PROJECT ICARUS: SOLAR SAIL TECHNOLOGY FOR THE ICARUS INTERSTELLAR MISSION

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ABSTRACT

Project Icarus is an in-depth theoretical engineering design study of a mission to another star, following on from the historically successful Project Daedalus. While the terms of reference for the project specify that the spacecraft propulsion system will be mainly fusion-based, aspects of the mission and overall architecture could be implemented or assisted by the use of solar sails. This discussion paper gives a brief overview of the aims of Project Icarus, and examines the potential application of solar sails in several areas of the mission. This includes: assisted boosting of the Icarus probe out of our solar system; deploying sub-probes in the target solar system for exploring local planets and other objects of interest; deploying a relay station at the Sun's gravitational focus to receive transmissions from the distant Icarus craft. This paper discusses some of the engineering requirements for these potential roles as well as any potential performance enhancements to the mission. This is a submission of the Project Icarus Study Group.

INTRODUCTION

Project Icarus[1] is a comprehensive study of an interstellar mission to launch an unmanned probe to a star, with arrival no later than 100 years after launch. This investigation revisits the original Project Daedalus study conducted in the 1970s [1].

The aims of Project Icarus are to design a credible interstellar probe that is a concept design for a potential mission in the coming centuries; to allow a direct technology comparison with Daedalus and provide an assessment of the maturity of fusion based space propulsion for future precursor missions; to generate greater interest in the real term prospects for interstellar precursor missions that are based on credible science; and to motivate a new generation of scientists to be interested in designing space missions that go beyond our solar system [2].

While Daedalus was planned to be a flyby mission to Barnard's Star, the terms of reference for Icarus specify that there will be some measure of deceleration at the target to allow for greater science return. They also specify that the primary propulsion system for Icarus will be fusion-based. However, other forms of secondary propulsion are being investigated to establish whether they might assist certain aspects of the mission. Icarus may also deploy sub-probes in the target system to perform up-close examination of individual objects.

This paper examines the potential application of solar sails to various phases of the Icarus mission. The configuration of the Icarus craft has not yet been determined, so we look at various possible configurations and the limiting cases, in order to establish the boundary conditions. Where quantitative assumptions need to be made about the Icarus craft, we take the Daedalus design as a starting point.

Although the target star for Icarus has not yet been chosen, in this paper for convenience we choose the target star to be Alpha Centauri A.

1 SOLAR SAIL APPLICATIONS

1.1 Deceleration at Target Star

In interstellar space, Icarus is expected to reach speeds of 0.1–0.2c. The craft must be decelerated in order to either enter orbit around the star or to increase the encounter time within the target system. The fusion engine may provide

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[1] Project Icarus is a Tau Zero Foundation (TZF) initiative in collaboration with The British Interplanetary Society (BIS).

some measure of this deceleration, but here we will establish whether a solar sail can supplement this usefully[2].

Firstly, we examine the potential for a realistic sail to decelerate Icarus.

Following Matloff's analysis [3] we assume the limiting case of entering a parabolic orbit, using a hollow-body (i.e. inflated) beryllium sail [4]. This type of sail is potentially capable of withstanding the high temperatures that might be encountered in the deceleration maneuver. We obtain v_i, the maximum initial velocity that the craft must have on starting sail deceleration in order for the sail to be able to capture it into a parabolic orbit:

$$v_i = \sqrt{\frac{L}{2\pi c}\frac{(1+\rho)}{\sigma}\frac{1}{R_f}} \tag{1}$$

where L is the target star's luminosity, ρ is the sail's reflectivity, σ is the sail loading (i.e. mass per unit sail area, consisting of sail and payload mass), and R_f is the distance from the star at which deceleration ends (and the craft is captured). As we are considering a mission to Alpha Centauri A, we take $L = 1.56\mathrm{L}_\odot$ (where $\mathrm{L}_\odot$ is the Sun's luminosity, 3.845×10^{26} W). The total sailcraft loading σ is given by $\sigma = \sigma_{\text{sail}} + m_p/A$, where m_p is the payload mass, and A is the area of the sail.

For the sail characteristics, we choose optimistic values (as we are attempting to establish what the limits are). So we set $\sigma_{\text{sail}} = 4 \times 10^{-5}\ \mathrm{kg/m^2}$, and $\rho = 0.9$, which are at the optimistic end of the values Matloff provides for a beryllium hollow-body sail [5]. We assume that the closest that this sail can safely approach the star unfurled is $R_f = 0.066$ AU (i.e. the end point of the deceleration), and that Icarus will be heading directly for the star, so that the solar radiation is normal to the sail.

As the limiting case where we have only a sail with no payload, we find that $v_i \approx 0.004$c (1200 km/s). This is the maximum initial velocity possible given these assumptions about the sail properties. Adding payload will bring this velocity down (thus requiring greater prior deceleration using other means), though this can be compensated to some degree by increasing the sail area, as can be seen in Fig. 1 which shows the relationship between the parameters.

