Solar One: A Proposal for The First Crewed Interstellar Spacecraft

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Abstract

In this paper it is presented the concept and design of a beam-powered propulsion system that could become the first manned interstellar spaceship. Light-sail spacecrafts such as the so-called StarChips from the Starshot project have already been designed, but this type of spaceship might not be the best option to explore exoplanets in detail. Solar one would be a manned spaceship that would integrate three existing or near-term technologies, namely: the US Navy CFR fusion reactor, a larger version of NASA's Sunjammer light sail, and a continuous-wave version of the Teramobile laser system. With a mile-long light sail, Solar One could accelerate at almost 1 g and reach 30 percent the speed of light, arriving at the Alpha Centauri system in around 15 years.

1 Introduction

Several light-sail spacecrafts have already been tested. Some examples are LightSail 1 and LightSail 2, from the Planetary Society. However, these light-sails are propelled by sun light, and the solar radiation pressure is very small (just 6.7 Newtons per gigawatt, which equals to 9 Newtons/km2 or 1,400 watts/m2 at 1 AU). Lasers can provide radiation pressures much higher than the Sun.

Previous experiments with directed-energy weapons have proved successful. The Boeing YAL-1, a spacecraft equipped with a Kilowatt-laser, was able to deliver a power density over 100 watts/cm2 at a distance of 1 km (US Air Power, 2008).

In 2016, scientists announced the first design for a beam-powered spacecraft that could reach speeds of 0.2c. The project, called StarShot, entailed the idea of sending 1,000 nanocrafts with light sails attached that would be powered by a 100 GW laser array. As of today, the concept is still considered to be the best option for unmanned interstellar travel. Potentially habitable exoplanets such as Proxima b could be reached in only 20 years.

However, the idea is to send the Starshot nanocrafts 1 AU away from Proxima b. This distance would be enough to photograph the exoplanet, but perhaps not sufficient to notice the presence of a possible intelligent civilization less advanced than humanity. For this reason, and to better study the exoplanet, a manned interstellar spaceship becomes necessary.

The proposal more similar to Solar One was presented by Robert Forward in 1984. Forward proposed a 64-ton and 30-km payload sail surrounded by a 644-ton and 100-km decelerator sail, launched by a 7.2-Terawatt laser system to reach 21 percent the speed of light. As the spacecraft approaches Alpha Centauri, another 26-TW laser is pointed towards a 1000-km Fresnel lens that decelerates the spacecraft.

2 Concept

Solar One is a design for a manned spaceship that would be powered by beamed and photon propulsion. The name ‘Solar One’ has been chosen to better represent our civilization: the term ‘Solar’ refers to the solar system and the term ‘One’ refers to the first design of a possible fleet of future spaceships. Three are the technologies that would be used: the US Navy CFR nuclear fusion reactor, a slightly larger version of the NASA’s Sunjammer light sail, and a Terawatt-mobile laser called Teramobile.

Firstly, the US Navy CFR (Compact Fusion Reactor) is a mobile unit that could provide one Terawatt of power (Forbes, 2019). Instead of using large superconducting magnets, this reactor uses small conical dynamic fusors (Salvatore Pais, 2018). The weight of similar CFR units has been estimated to be around 200 tons, but Solar One would need 220 Terawatt-reactors. To minimize weight, the use of a Petawatt reactor would be ideal. The units would probably have to be assembled in orbit due to their size.

Solar One would also carry 38 Terawatt reactors on board to power the laser system needed for deceleration. The size of each of them would have to be reduced to around 3 tons per unit. The system would have to incorporate radiators to dissipate the heat, whose weight would have to be taken into account. Lockheed Martin has already suggested the possibility of building 20-ton reactors of 1 Megawatt (Besa Center, 2018). Although this would be far from what Solar One needs, it would be a starting point. In any case, a compact Petawatt reactor would, again, be ideal to reduce weight.

