} the rocket equation tells us that the Space Shuttle's engine would be capable of accelerating to one fifth the velocity of light a spacecraft of mass M given by

$M = M_{\text{fuel}} / [10^{(V/2.30 \times V_{\text{exhaust}})} - 1]$
$M = 2 \times 10^{14}$ kilograms $/ [10^{(V/2.30 \times V_{\text{exhaust}})} - 1]$
$M = 2 \times 10^{14}$ kilograms $/ [10^{5,930} - 1]$

Again, the factor in square brackets is a one followed by 5,930 zeroes. So we see that the mass M of the "spacecraft" would be far less than the mass of a single electron!

<u>Problem</u> *Suppose we send our voyager off at a lower velocity – say one percent the velocity of light. (a) How long would this mission take to get to Proxima Centauri? (b) How much fuel is required to send off a 70-kilogram payload if the Space Shuttle's engine is used? Does this amount of fuel exist?*

<u>Problem</u> *Suppose we use up the entire oil reserves of the Earth to send off a 70-kilogram spacecraft. How long would it take to reach Proxima Centauri if it used the Space Shuttle's* $V_{exhaust}$*?*

<u>Problem</u> *What sort of* $V_{exhaust}$ *is required if we wish to use the entire oil reserves of the planet Earth to send off that 70-kilogram payload at 1/5 the velocity of light? How much greater is this than the Space Shuttle's* $V_{exhaust}$*?*

(7) THE NEW IDEA: PUSH THE SPACECRAFT WITH LIGHT

(A) The Basic Idea

Now we understand why interstellar travel is so hard:

- The stars are very far away
- Therefore, to get to the stars in a reasonable amount of time, great velocities are required
- The quantity of fuel required to reach these velocities is impossibly large -- because <u>a rocket lifts not just its payload, but also its fuel.</u>

It is this worm-eating-its-tail situation which makes the fuel requirements so great. How can we find a way around it? We need to come up with some way to avoid having to accelerate the fuel! For after all, the fuel is not the point. It is the payload that is the point. That is the only thing that we really want to send off on its way.

Let us return to the analogy we gave earlier of taking a long automobile trip. The problem there was that we needed not just our car to make the trip – we also needed to carry along with us all the fuel we were going to need. How can we get around this?

Here’s a thought. Suppose we put up a sail on our automobile. And suppose there just happened to be a wind blowing – blowing from behind us, so that the wind would push us along.

Is this a promising thought? Well, it certainly obviates the need to carry along any fuel. As a matter of fact, it also obviates the need to carry along the car’s engine, which itself weighs a lot. So this looks like a good start.

The problem, of course, is that the wind might be blowing in the right direction – but, then again, it might not. And furthermore, if we want to travel very fast we would need a very strong wind, a wind stronger than any that blows in nature. How can we modify our new idea to take these into account?

How about an artificial wind – a wind that we ourselves have created? Let us imagine some sort of fan -- a fan that we set up on the ground behind the car (Figure 7.1).

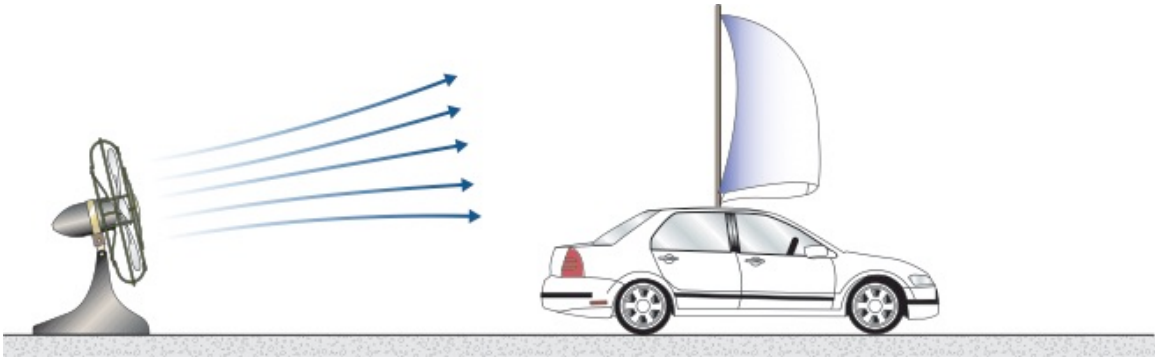

Figure 7.1 <u>Propel A Vehicle With A Wind</u> If we do so, we don’t need to carry along with us any fuel.

Now we seem to be getting somewhere. There still is no heavy engine on board our automobile, and the wind always blows, and it always blows in the right direction. And if our fan is very powerful, maybe our wind can be made sufficiently strong. And best of all, the fuel that powers the fan no longer needs to be pushed along. It just sits there on the ground alongside the fan, motionless. So we have escaped our circular, worm-eating-its-tail situation: we don’t have to push the fuel.

Philip Lubin’s concept was to use a “wind” of pure light.

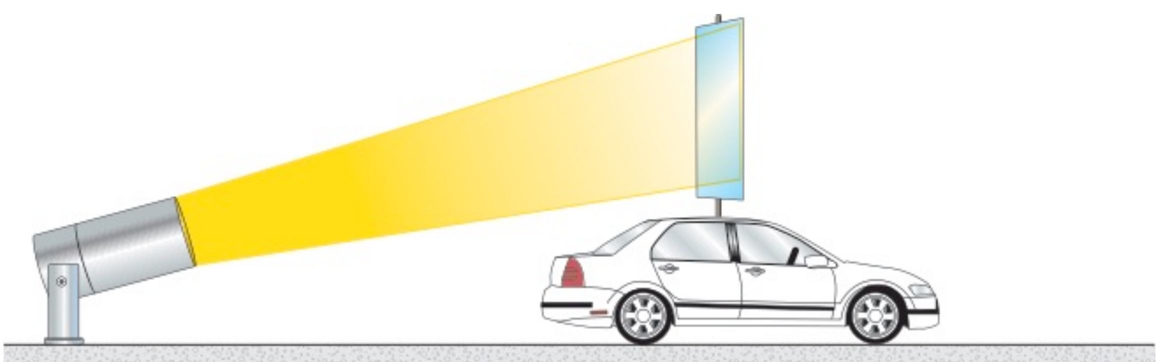

Figure 7.2 <u>Propel A Vehicle With A “Wind” Of Light</u> This is the Starlight / Breakthrough Starshot concept.

In normal experience we never notice that light exerts a force. But this is because in normal experience light is relatively faint. Even something as powerful as a giant searchlight is faint” in this sense. But if we had a truly bright light, a light incomparably more brilliant than a searchlight, it would exert a great force. The plan is to use a gigantic laser.

The nice thing about this design is that this laser need not be in orbit about the Earth. It can sit right here down on the ground, which makes things a lot easier. The laser sends forth an intense burst of light. Mounted on the back of our spacecraft is a mirror. The light shoves on the mirror:

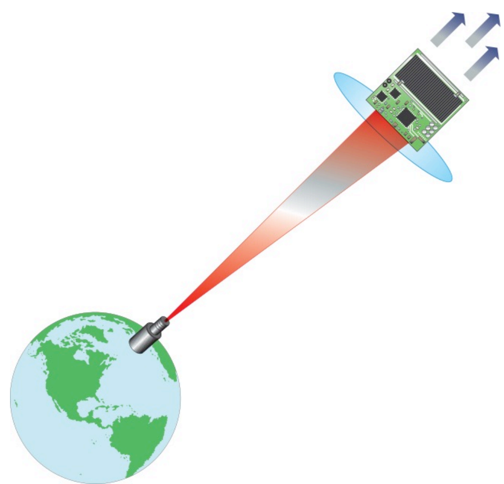

Figure 7.3 *<u>The Breakthrough Starshot Concept</u>* *is to place the spacecraft in orbit about the Earth. As it passes overhead, the laser fires. The light exerts a push on the spacecraft, sending it on its way.*

(Remember that the plan is to launch an entire flotilla of such spacecraft. We are illustrating only one.)

If we use this scheme, it turns out that the amount of fuel required to achieve interstellar travel is no longer so impossibly great. In what follows we will see how this comes about.

(B) The Energy of Light

The physical principle behind the new concept is that light exerts a force. In technical terms, we say that light carries momentum. So our mighty laser, shining its brilliant light on the spacecraft, is bouncing momentum off it. Some of the light’s momentum is transferred to the spacecraft and sends it on its way. It’s just the same as our analogy of a wind blowing along a car: the moving air carried momentum, and when it hit the sail it transferred momentum to it.