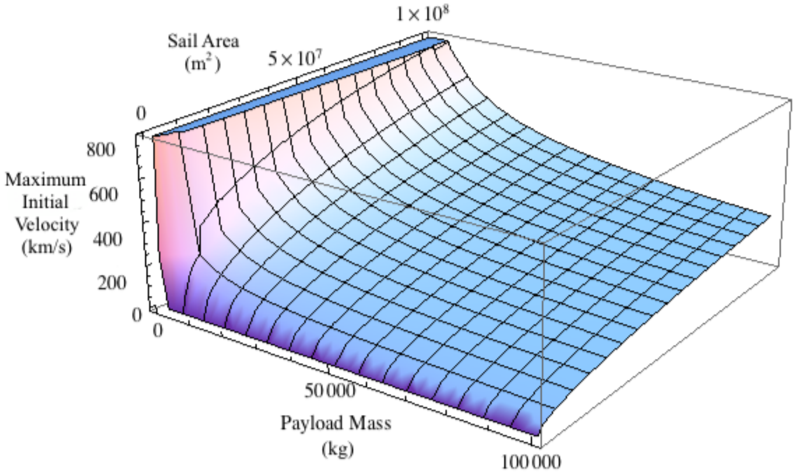

Fig. 1: Hollow-Body Beryllium Sail for deceleration at Alpha Centauri A

As even the limiting case requires 96–98% of the deceleration to be performed by other means before the solar sail is deployed, it is hard to make a case for using this type of solar sail to perform the last part of the deceleration which is trivial in comparison.

Having ruled out this realistic sail, we now look at the problem from another perspective, establishing the absolute theoretical limits for the capabilities of an "ideal sail". For this ideal sail, we assume perfect reflectivity ($\rho = 1$)

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[2] We are considering only solar sails in this paper. Project Icarus is also looking into other techniques, such as the MagSail.

and a mass greater than zero ($\sigma_{\text{sail}} > 0$). With these assumptions, it is easily shown that the minimum area for the ideal sail which could result in orbital capture is given by

$$A_{\min} = m_p {v_i}^2 \frac{\pi c R_f}{L} \tag{2}$$

where we choose, for convenience, $R_f = 0.066$ AU as before. The relationship is shown in Fig. 2. Plausible masses for Icarus on arrival at the target system (based on the Daedalus figures) are on the order of tens to hundreds of tonnes. Assuming an Icarus mass of 50,000 kg (after total fuel depletion) and an interstellar speed of 0.1c (i.e. at the slow end of the scale), then to perform the entire deceleration to parabolic orbit capture using the sail alone, the calculated ideal sail area is 7×10^{11} m; a circular sail of diameter 944 km.

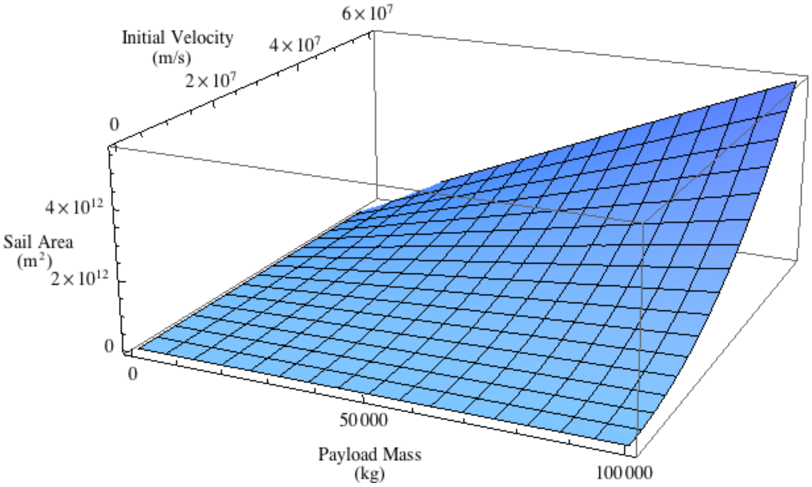

Fig. 2: Ideal Sail for deceleration at Alpha Centauri A

1.2 Deployment of Gravitational Lens Relay Station

Maccone shows that if a receiver craft is placed further than 550 AU from the Sun on the axis joining the center of the Sun and a distant transmitter so that the Sun is between the transmitter and the receiver (Fig. 3), then the Sun will act as a gravitational lens focusing the electromagnetic waves onto the receiver, enormously increasing the antenna gain [6]. In fact, due to effects of the Sun's corona, the receiver needs to be at least approximately 700 AU from the Sun. There are a number of technical difficulties to overcome, such as maintaining the receiver's lock on the signal [7], but here we consider the possibility of using solar sails to aid the deployment of the receiver craft. First, note that the receiver craft does not necessarily need to be deployed at the same time as Icarus is launched. In the very early phases of the mission Icarus will be close enough to Sol that direct contact can be made with reasonable bandwidth.

