Let's Build an Interstellar Spaceship (or not)

S. Redner

Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501, USA

Abstract.

We use elementary physics concepts to determine the power requirements for a minimal manned spaceship to travel to the nearest star and back within one generation.

Suppose that we want to build a manned spaceship to travel to the nearest star (roughly 4 light-years away) and return within one generation. What is the power requirement for such a mission? I make the basic assumption that the crew would like to return from such a mission alive. Thus I envision that the crew members are their 20's or 30's at the time of departure and return after 40 years. This time frame should give the crew members confidence that there is a reasonable probability that they could return alive.

Thus a reasonable kinetic profile of the mission would the following:

(i) Accelerate from earth to reach a cruising speed of $c/5$, where c is the speed of light.

(ii) Glide at constant speed $c/5$ until the destination star is approached.

(iii) Upon nearing the destination, decelerate until planetary speeds are reached.

(iv) Explore the star system for roughly a year or for several years.

(v) Return by the same kinetic profile as the outbound segment.

One advantage of using a cruising speed much less than the speed of light (although it is a disadvantage for a quick mission) is that we can ignore the complications of relativistic effects to a good approximation.

What is a reasonable value for the acceleration? I argue that it should be $g = 9.8\text{m/sec}^2$, the gravitational acceleration of the Earth. If the acceleration is much larger than g, it would pose unacceptable stress to the human body if it lasted for more than a few minutes. If the acceleration is much less than g, it would take an unacceptably long time to reach cruising speed (see below).

Thus we assume that our spaceship accelerates to a final speed $c/5$ with an acceleration g. The time needed for this acceleration phase is

$$T = \frac{c/5}{g} = \frac{3\times 10^8\,\text{m/sec}}{9.8\,\text{m/sec}^2} \approx 6.12\times 10^6\,\text{sec} \approx 71\,\text{days}\,. \tag{1}$$

Now let's determine the power needed to accelerate an object of mass $m = 1$ kg up to this cruising speed in 71 days. Since the object is undergoing a constant acceleration

g, the (constant) force exerted on it is $F = mg$. The work done on the object when it is moved a distance x under the action of this force is $W = mgx$, where x is the distance traveled during the acceleration phase. When an object undergoes a constant acceleration for a time T, the distance that it travels is $x = gT^2/2$.

The power needed to accelerate a 1 kg object to a speed of $c/5$ over a 71-day period is just the work done on the object during this period divided by the time. Thus

$$\begin{aligned} P_1 &= \frac{mgx}{T} = \tfrac{1}{2} m g^2 T \\ &\approx \tfrac{1}{2} \times 1 \times (9.8)^2 (\mathrm{m/sec}^2)^2 \times 6.12 \times 10^6 \,\mathrm{sec} \approx 294\,\mathrm{MW}\,, \end{aligned} \tag{2}$$

where MW denotes megawatts. This same power is needed during the deceleration phase of the mission and again in the return acceleration and deceleration phases of the trip. Thus to send a 1 kg object on a return trip to the nearest star on a mission that takes 40 years is, approximately 300 MW; this power would be needed only over the 284-day acceleration/deceleration phase of the 40-year mission. To get a sense of scale, the infamous 3-Mile Island power station consisted of two units (before the accident), each of which could deliver roughly 900 MW.

What if we are satisfied with a more modest acceleration? Because we still want to accelerate to a speed of $c/5$ so that the mission again takes one generation, we could reduce the acceleration to αg, with $\alpha < 1$, but then time for the acceleration phase would be correspondingly increased by $1/\alpha$. According to Eq. (2), the power requirement would be reduced by a factor α. Thus if we take $\alpha = 1/10$, we would need "only" 30 megawatts to send a 1 kg object to the nearest star and back, but now the two acceleration/deceleration phases will take 2840 days, which is roughly 7.8 years, rather than the 284 days (roughly 9 months) when the acceleration equals g. If the acceleration is any smaller than $g/10$, then the mission would take longer than a single generation. For the purposes of the rest of this note, I consider a mission in which the acceleration and deceleration are both equal to g.

Now we need to consider the minimal size of the spaceship. As a preliminary, to get a sense of the scale, the mass of the empty space shuttle is roughly 35,000 kg. The power P_{shuttle} needed to send a payload of the capacity of the space shuttle on a one-generation mission to the nearest star is:

$$P_{\mathrm{shuttle}} = 35,000 \times P_1 \approx 35,000 \times 294\,\mathrm{MW} \approx 10\,\mathrm{TW}\,, \tag{3}$$

where TW denotes terawatts $= 10^9$ watts. Again to get a sense of scale, the current power usage of planet Earth is roughly 20 TW. To give this number a human perspective, Earth's power usage translates to roughly 20 TW/7.5 billion people $\approx$ 2.7 kilowatts per person. Since typical adult physical labor has a power requirement of roughly 100 watts (1 large incandescent light bulb), each of us uses the labor of 27 "slaves" in our typical power usage. If we were willing to accept an acceleration/deceleration of $g/10$, then such a mission, which would last closer to 50 years, would require "only" 1 TW, which is roughly one twentieth of the power usage of the planet.