The momentum carried by light depends on its intensity – and the intensity of a source of light is the brightness of the light: the rate at which the source emits energy. The technical term for this rate of energy emission is power. So before discussing light’s momentum, we need to start with light’s energy.

A lamp pours out energy, which we perceive as visible light. The more energy it emits per second, the greater is the brightness we perceive. A dim lamp (low power) emits a small amount of energy each second: a brighter one (high power) emits lots of energy each second.

The unit of light energy in the MKS system is the Joule. So we measure the rate of emission of energy (the power) in Joules per second. A subsidiary unit is the Watt, which is just one Joule per second. So a 100-Watt light bulb emits 100 Joules of light energy in one second. In the next second it emits another 100 Joules of energy, and so on. A 200-Watt light bulb emits 200 Joules in a second and so forth.

(As an aside, I should mention that even a faint light bulb emits a good deal of energy. In the fitness center that I use, the stationary bicycles tell me how many Watts I am expending as I puff and pant along. I find that, even if I am cycling at a pretty stiff rate, I find it hard to generate as many as 100 Watts. Of course, I am in my 70’s: you will probably be able to do better.)

Problem Head over to your fitness center and see how many Watts you can achieve.

Problem Keep on cycling at that rate for a minute. How many Joules have you expended? Where did that energy came from?

Problem Cycle at a more comfortable pace. For how long must you cycle to expend one thousand Joules?

Problem Consider a one MegaWatt laser. How many Joules does it emit in a second?

Problem For how long must you leave a 100-Watt light bulb on for it to have emitted one thousand Joules? How how long does it take two such light bulbs to emit the same total energy?

A further unit we sometimes use is the kilowatt – hour. Although it sounds like a unit of power, actually this is a unit of energy: it is the amount of energy emitted by a kilowatt light source in one hour. Let us calculate:

Energy emitted by that light source in one second = (1,000 Watts)(1 second)
= (1,000 Joules/second)(1 second)
= 1,000 Joules

So energy emitted in one hour = (1,000 Joules)(60 minutes/hour)(60 seconds/minute)
One kilowatt - hour = 3.6 X 10^6 Joules

This energy costs money: the nationwide average is about 12 cents for every kilowatt hour used. Let us calculate how much it costs to turn on a light bulb. Suppose I have left on a 100-Watt light bulb for an hour. In that time

Energy emitted = (100 Joules / second)(60 minutes/hour)(60 seconds/minute)
= 3.6 X 10^5 Joules

Comparing this to our previous result, we see that my bulb has emitted 1/10 of a Kilowatt – hour. (We could also have gotten this result by noticing that my light bulb is 1/10 as bright as our 1,000 Watt light source!) So the power company will charge me

(12 cents per kiloWatt – hour)(0.1 KiloWatt – hour)

which is a bit more than one cent. Cheap!

Problem: In my living room there are 5 lamps, each of which has a pair of 100-Watt light bulbs. Suppose I turn all of them on. How much money am I spending per hour?

Problem: Suppose that, just before going to bed, you turned on every light in your home and left them shining all night. Would this cost more or less than the dinner you ate that night?

(C) The Momentum of Light

Here we analyze the push delivered by light: the force it exerts. It will turn out to depend on the light’s energy.

Let us begin with something that might be more familiar: the momentum of material objects. Consider some object – a stone, say. Suppose it is flying along (Figure 7.4).

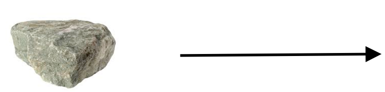

Figure 7.4 Momentum Of A Moving Object is its mass times its velocity.

This stone carries momentum, which we denote as P. The formula for this momentum is

P_{stone} = (mass of the stone)(velocity at which it moves)
$P_{stone} = MV$

where the stone's mass is M and its velocity is V. So the units in which we measure momentum are kilogram – meters / second.

Less familiar is the fact that light also carries momentum. Imagine turning on a flashlight for a short amount of time, and then turning it off. A pulse of light has been emitted (Figure 7.5).

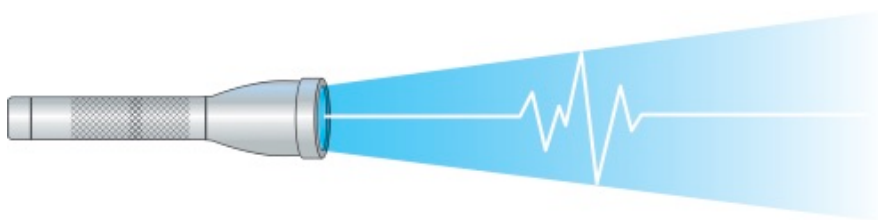

Figure 7.5 Momentum Of Light is its energy divided by the speed of light.

And just like the stone, the pulse of light carries momentum. The formula for it is

P_{lght} = (energy of the light pulse) / (velocity of light)
$P_{lght} = E / C$

Where "E" is the energy in the pulse (in Joules) and "C" the velocity of light (in meters per second).

> Interlude on units. From our example of the stone we see that the units of momentum are those of mass times velocity. But in our example of the light pulse, the units are energy divided by velocity. You might think that the two units are completely different. We can see, however, that in fact they are not.
>
> This is because energy has units of mass times velocity squared. To see this, recall the formula from mechanics for kinetic energy KE:
>
> $KE = (1/2)MV^2$
>
> Or alternatively remember Einstein's famous formula
>
> $E = MC^2$

> Both of these tell us that energy has the units of mass times velocity squared. So if we divide Joules by the velocity of light we get units of mass times velocity. So the units work out all right.
>
> In what follows we will just go ahead and replace Joules / (meter per second) with (kilograms – meter) / second whenever we feel like it: they are interchangeable.

Here is a conundrum: if light carries momentum, why don't we notice the fact? Why don't we feel our lamps and the headlights of our cars shoving us around? Let us do a calculation to see why. Imagine that we turn on a 100 Watt light bulb for one second. How much momentum has it emitted? We will now show that the answer is: only a tiny amount.

We calculate

Energy "E" emitted by that light bulb = (100 Joules / second) (one second)
E = 100 Joules
So the momentum it emitted was

Momentum = (energy emitted) / (speed of light)
= (100 Joules) / (3.00 x 10^8 meters/second)
= 3.33 x 10^{-7} kilograms – meter / second

This is certainly a small amount of momentum. But is it too small for us to notice in everyday life? To get a feeling for this, let us compare it with something that we all agree carries a tiny amount of momentum. Specifically, let us consider a tiny speck flying along. Maybe it is a little speck of dust. How rapidly – or rather, how slowly – must we imagine it to be moving in order for it to carry such a small amount of momentum?

Suppose that the speck is a tiny cube, one millimeter (10^{-3} meters) on a side. Then its volume is

Volume = $(\text{side})^3$
= $(10^{-3})^3 = 10^{-9}$ meters^3

And what is its mass? Imagine that the speck of dust has a density twice that of water. (That's more or less the case for minerals.) Since the density of water is 1,000 kilograms per cubic meter, we calculate

Mass of the grain = density x volume
= (2 x 10^3 kilograms / meter^3) x (10^{-9} meters^3)
= 2 x 10^{-6} kilograms

How rapidly – or rather, how slowly – must it move in order to have the momentum of our light pulse? We calculate

(Mass of speck)(its velocity) = (momentum of speck) = (momentum of light)
(2×10^{-6} kilograms) (velocity of speck) = 3.33×10^{-7} kilograms – meter / second

So

velocity of speck = (3.33×10^{-7} kilograms – meter / second) / (2×10^{-6} kilograms)
= 0.17 meters / second
= 0.38 miles / hour

Would you notice the shove if a tiny bit of dust ambling along at one-third of a mile an hour were to bump into you? No you would not. And this tells us why we never notice the momentum of light in everyday life: a 100 Watt light bulb is emitting a tiny amount of momentum each second.

But a giant laser is emitting a lot of momentum each second.

Problem *Let us imagine some sort of object flying along at one hundred miles per hour. What must be its mass if its momentum equals that of our light pulse from the 100 Watt light bulb? What sort of object has such a mass?*

Problem *Professional tennis players hit serves at more than one hundred miles per hour.(A) How many light bulbs must be left on for one second to emit the momentum carried by a tennis ball moving at such a velocity? (B) Would this collection of light bulbs be enough to blind you?*

(D) Push the Spacecraft by Bouncing Light Off Of It

Our laser emits a short burst of light, which rises up to meet the spacecraft. That light carries energy and momentum. Mounted on the back of the spacecraft is a mirror: when the light reflects off the mirror, it transfers energy and momentum to it. The reflected light also carries energy and momentum as it heads back downwards (Figure 7.6).