Antimatter would be a better source of energy for the laser. Only 10 milligrams of antimatter could yield power densities in the Terawatt order. To produce the antimatter needed, an engine such as the VARIES Mk 1 could generate Schwinger antiparticle pairs directly from the vacuum (Next Big Future, 2012). The matter-antimatter GeV gamma ray laser proposed by Winterberg in 2012 could also be used.

Secondly, the Sunjammer light sail is a proposed NASA sail with a size of 38 x 38 m (1,444 m) (NASA, 2017). Solar One would need a 1.6 km by 1.6 km light-sail.

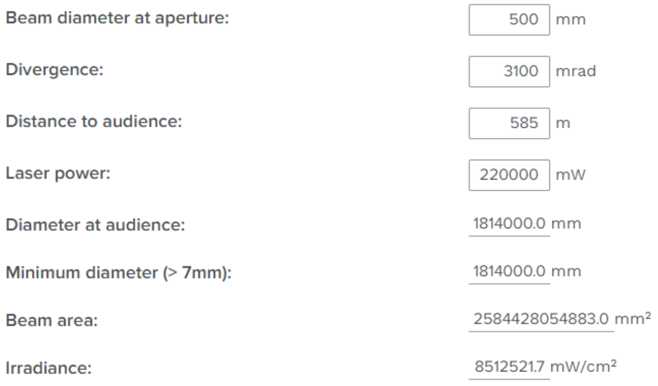
Finally, Teramobile is a 10-ton portable 5-Terawatt laser currently funded by the French National Research Agency (Wille, 2002). It has a wavelenght of 793 nm, slightly lower than the 100-GW DE-STAR laser operating at a wavelength of 1064 nm (James Clark 2018). Solar One would need 44 of these Terawatt lasers to achieve 85 MW/m2, although a Petawatt laser would be ideal. Current high-energy lasers are usually designed to emit short pulses, and a continuous-wave laser would be necessary for Solar One. The system would probably have to be assembled in orbit due to its size and sent to a Lagrange point.

To accelerate the spacecraft, an alternative solution would be to use a Fresnel lens 250 meters wide, which could collect around 85 MW/m2. A system of flexible mirrors would also be needed to continuously focus the light into the sail.

Solar One would also have a 38-TW laser system at the front of the cockpit in order to decelerate at destination using photon propulsion. If a continuous-wave version of the Teramobile laser system is used, between 7 and 8 units would be needed. The weight of each unit would have to be reduced from 10 tons, the original weight, to around 1 ton.

Carrying the necessary nuclear fuel on board might not be the best option. Considering that a proton-proton fusion reaction produces a maximum of 645 TJ/kg, 6,000 tons of fuel would be needed to produce 38 TW of power continuously for 3.3 years, or 5,000 tons to produce 6 TW for 17.6 years. However, as in the Bussard Ramjet, it would be possible to collect hydrogen from space with a scoop placed at the front of the cockpit. The electromagnetic fields produced would actually reduce the time of deceleration to only 7.5 years.

To accelerate Solar One, if a 500-mm laser is placed at 585 m from the light sail, and with a divergence of around 177°, an irradiance of 85 MW/m2 is theoretically achievable.



Beam diameter at aperture:	500 mm
Divergence:	3100 mrad
Distance to audience:	585 m
Laser power:	220000 mW
Diameter at audience:	1814000.0 mm
Minimum diameter (> 7mm):	1814000.0 mm
Beam area:	2584428054883.0 mm^2
Irradiance:	8512521.7 mW/cm^2