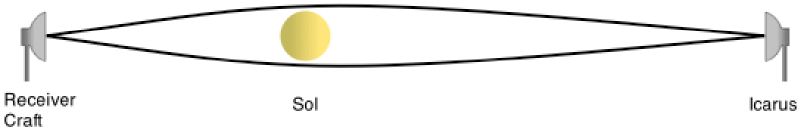

Fig. 3: Receiving transmissions via Sol's gravitational lens (not to scale)

The parameters of a mission to deploy the receiver are very similar to those for other suggested interstellar precursor missions. McInnes discusses the use of a beamed-power system to push a craft to the required distance in around a decade [8]. We follow this analysis here to obtain the parameters for a mission to 700 AU.

A powerful laser in Earth (or Sol) orbit is focused onto the receiver craft by a large Fresnel lens (Fig. 4). The craft is accelerated during this 'boost' phase until the craft is further away than the diffraction limit of the lens. The craft then enters the 'coast' phase for the rest of the mission. McInnes derives the equations that determine the total duration of the mission [8]:

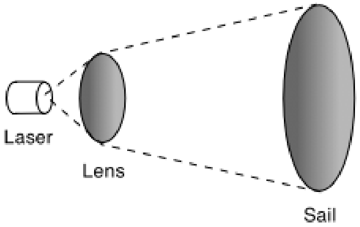

Fig. 4: Pushing the receiver craft with a laser

$$\tilde{s} = \frac{Dd}{2.44\lambda}\ , \quad \tilde{a} = \frac{4}{\pi d^2}\frac{1+\rho}{\sigma c}P \tag{3}$$

where d is the sail diameter, D the lens diameter, λ the wavelength of the laser light, P the laser power output and ρ and σ the reflectivity and sail loading, as above. $\tilde{s}$ gives the distance to the lens diffraction limit, and $\tilde{a}$ the acceleration during the boost phase.

To obtain the total mission duration to a specific distance s, we sum the boost and coast phase durations:

$$t = \sqrt{\frac{2\tilde{s}}{\tilde{a}}} + \frac{s-\tilde{s}}{\sqrt{2\tilde{a}\tilde{s}}} \tag{4}$$

McInnes assumes σ of 1 g m^{-2}, comprising sail and payload mass. The area of the sail is thus determined by the payload mass. We calculate the mission duration to 700 AU, with a 10 GW laser ($\lambda = 1\mu$m), a lens of diameter 1 km, and sail reflectivity $\rho = 0.85$. (Fig. 5.) Thus we can see that for a reasonable payload mass of 300 kg, the receiver craft could be deployed at 700 AU within ten years, using a 620 m diameter sail.

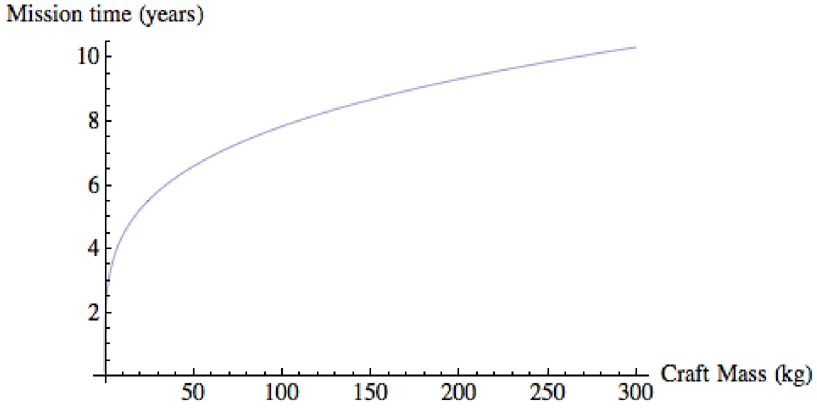

Fig. 5: Mission duration for a laser-pushed sail to the gravitational focus of the Sun

1.3 Boost from Solar System

The Daedalus design called for a craft with a mass at launch of 54,000 tonnes (including fuel), so we take this as a baseline figure for the mass of Icarus. This is a much bigger mass than that normally associated with craft accelerated by sails, so in the first instance we will look at the limits of an ideal sail.

Equation 1 can be trivially reformulated (by symmetry) to provide v_f, the final velocity, given R_i, the initial distance from the Sun. We use the same sail parameters as for the deceleration case, except that $L = \mathrm{L}_\odot$ as the star is Sol.