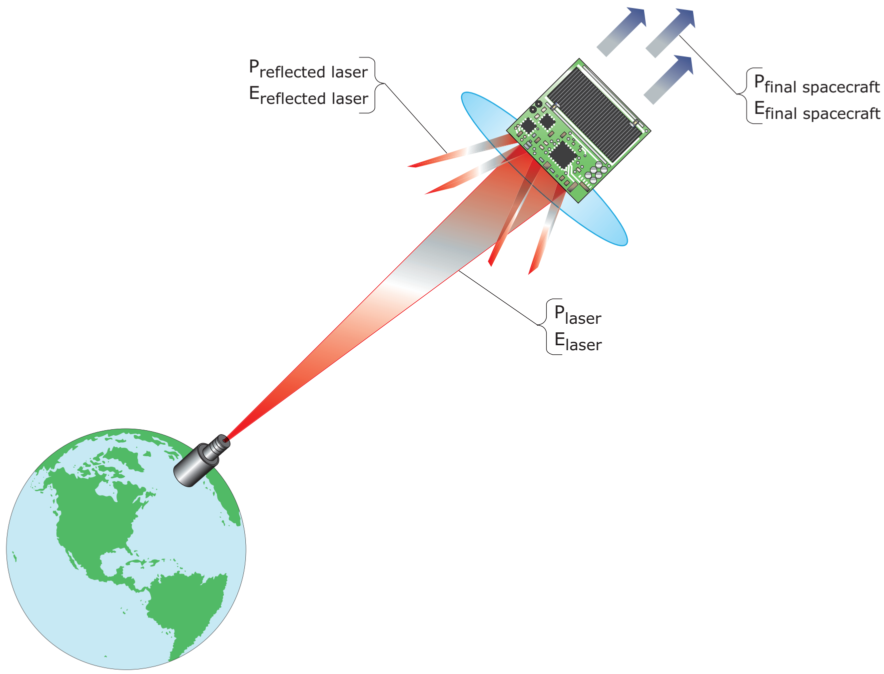

Figure 7.6 Push The spacecraft by bouncing light off of its mirror.

Let us analyze this reflection, and see how much of a shove the light gives to our spacecraft. In what follows our goal is to find the energy the laser must emit if it is to accelerate our payload to the desired velocity. And just to give it away: we are going to find that the energy is not going to be impossibly large!

The only things we need will be two principles of physics: the conservation of momentum and the conservation of energy. These principles state that, as the laser light reflects off the mirror, both the total momentum and total energy of the system remain the same.

Prior to the reflection, what were the total momentum and energy? As for the spacecraft, it was holding still so its momentum and energy were zero[6]. As for the light, it carried momentum

[6] We are making an error here. The starchips are certainly not holding still: they are orbiting the Earth! What can we do to remedy this error?

One simple approach is to point out that the velocity with which the interstellar voyagers are orbiting (17 thousand miles per hour) is very much less than the velocity with which they are going to end up moving (1/5 the velocity of light, which is 37,000 miles per second). So we can safely ignore it. This is certainly a correct conclusion insofar as it goes. But a complete approach,

P_{laser} and energy E_{laser}. So prior to the reflection, the total momentum and energy were

$P_{initial} = P_{laser}$

$E_{initial} = E_{laser}$

What are the total momentum and energy after the reflection? As for the spacecraft, it is now moving so its momentum and energy are no longer zero: rather we will denote them as $P_{final\ spacecraft}$ and $E_{final\ spacecraft}$. Similarly, the reflected light pulse now carries momentum and energy $P_{reflected\ laser}$ and $E_{reflected\ laser}$. There is, however, one crucial issue that we need to keep track of: because the light has reversed direction, we must now subtract its momentum when finding the total momentum. The light's energy, however, is not a vector but just a number (a scaler, in technical terms), so we add it in order to find the total energy.

So we have

$P_{final} = P_{final\ spacecraft} - P_{reflected\ laser}$

(watch that minus sign!)

And

$E_{final} = E_{final\ spacecraft} + E_{reflected\ laser}$

(and notice that plus sign!)

And now we use our two conservation laws. Conservation of momentum tells us

$P_{initial} = P_{final}$

which reads

$P_{initial\ laser} = P_{final\ spacecraft} - P_{reflected\ laser}$ Equation 1

And conservation of energy tells us

$E_{initial} = E_{final}$

$E_{laser} = E_{final\ spacecraft} + E_{reflected\ laser}$

Writing this energy equation in terms of the formulas for energy:

---

which might be great fun for advanced students, is to point out that the orbital velocity is perpendicular to the push from the laser, and that we are analyzing only one component of the problem. If the students analyze the situation correctly, they will end up demonstrating that the simple approach was valid.

$P_{laser}\ C = \frac{1}{2}MV^2 + P_{reflected\ laser}\ C$

solving this for the momentum of the reflected light we get

$P_{reflected\ laser} = P_{laser} - (MV^2 / 2C)$

Now put this into the momentum-conservation equation (Equation 1). We get

$P_{laser} = MV - P_{laser} + (MV^2 / 2C)$

From which we get a formula for P_{laser}

$P_{laser} = (1/2)\ [MV + (MV^2 / 2C)] = (MV/2)\ [\ 1 + (v/2C)]$

Multiplying this by the speed of light we find what we were looking for:

The energy our laser must emit
if it is to accelerate our payload (mass M) to velocity V

$$\mathbf{E_{laser} = (MVC / 2)\ [\ 1 + (V/2C)]}$$

or alternatively

$$\mathbf{E_{laser} = (MVC / 2) + (MV^2 / 4)}$$

<u>Problem</u>*: How efficient is our reflecting rocket?*

Our laser is going to emit a lot of energy. The energy that we care about is what ends up in the payload. The rest, the energy of the reflected light, is wasted. So just how wasteful is this approach? Calculate the ratio $E_{laser} / E_{final\ spacecraft}$ This is the ratio between the energy the laser emitted and the energy we care about. You will that the ratio is very big. This tells us that the energy emitted by the laser is far greater than the energy that ends up in the payload: most of the emitted energy has been reflected rather than given to the payload. So this is is a somewhat wasteful scenario.

(E) Try a Few Numbers: 1/5 the Velocity of Light

How difficult is such a project going to be? Let us put some numbers into our formula for the light energy required. If wish to reach 1/5 the velocity of light

$$E_{laser} = (MVC / 2) [1 + (V/2C)]$$
$$E_{laser} = (MC^2 / 10) [1 + 1/10]$$
$$E_{laser} = 0.11 MC^2$$

How much energy is this? We need to decide how big our payload is going to be.

First attempt: send a 70 kilogram payload

Let us return to the example that we have already considered when we were discussing the rocket equation. Recall that we had found the quantity of fuel required for a rocket to send a 70 kilogram payload to the stars was impossibly large. Is it still impossibly large if we use a beam of light?

In this case our formula tells us

$$E_{laser} = 0.11 MC^2$$
$$E_{laser} = (0.11) (70) (3.00 \times 10^8)^2 \text{ Joules}$$
$$E_{laser} = 6.93 \times 10^{17} \text{ Joules}$$

This is the total amount of energy that our laser needs to shoot off towards our spacecraft.

Is it a lot or a little? Are the energy requirements still impossibly large, or are they within our grasp? To place the question in perspective, consider the power requirements of a large city. The Web tells me that New York City consumes roughly 11,000 megawatt-hours each day. This energy is supplied by a network of power plants, all devoted to powering the city. Imagine for the sake of argument that we construct a similar network, and divert the power it generates into some sort of enormous battery. Time passes: more and more energy is stored in our battery. Eventually a sufficient amount has accumulated. And then we use it all at once, in a single burst as the laser fires. For how long would we have to wait before that battery has stored enough energy to power that burst?

Converting 11,000 megawatt-hours to Joules we find that each day New York consumes

$$E = 1.1 \times 10^4 \text{ megawatt-hours} = 1.1 \times 10^7 \text{ kilowatt-hours} = 3.96 \times 10^{13} \text{ Joules}$$

How many days pass before a quantity of energy sufficient to fire our laser has been accumulated? We calculate

# of days = energy required / rate of expenditure of energy
# of days = 6.93×10^{17} Joules / 3.96×10^{13} Joules each day
# of days = 17,500

which is 48 years

So what is our conclusion? On the one hand, it is a disappointing one, since 48 years is an awfully long time to wait. On the other hand, it is an encouraging one, since this is not insanely outside the bounds of possibility. Recall that when considering the rocket equation in contrast, we had found the energy requirements to be absolutely impossible. Our present scenario is only moderately impossible.

<u>Second attempt: send a wafer-sat / starchip</u>

That was our first try. It was encouraging but not encouraging enough. We need to think more modestly. And that means that we must think of a smaller payload. So let us consider our wafer-sat / starchip.