Figure 1: Power density
Source: Kvant Lasers

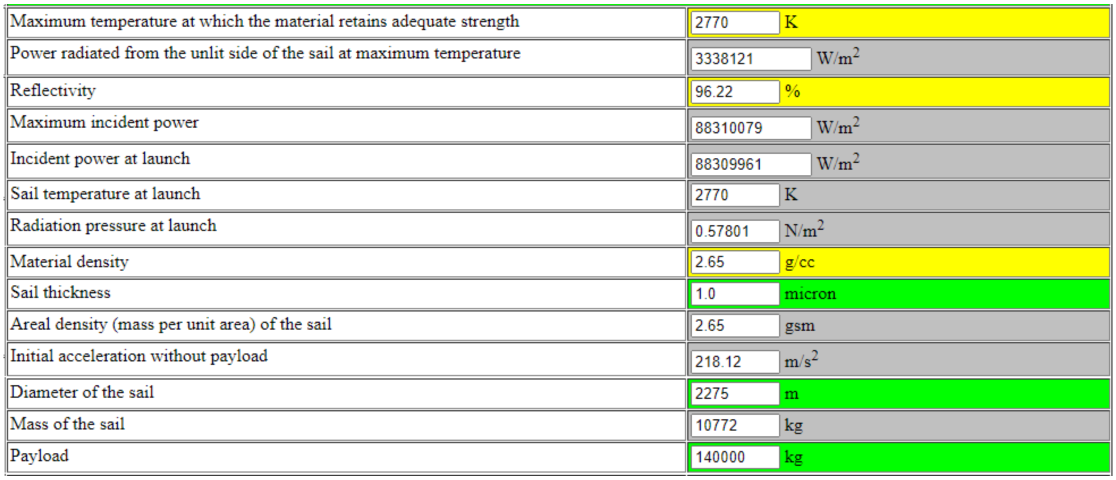
Due to the square inverse law, as the spacecraft moves away from the laser, the power density reduces. To maintain the same power density all the time, it would be necessary to incorporate in the laser system an automatic parabolic mirror that would gradually increase its diameter in order to reduce the divergence of the beam (from 3,100 mrad at 585 meters to 5 x 10-9 mrad at 2,400 AU. The mirror could be formed by several small mirrors, each of them with a specific orientation every time.

Beam diameter at aperture:	500	mm
Divergence:	0.00000	mrad
Distance to audience:	360000	m
Laser power:	220000	mW
Diameter at audience:	1800500.0	mm
Minimum diameter (> 7mm):	1800500.0	mm
Beam area:	2546103962451.4	mm²
Irradiance:	8640652.7	mW/cm²

Figure 2: Power density
Source: Kvant Lasers

The idea behind Solar One is to combine the three projects. A 4-crew spaceship with a total mass of 150 tons (120 tons from the reactors, 10 tons from the laser system, and 20 tons from the light sail, structure, equipment and crew - being a total mass equivalent to Project Icarus) could be powered by a 1,600 meters-long light sail and achieve the speed of 0.3c with a constant acceleration during approximately the first 100 days of the trip. The estimated weight for the cockpit module is based on the SForza (2015) calculation whereby a 4-crew spacecraft has a mass of 10 tons.

No light sail is able to reflect 100 percent of the light. A sail with a reflectivity of 96.22 percent and able to withstand 2,770 K (which is the limit for carbon fibre), could receive a maximum of 88 MW/m2. Such sail could have a density of 2.65 g/cc, a thickness of 1 micron, and a total mass of 10.7 tons.



Maximum temperature at which the material retains adequate strength	2770	K
Power radiated from the unlit side of the sail at maximum temperature	3338121	W/m^2
Reflectivity	96.22	%
Maximum incident power	88310079	W/m^2
Incident power at launch	88309961	W/m^2
Sail temperature at launch	2770	K
Radiation pressure at launch	0.57801	N/m^2
Material density	2.65	g/cc
Sail thickness	1.0	micron
Areal density (mass per unit area) of the sail	2.65	gsm
Initial acceleration without payload	218.12	m/s^2
Diameter of the sail	2275	m
Mass of the sail	10772	kg
Payload	140000	kg

Figure 3: Specifications of the light sail
Source: George Fishman

The power density would be 88.3 MW/m2, but considering an absorption slightly over 3 MW/m2, the effective power density would be around 85 MW/m2.

$$F^{*} = 2(P \times A)/c$$
$$F = 2(85,171,933 \times 2,588,881)/$$
$$300,000,000$$
$$F = 1,470,000 \text{ newtons}$$

F* = force (newtons)
P*= power (watts / m2)
A*= surface area of light sail (m2)
c* = speed of light

