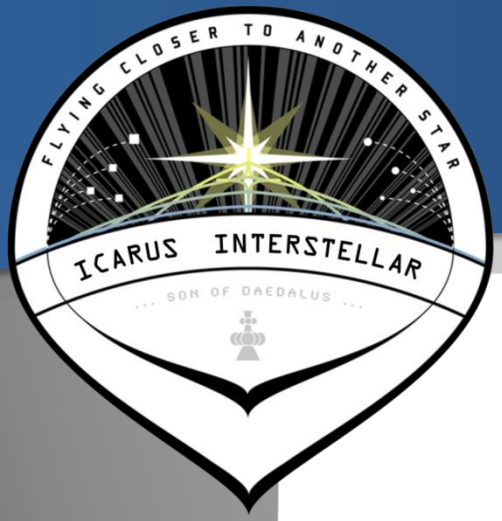

Icarus Interstellar

International Interstellar Spacecraft Design Team

Magnetic-Sails vs Two-Stage Fusion Rockets for Sub-Century Missions to Alpha Centauri

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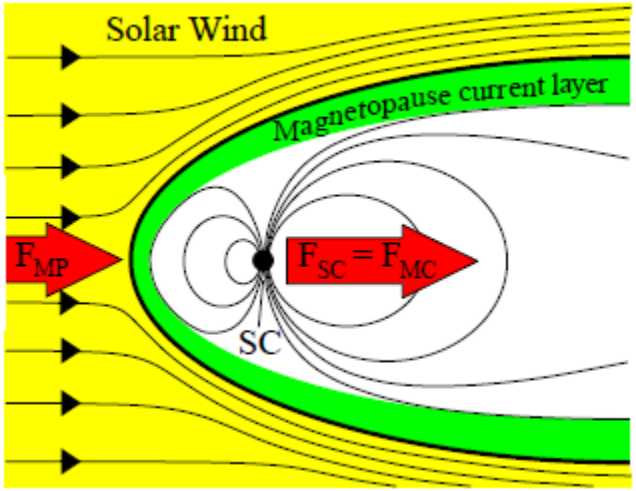
Icarus Designers

Introduction

- The minimum mission requirement for “Project Icarus” is data from Alpha Centauri in 100 years.
- For maximum data-return the probe needs to brake into orbit around the target star from interstellar transit speeds.
- Vehicle needs to undergo a total velocity change of 0.09c (27,000 km/s.)
- Option 1: Use fusion thrust for the whole velocity change, but this increases the required fuel considerably, even using a two-stage rocket, as assumed in this paper.
- Option 2: Use Magnetic-Sails (Mag-Sails), a non-propellant means of reducing the vehicle’s speed from its cruise speed via creating drag against the thin gas between the stars known as the Interstellar Medium (ISM).

Magnetic Sails

- A Magnetic-Sail, or Mag-Sail creates drag (or lift) via an artificial magnetosphere interacting with the in-space medium
- A Magnetosphere is the border created between a dipolar magnetic-field and a large plasma flow, such as the Solar Wind (Figure 1).
- The border between plasma and the magnetic field is defined by equilibrium between the plasma flow's ram pressure and the magnetic pressure of the magnetic field.



Magnetosphere (from [6])

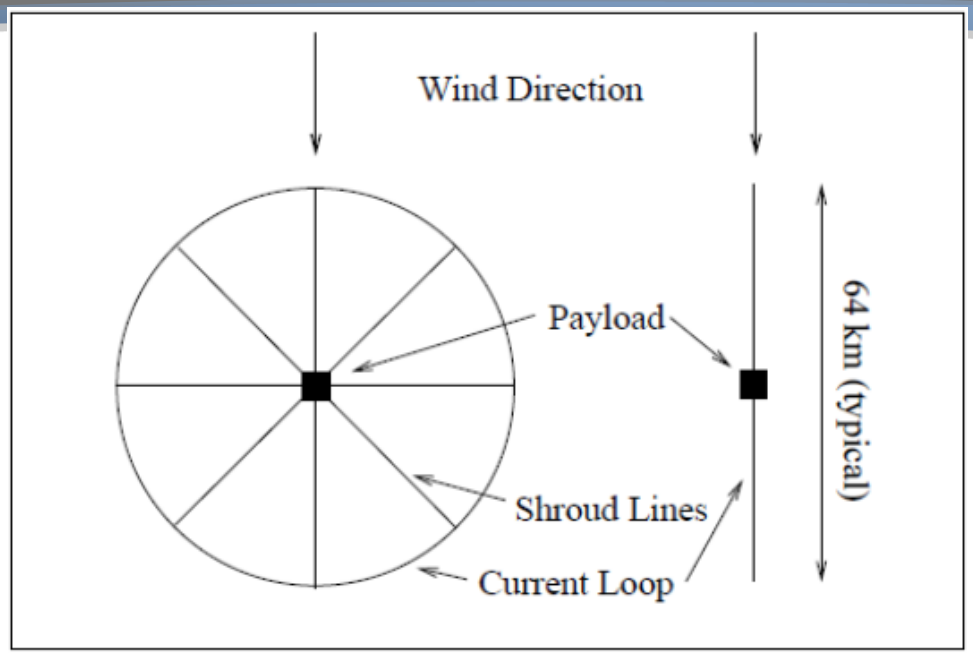
Magnetosphere Equations

Ram Pressure: $$P_r = nm_p v^2$$

Magnetic Pressure: $$P_m = \frac{B^2}{2\mu_0}$$

Magnetosphere Radius: $$R^6 = \frac{{D_m}^2}{2\mu_0 nm_p v^2}$$

Mag-Sail Engineering I



- Mag-Sail is a huge ring of superconducting wire attached to a space vehicle.
- Mass of wire depends on the Engineering Current-Density, J_e, which needs to include insulation, strengthening materials and protection against sudden loss of superconductivity.
- Will operate at close to 4 K, thanks to the relative cold of interstellar space. Detached when arriving in star-system, as heat increases quickly.