Simply as a guess, let us imagine that its mass is one ounce, or

$M_{\text{starchip}} = 0.028$ kilograms

Going through the same calculations again, using this smaller value for the mass of the payload, we find that the energy required to send such a tiny voyager to the stars is

$E_{\text{laser}} = 2.77 \times 10^{14}$ Joules

And the time required to accumulate this much energy

# of days = 7

This is a <u>very</u> encouraging result. In a mere week, a network of power stations sufficient to power a large city would generate enough energy to achieve interstellar travel. Perhaps we have found a feasible way to reach the stars!

<u>Problem</u>: verify the above results.

<u>Problem</u> research the power requirements of CERN's Large Hadron Collider, the particle accelerator that discovered the Higgs Boson in 2012. Perform a similar calculation for whatever energy source powers it.

<u>Project</u>: In February of 2018 the Space X corporation sent Elon Musk's Tesla sports car into an orbit carrying it outwards into the Solar System. Of course, that project used old technology: a rocket. How hard would it be to send Musk's Tesla to Proxima Centauri by using Breakthrough Starshot's technology? Analyze a variety of scenarios, choosing differing amounts of time required for the voyage.

Project: Of course we don't want to send a single wafer-sat / starchip – we want to send a whole flotilla. Take a guess for how many you would like to send, and analyze in detail the social and political and legal problems that we would have to solve in order to accumulate the required energy.

Project At the very beginning of this section we used the analogy of powering an automobile by blowing wind upon it from a fan. And we then replaced the wind in the analogy by light. But suppose we don't replace the wind by light!

Suppose that what we place on the ground is not a laser but a gigantic fan pointing upwards. Suppose that what we shoot up at our orbiting spacecraft is literally a wind – an exceedingly strong jet of air. The air blows on the spacecraft's mirror, and so accelerates it.

The idea sounds completely crazy, doesn't it? But every new idea sounds crazy. Just to place things in context, remember that the early pioneers of rocket flight were roundly ridiculed. Many people thought they were nuts. So, just for fun, let us become nuts ourselves. Let us take seriously this idea, and see if it might work.

Offhand, there seem to be many reasons to reject this notion. Here are just a few:

- *We will need a lot of air. And all that air will weigh a good deal. It is pulled back down to Earth by the tug of gravity. So a lot of energy must be expended in order to get it into space. The light from a laser, on the other hand, is not influenced by the Earth's gravity.*

- *Once it gets into space, our wind will be travelling more slowly than when it was ejected by our fan. So the momentum transferred to the spacecraft is correspondingly less.*

- *The Earth's atmosphere is pretty transparent to light – but it is certainly not "transparent" to our proposed upward-rising jet of air, and it will certainly slow that air down. By how much?*

Your task is to analyze this proposal in as much detail as possible. Is it really crazy?

(8) **THE LAUNCH: HOW POWERFUL A LASER DO WE NEED?**

Up to now our problem has been to come up with enough energy for our mission, and it seems at last that we have found a way to accomplish this. Now we need to address a new issue: this energy will be delivered by the light from a laser – and how powerful does that laser need to be? In this section we will show that it needs to be more substantial than anything we possess at present -- but that the required improvements may be within our grasp.

There is only a certain amount of time available in which to fire the laser, and within this time it must deliver enough energy to the spacecraft to send it on its way. The laser must be sufficiently powerful to do this. How powerful?

In Section 7 (E) we found the total amount of light the laser must deliver to the wafer-sat / starchip to be

$E_{laser} = 2.77 \times 10^{14}$ Joules

Recalling that the power of a light source is the energy it emits per second, we calculate

Required Laser Power = (E_{laser} / T) = (2.77×10^{14} Joules / T) Watts

(Remember that a Joule per second is a Watt!)

where T is the time during which the laser continues firing So now we need to evaluate the time T available to us: once we know this, we can figure out the required power.

<u>Problem</u> *Play with an example which sounds silly, but which has an important point: let us send our traveler off on its voyage by using a single 100-Watt light bulb! For after all – every source of light is emitting energy, and the longer we leave it on the more energy it will have emitted. For how long would we have to wait for the emitted energy to be enough to send our spacecraft on its way? Your result will make vivid why we need a very powerful laser.*

<u>Problem</u> *Suppose we fire our laser for a week. How powerful does it need to be?*

(A) For How Long Can We Fire Our Laser?

We have already described a launch scenario: we are down on solid ground in the control room of our laser, and the spacecraft is in orbit about the Earth. We fire our laser as the craft passes overhead.

In this scenario, the spacecraft does not just hover over the laser: rather it zooms across the sky. So we only have a certain amount of time in which to “shoot.” How much time? We can only shoot when the spacecraft is high above the horizon. Let us say that we do so only when it lies

45^{o} from the vertical. Suppose that the spacecraft is at a height D above our heads, and it is moving with velocity V. Then in Figure 8.1

1. the distance L just equals D
2. the time T during which we must fire our laser is T = 2D/V

<u>Problem</u> explain the above two assertions

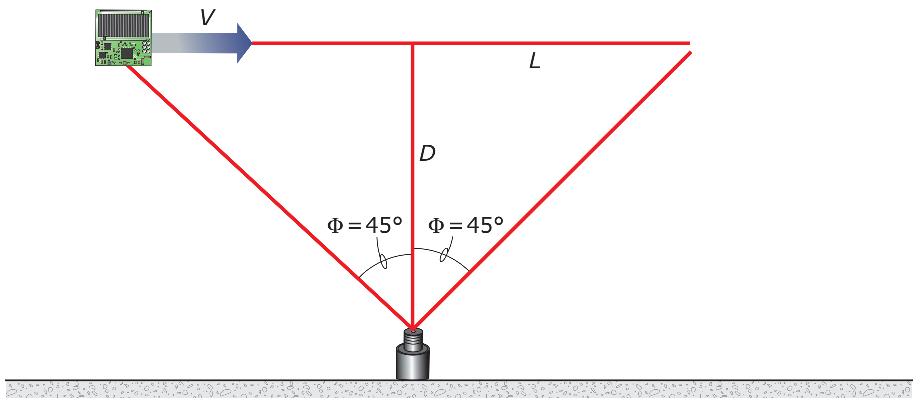

Figure 8.1 <u>Launch Of An Interstellar Voyager</u> must occur as it passes overhead

So how much time do we have to fire our laser? The answer depends on how high up our spacecraft is and how fast it is moving. These are things we can play with: we just assume something and see what our choice implies. Let us begin by imagining that our spacecraft is in the same orbit as the International Space Station, which is at an altitude of 254 miles and is orbiting at a velocity of 4.76 miles per second:

D = 254 miles = 4.09×10^{5} meters
V= 4.76 miles / second = 7.66×10^{3} meters / second

In this case we calculate:

T = (2) (4.09×10^{5} meters) / (7.66×10^{3} meters / second)
T = 107 seconds = 1.78 minutes

That is a very short amount of time in which to emit the energy required to send our starchip on its way. We calculate

Required Laser Power = E_{laser} / T = 2.77×10^{14} Joules / 107 seconds
= 2.59×10^{12} Watts

In words: 2,590 trillion Watts. And recall that this is the power required to launch only a single voyager – and that in reality we need to launch many.

Problem: *the higher up a satellite orbits the slower it moves, so different choices lead to different answers. Choose another possible orbit from the following table and go through a similar calculation:*

Table I

Altitude	***Velocity***
Twice the altitude of the Space Station	*7.43 kilometers/second*
6,000 kilometers	*5.67 kilometers/second*

Problem: *Play around with other choices for the angle ϕ illustrated in the above figure. Does this make our task any easier?*

(B) Laser Power

Let us summarize our result, simplifying it for clarity:

The laser must fire with a power of around 2,600 trillion Watts for around 2 minutes, emitting a total of around 3 X 10^{14} Joules

And let us repeat that these are only the requirements for sending a single voyager on its way, and in reality we want to send many.

How close are we to achieving this? Not long ago I came across the following article[7]

Japan Fires The World's Most Powerful Laser

"Researchers at Osaka University are claiming have fired the most powerful laser in the world. The 2-petawatt (two quadrillion watt) pulse lasted just one picosecond (a trillionth of a second). . . . Osaka's mega-powerful laser is called LFEX or Laser for Fast Ignition Experiments, and measures more than 300 feet long."

Would such a laser be sufficient for our purposes? We calculate:

Laser power = 2 petawatts = 2 x 10^{15} Watts

This is even more than our required laser power! So this is good news so far.