The acceleration obtained would be 1 g:

$$\mathrm{a = F/M}$$
$$\mathrm{a} = 1,470,000/150,000$$
$$\mathrm{a} = 9.8\mathrm{m/s2} = 1\mathrm{g}$$

a* = acceleration (m/s2) M = mass (kg)

And it would take around 100 days to reach 0.3 c:

$$\mathrm{t = v/a}$$
$$\mathrm{t} = 89,994,000^{*}/9.8$$
$$\mathrm{t} = 9,183,061\mathrm{sec} = 107 \text{ days}$$

To reduce the power needed, it would be necessary to increase the size of the light sail. A 5-km light sail could reduce the power requirement to 60 TW with a light sail mass of 100 tons, bringing the total mass of the spacecraft to 250 tons. The acceleration obtained would be 1.5 m/s2 and it would last one year and a half to reach 25 the speed of light. If this option is taken, the spacecraft would probably have to be assembled in orbit.

For the deceleration, considering that photons have a thrust to power ratio of 3.34 x 10-9 newtons per watt, the laser system would provide the following opposite force:

$$F = 38.1 \times 10^{12} \text{ watts } \times 3.34 \times 10^{-9} = 127,500\text{N}$$

To use less power for deceleration or perform it in less time, the spacecraft would detach from the light sail, ideally just after the acceleration stage finishes. The acceleration obtained during deceleration would be around 0.1 g:

$$\begin{gathered}\text{a} = \text{F/M} \\ \text{a} = 127,500/150,000 \\ \text{a} = 0.85\text{m/s2 } = 0.08\text{g}\end{gathered}$$

And it would take around 3 years to stop the spacecraft:

$$\begin{gathered}\text{t} = \text{v/a} \\ \text{t} = 89,994,000^{*}/0.85 \\ \text{t} = 105,875,294\text{sec} = 3.3\text{years}\end{gathered}$$

At the speed of 0.3 c, the crew would arrive to the Alpha Centauri system in slightly more than 15 years. All the necessary measures would be taken in order to enable the crew to withstand the lack of gravity during such a long trip.

$$\begin{gathered}\text{Average speed } = 0.23^{*} \cdot 0.15^{*} + \\ 0.77^{*} \cdot 0.3^{*} = 0.2655\text{c}\end{gathered}$$

0.23* = approx. percentage of trip time during acceleration and deceleration
0.15* = average speed during acceleration and deceleration
0.77* = approx. perfentage of trip time with constant speed
0.3* = cruise speed

Duration of the trip to Alpha Cen =
Distance / Average speed = 4.37/0.2655
$\approx$ 16 years

Another possibility would be to increase the amount of time that the deceleration laser is active in order to reduce power requirements. Six 1-Terawatt compact nuclear fusion reactors of 20 tons each together with one laser of 6 Terawatts and 10 tons of weight could provide 20,000 newtons of thrust, which would allow an acceleration of 0.134 m/s2 for a 150 ton spacecraft.

It would take 17.7 years to completely stop a spacecraft travelling at 25 percent the speed of light. Considering that the trip to Alpha Centauri at 25 percent the speed of light takes 17.6 years, the spacecraft would have to be decelerating during most of the trip. This would be, however, if the spacecraft is not equipped with a Bussard scoop.

Considering that a proton-proton fusion reaction can produce up to 645 TW, a 6-TW photon rocket would only need 9.3 grams of hydrogen per second. The density of hydrogen atoms is about one H-atom per cubic centimeter, so a 250-ton spacecraft would likely need a scoop several hundred meters wide (Freitas, 2008). However, taking advantage of the CNO cycle and using the photon rocket on-board to ionize the hydrogen could greatly reduce the size of the scoop.

Actually, the electromagnetic fields would help to decelerate the spacecraft. The drag is calculated multiplying the mass of hydrogen collected per second, which would be 0.0093 kilograms, by the speed at which the spacecraft travels, which would be an average of 0.125c or 37,474,057 m/s at deceleration. We obtain a force of almost 350,000 Newtons. This force together with the force produce by the photo rocket would be 476,000 Newtons. The resulting acceleration would be 3.17 m/s2, and it would take 7.5 years to stop a spacecraft travelling at 0.25c.