Using an ideal sail as in the analysis above, we find that to accelerate a 50,000 tonne craft to 0.1c, a sail of area 1.1×10^{15} m^2 would be required. Of course, we are not expecting the sail to perform the entire acceleration, as the bulk of it is to be performed by the fusion engine. To provide even a tenth of the speed (i.e. 0.01c), an ideal sail would need to be 1.1×10^{13} m^2 in area, or a circle of diameter 3742 km.

We now consider the use of a laser to push Icarus. From McInnes again we have the terminal velocity for Icarus when it has passed the diffraction limit of the lens [8]:

$$v_\infty = \sqrt{\frac{2.09}{\lambda}\frac{\mathrm{D}}{d}\frac{1+\rho}{\sigma c}\mathrm{P}} \tag{5}$$

For an Icarus mass of 50,000 tonnes, the results are shown in Fig. 6. In reality, higher laser powers could cause problems with the sail's ability to withstand high temperatures; this has not been analysed in this paper. Nevertheless, we can see that using a 100 GW laser with a 100 km diameter lens to push Icarus, v_∞ is 0.002c, which does exceed the Sun's escape velocity a few AU from the Sun, so could potentially enable Icarus to delay starting the fusion engine until it has left the solar system. This would, however, require a very large sail of 250 km diameter on Icarus.

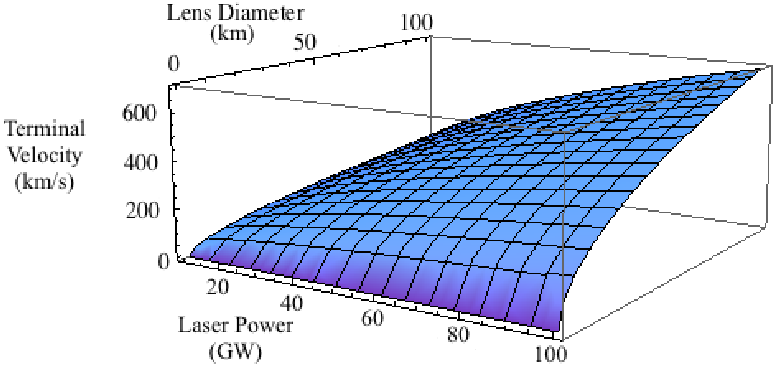

Fig. 6: Laser pushed Icarus boost from solar system

1.4 Deployment of Sub-Probes

The Daedalus design specified that up to eighteen sub-probes would be dropped in the target system to investigate planets and other objects of interest. Icarus may also drop sub-probes, though the number and nature of these craft has not yet been determined.

Calculation of intra-system orbits is complicated by the facts that they are more complex than the simplistic cases covered above, and also that the optimal injection orbit and sub-probe trajectories depend upon the details of the 'interesting object' distribution in the system. So for convenience here, we consider a mission to a hypothetical solar system that is identical to ours.

If Icarus decelerates into a circular orbit approximately 1 AU from the Sun, then it will be operational in the system and retrieving data for a number of years, giving the sub-probes an opportunity to traverse to their destinations and still be able to use Icarus as a communications relay. Also, the relatively close proximity to the Sun will enable the sub-probe solar sails to work effectively.

As intra-system transfer orbits have been considered extensively in the literature, the details will not be repeated here. In summary, sub-probes using solar sails could reach the range of planets in the solar system out to Uranus in 1–16 years [8].

The use of sails on the sub-probes also raises the possibility of visiting objects that may be awkward to reach by other means. The 'cranking' maneuver enables a sub-probe to increase its orbital inclination over the course of many orbits. Thus it would not be restricted to objects in the orbital plane of Icarus. Also a sub-probe could be despatched to 'hover' over a pole of the Sun, or some other non-Keplerian orbit that would be difficult to achieve otherwise [8].

2 FURTHER WORK

The storage of a sail for several decades followed by its subsequent deployment presents challenges for reliability. Studies of the long-term deterioration of sails and deployment mechanisms, together with mitigation techniques, would provide confidence that the solar sail technology is useful in the destination system.

The deployment of sub-probes has been considered as analagous to launch from Earth orbit. Other deployment schemes should be investigated. For example, Icarus could enter the target system having decelerated, but still not been fully captured. Could solar sail sub-probes be usefully deployed in this scenario and visit targets in fly-by mode? Also, is it possible to drop off a sub-probe while en-route to Alpha Centauri A that can visit Proxima Centauri, which is some distance away?

CONCLUSIONS

The likely large mass of the Icarus craft at launch and arrival in the target system, together with the high interstellar speed renders the use of solar sails implausible for useful acceleration or deceleration of the craft as a whole.

However, the two aspects of the mission that could usefully use sails are the deployment of sub-probes in the target system, and the deployment of the gravitational lens communications receiver (albeit with the use of a powerful laser to push it). Both of these types of craft have similar requirements to solar sails that are traditionally discussed for interplanetary missions.

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