[7] source: https://www.popsci.com/researchers-japan-fired-worlds-most-powerful-laser

So is interstellar travel within our grasp? Unfortunately, the answer is No. The reason is that this laser only fired for an exceedingly short interval of time: 1 picosecond, or 10^{-12} seconds. So the total energy emitted in this firing was

Energy emitted = $(2 \times 10^{15}$ Joules / second$)(10^{-12}$ seconds$)$ (2) = 2,000 Joules

Which is nowhere near enough!

We have, however, reached an important conclusion – for now we know what direction technology needs to head. We do not need more powerful lasers! What we need is for them to fire for longer amounts of time.

But I believe that we need to take a broader view than just this. The really important point we have demonstrated is that such a technological improvement is not absolutely impossible! <u>For the first time in history, humanity may be capable of sending a spacecraft to the stars.</u>

<u>Problem</u> For how long would LFEX have had to continue firing in order to send one interstellar voyager on its way. How about a flotilla of one thousand of them?

<u>Problem</u> research other ultra-powerful lasers that we possess at present, and go through a similar analysis.

<u>Project</u> There is an element in the situation that we have not yet considered. The light from the laser always pushes the spacecraft directly away from the laser. Therefore, during the time interval during which we are firing our laser, the direction of the push we are exerting on the spacecraft is continuously changing (Figure 8.2). This means that the analysis we have given above is too simplified.

In this project, your task is to correct this error.

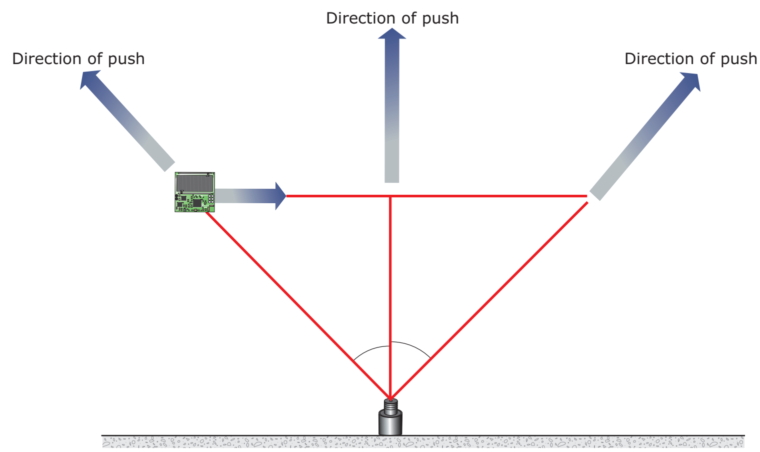

Figure 8.2 <u>The Push On The spacecraft</u> is in different directions at different times.

(9) DESIGN THE LIGHT SAILS

(A) How Big A Mirror Do We Need?

No source of light sends out its rays in a perfectly narrow line. A light bulb sends its rays out in all directions: a flashlight in a cone. Even lasers send their rays out, not in a perfectly narrow beam, but into a cone of some opening angle ϕ. And we need to be careful about that angle.

We can see why from Figure 9.1

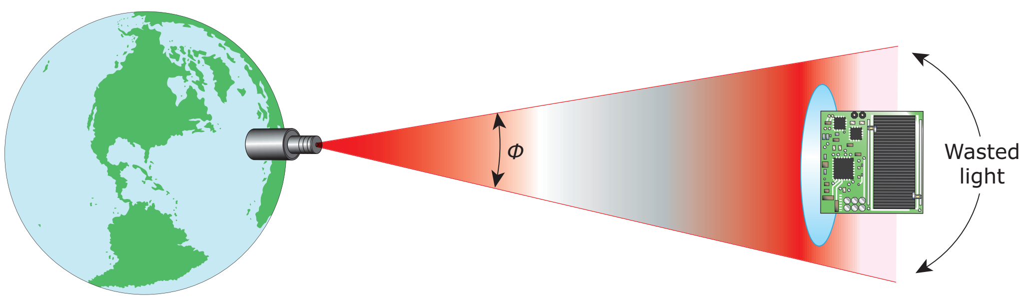

Figure 9.1 *Some Light Is Wasted* *if the mirror is too small or the opening angle too large*

In this configuration some of the light from the laser is wasted. It misses the mirror and does not push upon it. We need to solve this problem – either by making our mirror bigger or by making the opening angle smaller. Then there is no wasted light (Figure 9.2).

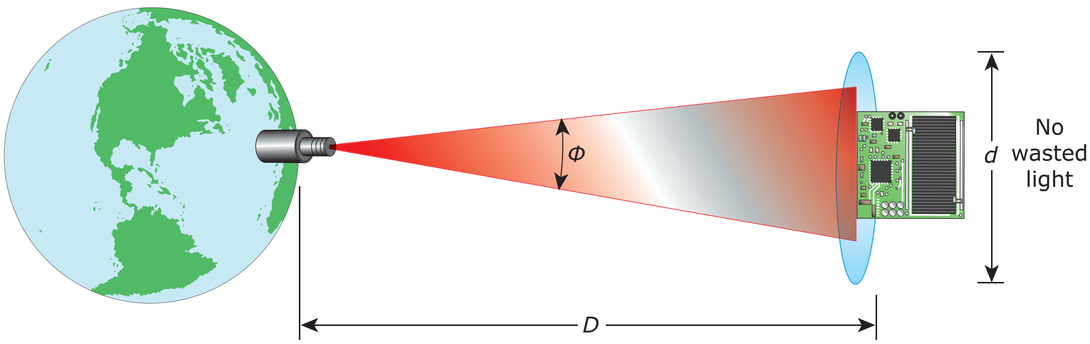

Figure 9.2 No Light Is Wasted if the mirror is big enough or the opening angle small enough

Clearly we would want to make our laser beam as narrow as possible. Let us arbitrarily adopt a value for the beam angle ϕ and see what it implies. Suppose we choose ϕ = 1 second of arc. How big do we need to make our mirror in this case?

Notice that there is a triangle in the above figure: its base is the mirror, and its two sides are the rays connecting the mirror's edges to the laser. Mathematically we are looking for the value of d in that triangle once we are given D. If students are familiar with trigonometry they will know how to do this. But even if they are not, there is a simple formula that works if the angle ϕ is small[8]:

The small-angle formula:

$$d = [\phi / 360^{o}]\ 2\pi D$$

where ϕ is in degrees of arc.

One degree contains (60 minutes/degree)(60 seconds/minute) = 3600 seconds. So one second of arc = 1/3600 degrees = 2.78×10^{-4} degrees. So our small-angle formula gives us d, the size of our mirror:

[8] "Small" means "very much less than 1 when measured in radians." (One radian is 57.3 degrees.)

$d = [2.78 \times 10^{-4} / 360]\ 2\pi D$
$d = 4.85 \times 10^{-6}\ D$

<u>Problem</u> according to this formula, the bigger D is the bigger we need to make our mirror. Does this make intuitive sense to you? Can you illustrate why using a figure? Using words?

Let us use this result to find the required size of our mirror in the case we have been studying above, in which we placed our spacecraft in an orbit as high as that of the International Space Station:

$D = 4.09 \times 10^5$ meters

we find

$d = (4.85 \times 10^{-6})\ (4.09 \times 10^5 \text{ meters}) = 1.98$ meters

Our mirror is quite modest in size: just under 2 meters across.

<u>Problem</u> to get an intuitive feel for this, compare it to some familiar object that we encounter all the time.

<u>Problem</u>: carry out the above calculation for the alternative choice for a possible orbit that you studied above.

<u>Problem</u>: Get hold of a laser. You can measure its angle ϕ by shining it on a wall and measuring the diameter of the spot of light it produces. Then carry our the above calculations for this case.

(B) Protect The Mirror

Here are some other technological problems, which are also currently being addressed.

In the brief, cataclysmic interval of launch, our fragile wafer-sat / starchip with its gossamer light sail will have been accelerated up to 20% of the velocity of light. That is a huge burst of acceleration. Will it destroy the spacecraft? Will it destroy the light sail?

Just how great an acceleration is it? We calculate

Acceleration a = change in velocity / time
$a = (c/5) / (107 \text{ seconds})$
$a = (3.00 \times 10^8 \text{ meters/second}) / [\ (5)\ (107 \text{ seconds})]$
$a = 5.61 \times 10^5$ meters / second^2

To get an intuitive feel for this, let us compare it to the acceleration of gravity, which is
$g = 9.81$ meters / second^2

$a/g = 5.61 \times 10^5$ meters / second^2 / 9.81 meters / second^2
$a/g = 57{,}200$

In words: the acceleration will be 57,200 times that of gravity. This means that there will be enormous forces on the spacecraft and its light sail.