3 Design

The spaceship would be composed of the following main elements: a laser system, a light sail, a nuclear micro-reactor, a bussard scoop, and a cockpit protected from space radiation. An extra amount of light sail would be ideal in case of damage caused by micro-meteorites.

To reduce damage and drag, the light sail would be rolled when the spaceship is neither accelerating nor decelerating, that is, 80 percent of the time. However, as it was mentioned before, detaching the sail after the acceleration stage would be ideal to reduce weight for the deceleration. The spacecraft could be located behind the light sail, as in the following image.

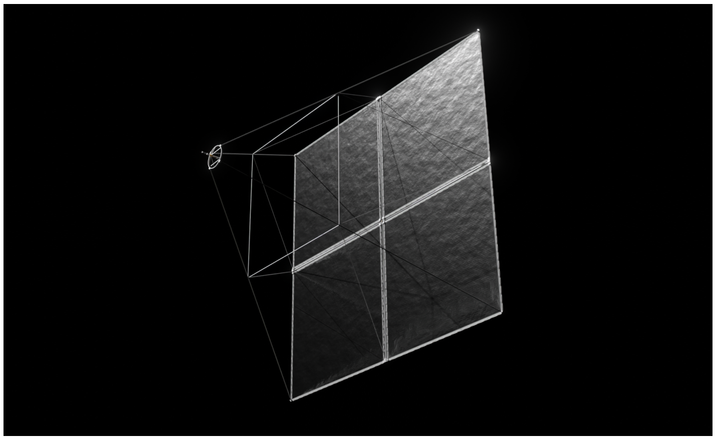


Figure 4: Solar One
Animation made by Marco Purich

During the acceleration, the light of the laser reflected by a primary mirror placed inside the laser system would be sent to a secondary parabolic or hyperbolic mirror that would also gradually change its form in order to give the divergence needed at any given moment.

Another possibility would be to use parabolic mirrors such as the one of the DE-STAR laser, but instead of being fixed, they would gradually change their orientation in order to change the divergence of the beam.

Instead of being located behind the light sail, the spacecraft could be placed in the middle of the sail, reducing the amount of structure needed and probably the overall weight of the spacecraft.

Figure 5: Solar One - Nuclear reactors at the right, cockpit in the middle, and photon rocket at the left
Animation made by Marco Purich

Once the destination is reached, the crew could orbit the exoplanet, take images and send a robot to the surface. If the air turns out to be breathable, the crew could choose to land in order to personally explore the exoplanet.

4 Challenges

Engineers would likely face several challenges while building Solar One. One of them would be to make a laser able to produce a high-energy continuous wave with the smallest possible energy loss. The ideal would be to reduce it to a value closer to zero. Another obstacle would be to reduce the weight of the small nuclear reactors to that of a car, or build a compact fusion Petawatt reactor.

Other challenges would be to protect the reactor module and the light sail from micro-asteroid impacts. Potential nuclear failures include neutron radiation damage and tritium release. The module containing the nuclear micro-reactor would have a protective coating thicker than the rest of the spaceship.

The cockpit could also be equipped with an emergency propulsion system such as an ion thruster in case there is a nuclear failure and the crew has to separate from the spaceship. However, this additional system would probably increase the budget and there is also a low chance of survival if the failure occurs outside the solar system.

5 Conclusions

In this paper it has been analysed the possibility of building a manned interstellar spaceship with a light sail propelled by an external laser system in space. To decelerate, the spacecraft would use an on-board laser system that would receive the necessary electricity from small nuclear fusion reactors.

Small modular reactors such as the US Navy CFR have already been patented, large light sails such as Sunjammer have already been built, and portable Terawatt-class lasers such as Teramobile have proved successful. Nuclear fusion is the most near-term technology that could be used to power the laser system of Solar One.

However, research on antimatter propulsion is advancing at a rapid rate. If scientists are able to produce more antimatter than the energy used to generate it, this would be the best way to power the laser system of Solar One.

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