Returning now to the issue of the minimal spaceship size when the acceleration/deceleration equals g, we need to keep in mind that the occupants must live in this ultimate-security prison for roughly 40 years. Under the assumption that they are fully sentient during the mission, we need to keep them alive and healthy enough so that they can fruitfully explore their destination and return to Earth in a reasonably intact state. I would argue that the minimal requirements for the survival of the travelers are sufficient air, food, water, activity, and gravity. Let us first consider the issue of gravity. We have already seen that astronauts are significantly debilitated after spending roughly one year under zero gravity conditions. Thus I make the assumption that to maintain body integrity our travelers should experience a gravitational acceleration equal to that of the Earth throughout the entire mission.

The simplest way to achieve such a gravitational field during the glide phase of the mission is to have our spaceship rotate with angular frequency ω. We then need that the angular acceleration of the spaceship, $\omega^2 R$, where R is the radius of spaceship, equals g. The natural geometry for this spinning spaceship is a torus. Let us assume that the radius of our torus is 100 m, so that its circumference is $L = 2\pi R \approx 628$ m. The angular frequency of the spaceship therefore needs to be $\omega = \sqrt{10/R} \approx 0.315$ radians/sec, which means that the spaceship rotates once roughly every 20 sec.

To estimate the mass of this torus, I assume that its skin has a thickness $\ell = 2$ cm, or 0.02 meters. I further assume that the radius of the tube itself is $a = 5$ meters. Thus our travelers will be confined to a tube of length roughly 628 meters and radius 5 meters (for 40 years). The mass of this tube is

$$M = L \times \pi a^2 \ell \times \rho\,, \tag{4}$$

where ρ is the mass density of the material that makes the toroidal enclosure. I assume that this material is a typical metal with a density of 5000 kg/m^3. Then the numerical value of the tube mass is

$$M \approx 628 \times \pi\, 25 \times 0.02 \times 5000\,\text{kg} \approx 4.93 \times 10^6\,\text{kg}. \tag{5}$$

This mass is roughly 100 times that of the empty space shuttle. The power requirement to send this torus on a one-generation mission to the nearest star is therefore

$$P_{\text{torus}} = 4.9 \times 10^6 \times P_1 \approx 1.5\,\text{PW}\,. \tag{6}$$

Here, PW stands for petawatt = 1000 terawatts. Thus the power requirement of to send a toroidal spaceship to the nearest star and back within one generation requires 75 times the current usage of planet Earth.

However, this is still not the entire story because we've only included the mass of the empty toroidal tube in estimating the power requirement, but not the mass of the power plant itself. We've also neglected the mass of food, water, and air for our travelers, but I assume that these will be negligible compared to the mass of the power plant. I can only speculate (as if the rest of this missive is not speculation) on the mass of the power plant, but I assume that it is much more efficient than any power generation mechanism that currently exists. Controlled thermonuclear fusion, or even more crazily, controlled matter-antimatter annihilation seem to be the only possible alternatives. Let me assume that power generation occurs by controlled thermonuclear fusion. While haven't yet achieved controlled fusion, the ITER machine now under construction might get close. The tokomak itself is supposed to produce a dinky 500 MW of power and it will have a mass of 23×10^7 kg. So let me assume that in some future time, a machine of this mass can actually produce the power required for our mission. The total mass of our spaceship that includes the toroidal tube and the power plant is $\mathcal{M} = 23 \times 10^7 + 4.9 \times 10^6\,\text{kg} \approx 23.5 \times 10^7$ kg. That is, the dominant contribution to the mass of the spaceship will come from the power plant.

Finally, the power requirement to send this minimal, but half complete spaceship (minimal space for human motion and sufficient mass for power generation, but no food, water, or air included) is

$$P_{\text{ship}} = 23.5 \times 10^7 \times P_1 \approx 70\,\text{PW}\,. \tag{7}$$

To get a sense of the magnitude of this power requirement, the total solar power that is incident on planet Earth is roughly 90 PW. Thus our minimal spaceship requires harnessing nearly the entire amount of solar power that hits planet Earth, and this amount is roughly a factor 4500 times larger than the current power usage of the Earth.