A further issue is that all of the energy falling upon the mirror must be reflected back away from it. But no mirror is perfectly reflecting. It is inevitable that some fraction of the laser energy will be absorbed by the mirror. And this absorbed energy will heat both the mirror and the spacecraft. Since the incident energy from the laser is so great, this heat might have devastating effects. Much research will be needed to make sure that they are not simply destroyed in the launch.

(10) WHERE SHALL WE PUT OUR LASER?

If we ever do build that laser, it is going to represent a gigantic effort, extending over many years and costing great sums of money. Once it is built, we will want to be careful about where we put it. It turns out that some places would make terrible choices. And unfortunately, many of these bad choices lie within the continental United States. We won't be able to place our mighty laser just anywhere that strikes our fancy. This is because, from these places, there is no path to Alpha Centauri.

What is the path that our interstellar traveler will follow? Remember: it carries no rocket engine and no fuel. So on its journey it will simply be coasting along helplessly in a straight line.[9] We will need to situate our laser at a spot from which we can draw a straight line from laser to star. Another way of saying this is that we need to build our laser at a place from which we can see our destination. Unfortunately Proxima Centauri is too faint to be seen by the naked eye. But recall that it is part of the Alpha Centauri triple-star system – and to the naked eye Alpha Centauri one of the brightest stars in the sky.

And have you ever seen Alpha Centauri? Probably not. But why not?

We live on a great sphere which is the Earth. This sphere floats in space, surrounded by stars in all directions. But not all these stars are visible to us. In Figure 10.1 the various arrows point to various stars: we have indicated the one to Alpha Centauri. The woman in this figure is pointing towards it. But notice that her arm just happens to be pointing through the solid body of the Earth! From her location, Alpha Centauri cannot be seen. The Earth is in the way. And that is why, unless you live far to the South, you have probably never seen it.

[9] In reality our spacecraft will be travelling in an orbit through the galaxy. But because our craft's velocity is so large this orbit is very nearly a straight line. Advanced students can do a *Project* investigating this issue.

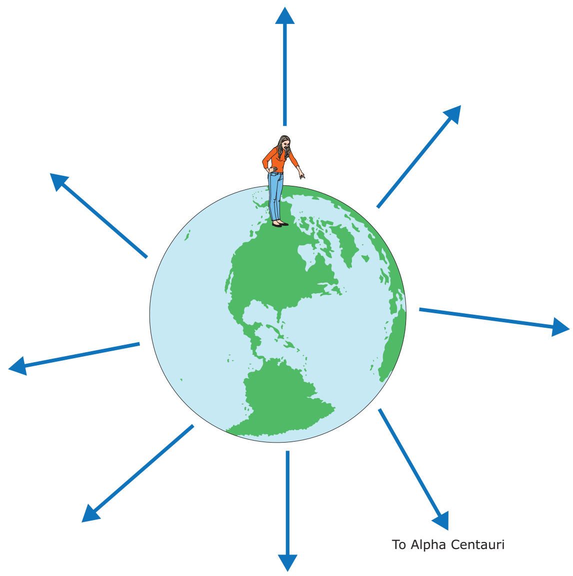

Figure 10.1 <u>Alpha Centauri Cannot Be Seen</u> by the indicated observer. The Earth is in the way.

Another way of making the point is to say that from the indicated location Alpha Centauri lies below the horizon. The horizon separates those stars that can be seen from those that cannot. It is plane, tangent to the Earth at your location (Figure 10.2).

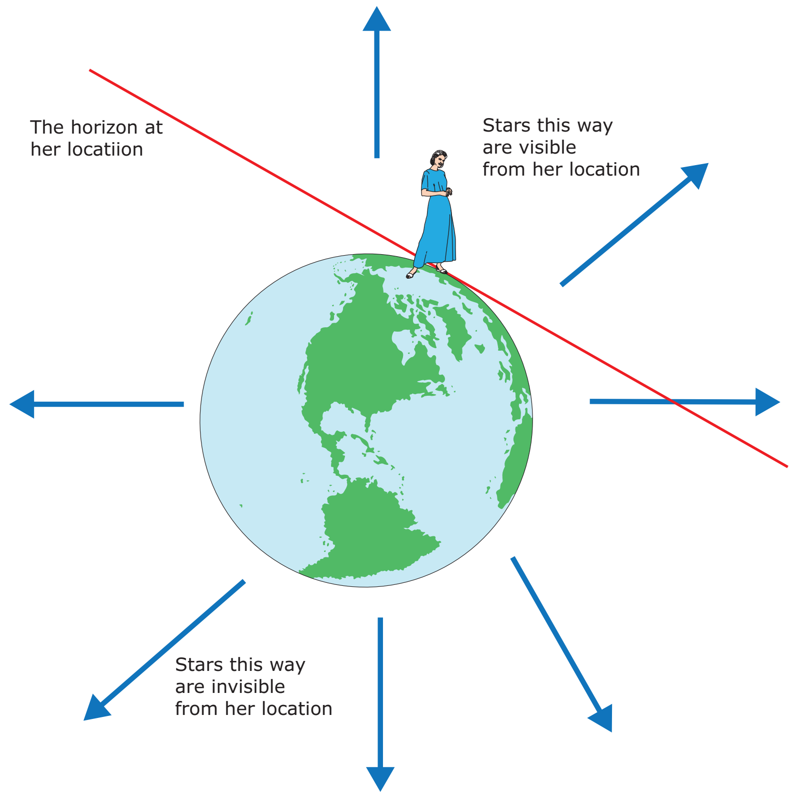

Figure 10.2 <u>The Horizon</u>

It is clear from this figure that the horizon is different at different places. So different stars can be seen from different places. We need to situate our laser at a place where our voyager’s destination is above our horizon.

In Figure 10.2, which arrow points to Alpha Centauri? We can get a clue from the very name of this star! The name means “the brightest star in the constellation The Centaur” – just as Beta Centauri is the second brightest star in that constellation, Gamma Centauri the third and so forth. So the very fact of the name “Alpha” tells us that Alpha Centauri is a pretty brilliant star. The only way you could have failed to notice it is if it lay below the horizon from where you live. As indeed it does. As a matter of fact, the same is true of the entire constellation of The Centaur. If you are familiar with the nighttime sky you will be familiar with the constellations Orion, Ursa Major and so forth. That is because they lie far above the horizon from the northern hemisphere. But The Centaur is a southern constellation.

<u>Problem</u> Sirius is the brightest star in the sky. It lies in the constellation Canis Majoris (“the Greater Dog”). What is another name for Sirius?

<u>Problem</u> The European Southern Observatory is funded by a consortium of European nations. Nevertheless it is not located in Europe: it is in Chile. Why is this?

Let us more carefully investigate where our laser must be situated. Astronomers have devised a coordinate system for the sky (Figure 10.3). It is exactly analogous to the latitude / longitude system that we have for the Earth. The celestial counterpart to latitude is known as <u>declination</u>, and the counterpart to longitude is <u>right ascension.</u> The celestial equator lies directly above the earthly equator, and the celestial poles lie above the earthly poles (the geographic poles, not the magnetic poles).

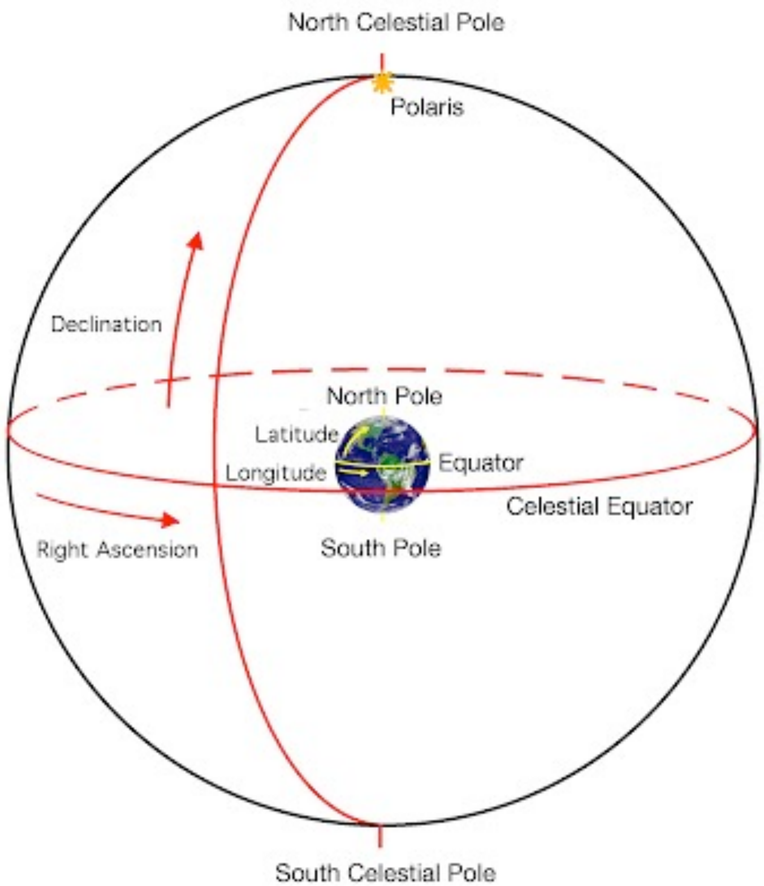

Figure 10.3 <u>The Astronomical Coordinate System</u> mirrors the geographical coordinate system we use for the Earth.

Where on this diagram does Alpha Centauri lie? Its declination is 61° South. That is pretty far south of the equator. So we can immediately see that our target star lies below the horizon as seen from much of the northern hemisphere. We will have to situate our laser pretty far south.

How far south? Figure 10.4 diagrams the configuration:

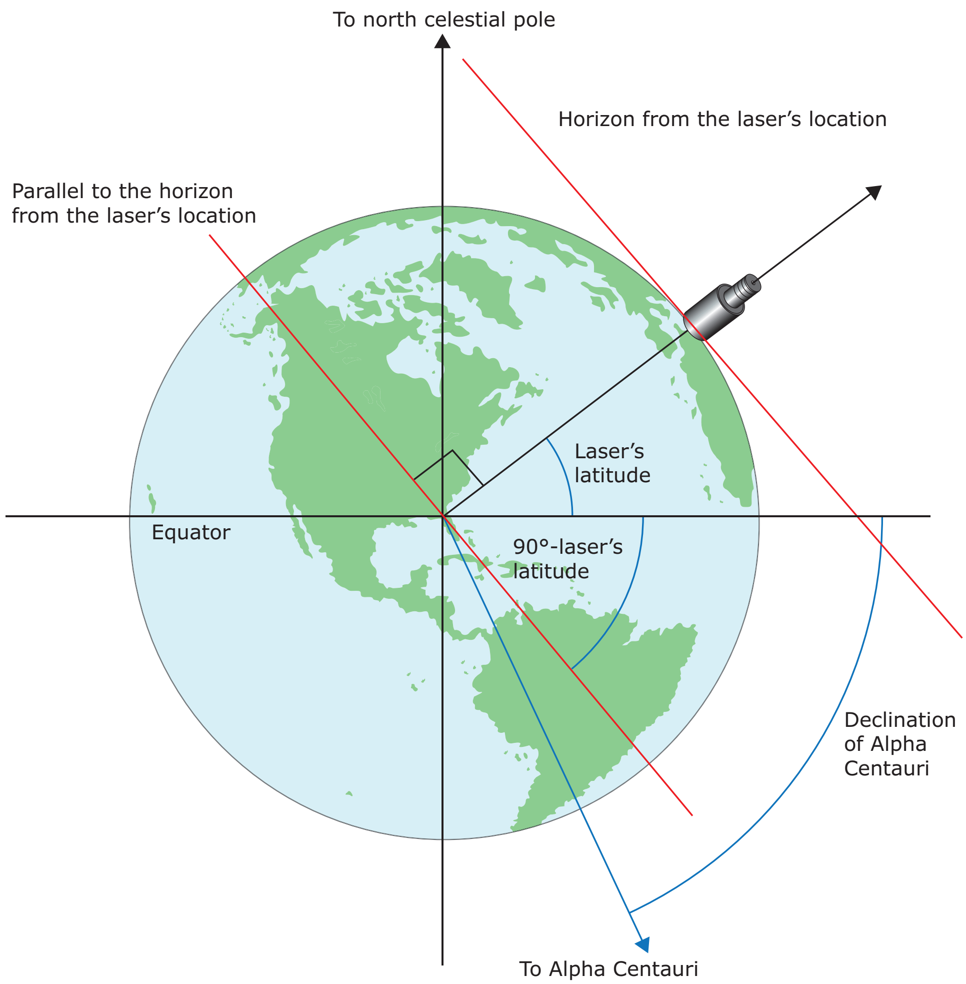

Figure 10.4 Situating Alpha Centauri in the astronomical coordinate system

Let us begin by asking: from which critical latitude does Alpha Centauri lie just on the horizon? From Figure 10.4 we can see that in this case[10]

[10] Students may be worried that in this case the line marked “parallel to the horizon from the laser’s location” is not exactly parallel to the line “horizon from the laser’s location,” since both are supposed to point towards the same star. But because that star is so very distant (remember

90^{o} – critical latitude = declination of Alpha Centauri

So

critical latitude = 90^{o} – declination of Alpha Centauri
critical latitude = $90^{o} - 61^{o}$
critical latitude = 29^{o}

If we are situated anywhere south of 29^{o} Alpha Centauri will be above the horizon. But if we live north of 29^{o} Alpha Centauri will lie below the horizon.

Problem list some nations from which Alpha Centauri is visible. Is there anywhere in the United States from which it can be seen?

But we do not simply need our target star to lie above the horizon. We need it to lie high above the horizon. Let us see why.

Here’s a conundrum which will give us a clue: you can look at the Sun as it sets – but if you look at the Sun when it is high in the sky you will do serious damage to your eyes. What does this tell us? It tells us that, when the Sun is on the horizon, only a little of its light is reaching your eyes. But when it is high in the sky more light is reaching you.

Why should this be? It has to do with the atmosphere. Our atmosphere lies in a thin shell surrounding the Earth. And as we can see from Figure 10.5

- light from the Sun when it is setting passes through a lot of air

whereas

- light from the Sun when it is high in the sky passes through less air.

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section 3!) this error is tiny and there is no reason to worry about it. As an interesting *Problem* students can investigate this.

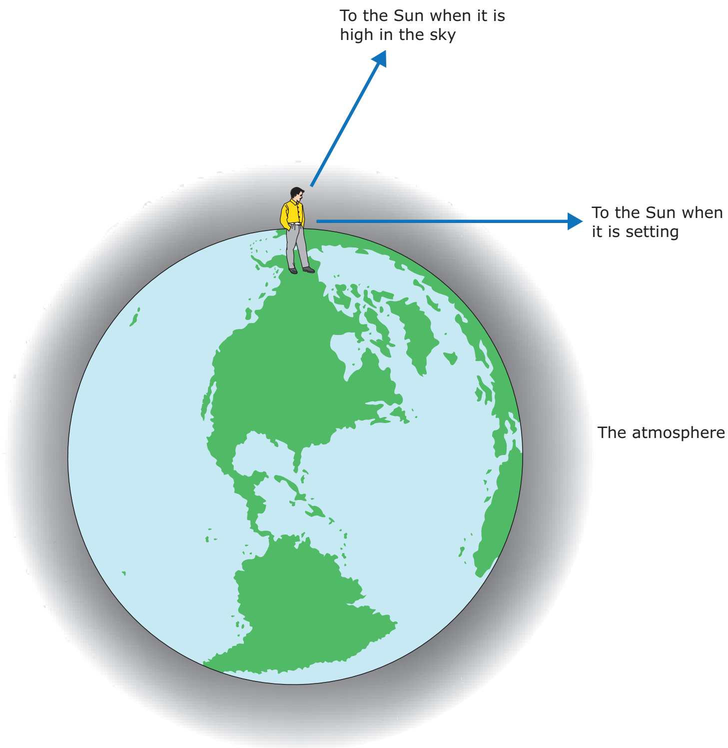

Figure 10.5 Lines Of Sight pass through differing amounts of air depending on their direction.

This is telling us that our atmosphere is not entirely transparent. It absorbs a certain amount of light – and the more air there is, the more light is absorbed. So the closer a light ray is to the horizon, the more of the light is absorbed.

As with light from the Sun, so too with light from our laser. We want it to pass through the least amount of air on its way upwards to the spacecraft. So we do not just want Alpha Centauri to lie above the horizon -- we want it nowhere near the horizon! Best of all would be for our target star to lie directly overhead.

Problem in the above figure indicate the direction that lies directly overhead. Explain why a star that lies directly overhead at any location has a declination equal to that location’s latitude.

Problem explain why the best place to situate our laser is one whose latitude is as close to 61^{o} *south as possible. Use this new information to refine your list of desirable locations for the laser.*

Problem Because this project is so expensive, we will probably want to situate our laser in a politically stable nation with a strong economy. Use this new information to further refine your list of desirable locations for the laser.

Problem (requires trig!) These last considerations may force us to end up placing our laser at a location from which Alpha Centauri lies high above the horizon -- but not directly overhead. Choose a nation from your refined list and calculate the angle between the direction to Alpha Centauri and straight overhead from there. Find a practicable location from which that angle is smallest.

(11) DANGER!

Sometimes it is useful to consider an old result in a new way. Let us take a fresh look at the energy required by our laser to send off a one-ounce starchip. In section 7(E) we had found:

$E_{laser} = 2.77 \times 10^{14}$ Joules

And now let us convert this result to another unit of energy, the kiloton

One kiloton = 4.18×10^{12} Joules

So that

$E_{laser} = 66.3$ kilotons

This is a lot of energy – and remember that this is the energy required to send off only a single spacecraft, but that in fact we will need to send off many.

Suddenly we realize that the energy shot off by our laser will be comparable to that of an atomic bomb! And suddenly our project, initially so innocuous, has assumed an element of danger.

Problem Compare our result for E_{laser} to the size of the bomb which destroyed Hiroshima.

Problem What is the most powerful Hydrogen bomb that has even been built? Suppose that somehow we were able to utilize all of its energy to power our laser. How many wafer-sats / starchips would it be capable of sending to Proxima Centauri?

(A) A Long Thin Atomic Bomb

Let us ask, for example, just how transparent to this energy is our atmosphere. Air is not, as we have just seen, perfectly transparent. At least some of the laser energy will not make it into space, but instead will be absorbed by air. The firing of the laser will be like exploding a long, thin bomb in the atmosphere.

Project: Research the transparency of air. How many kilotons will be absorbed in the atmosphere? What sort of environmental consequences will this have?

Project: discuss the political and legal problems associated with the firing of the laser. And, when doing so, remember that the laser may not be situated on United States soil.

(B) The Reflected Light

Remember that the light sails will reflect the laser energy incident upon them. And remember that we had calculated in section 7(D) that in fact most of the light hitting the light sails is reflected, and only a small fraction of it is deposited in the interstellar voyager.

Furthermore, that huge quantity of reflected light will be aimed right back down onto the place from which it came – right back down onto the laser! The firing of the laser will be followed by the equivalent of an enormous bomb exploded directly above it.

Problem a certain amount of time will elapse between the moment we fire the laser and the moment the reflected light comes back down. Will there be enough time to take protective measures? Or do these measures need to be in place before we fire?

What can be done about this frightening scenario? Here are a few possible strategies:

(1) Can we angle each light sail so that the reflected beam is not directed back down towards the laser (Figure 11.1)? Indeed, can we angle it so the reflected light completely misses the Earth? This would certainly mitigate the danger. But doesn't it mean that the light will deliver to the spacecraft a glancing blow? And in this case, doesn't this reduce the velocity imparted to the spacecraft? And how will we be able to send the voyager off in the required direction?

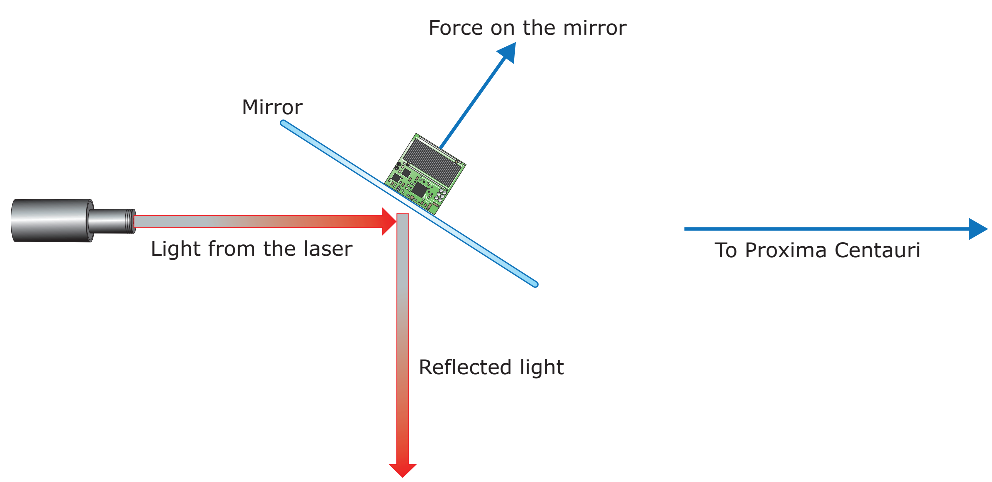

Figure 11.1 Protect The Earth By Angling The Mirror

(2) A second strategy might be to somehow protect the laser. Would it be possible, for instance, to have the laser hidden behind a mirror of its own (Figure 11.2)? Perhaps this protecting mirror might have a hole within it, through the laser peeks:

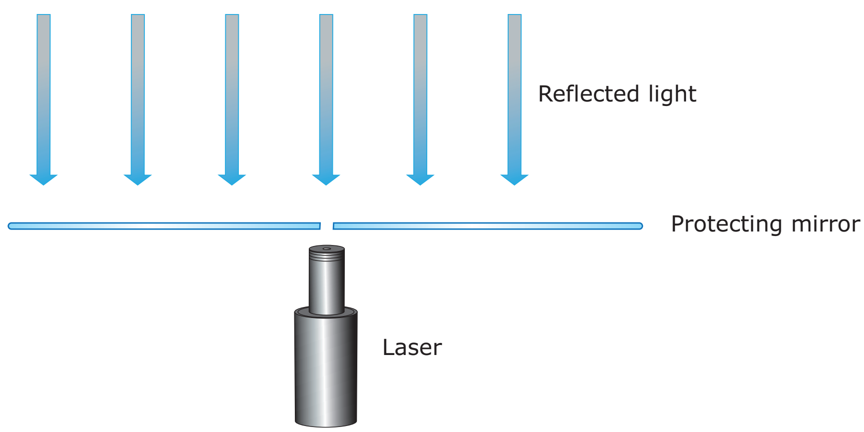

Figure 11.2 Protect The Laser With Its Own Mirror

(One interesting advantage of this design is that the light reflected from this protecting mirror will be heading right back into space. Can we use it to give yet another shove to the starchip? Can we imagine a whole series of back-and-forths, each one giving a shove?)

(3) A third strategy might be to lift the laser into space (Figure 11.3). This obviously avoids all the above problems.

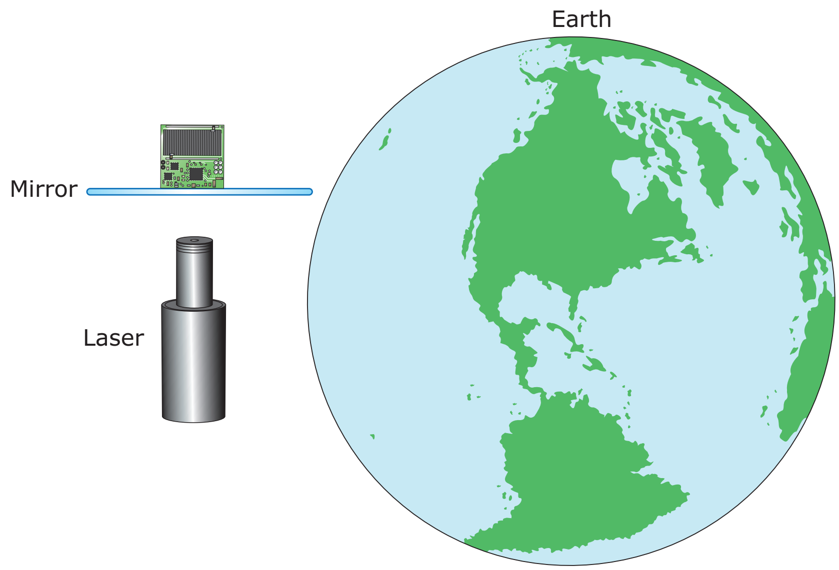

Figure 11.3 *<u>Protect the Earth By Situating The Laser In Space</u>*

But how hard would it be to do this? After all, that laser will weigh a good deal. And the fuel which powers it will also weigh a good deal.

<u>Project</u>: choose a favorite strategy and work out some of its details.

<u>Project</u>: A group of concerned citizens is worried about the danger posed by the "long thin atomic bomb," and by the reflected light. They have brought a lawsuit seeking to halt the entire project. Get together with some friends and divide yourselves into two teams. One team is working with the citizens who want to prevent the laser from firing. The other team is working with the Starlight / Breakthrough Starshot people, who want it to fire. Hold a mock trial in which the lawsuit is pressed, and the two sides present their cases.

THAT'S ALL

NOW IT'S YOUR TURN: GET GOING AND MAKE IT HAPPEN

(AND DON'T FORGET TO HAVE FUN!)