Mag-Sail Engineering II

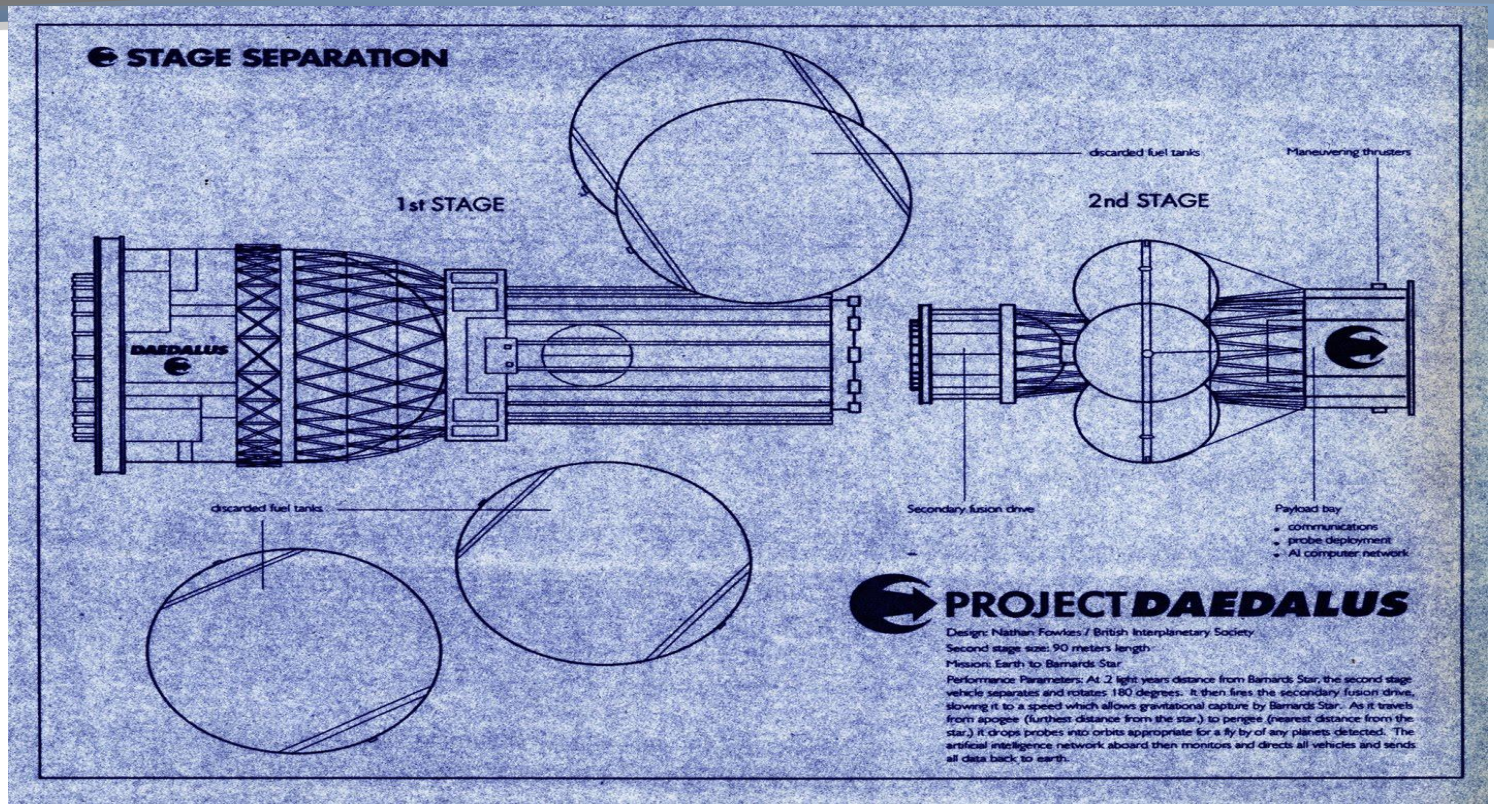
$$\kappa = \frac{\pi}{3M_v}\left(\frac{\mu_o}{16}\right)^{1/3}(nm_p)^{2/3}I^{2/3}{R_m}^{4/3}$$

- The Deceleration Constant, κ, determines the performance of a Mag-Sail of a given size, carrying a given current, in a given density of plasma flow.
- The maximum current is limited by the critical magnetic field for the superconductor used. To produce a given Deceleration constant, a larger Mag-sail radius needs a smaller current, and produces a smaller magnetic field intensity in the wire.
- For this study a κ value of 2E-11 $s^{2/3}/m^{1/3}$, a magnetic-sail mass of 1,000 tonnes, and 800 km radius, using a superconducting wire with a density of 2,500 kg/m^3 (similar to magnesium boride) will be assumed. Maximum magnetic field is 16 tesla.

Mag-Sail Equations

- Drag: $$D = \pi \left(\frac{\mu_o}{16}\right)^{1/3} P_r^{2/3} I^{2/3} R_m^{4/3}$$
- Mag-Sail Mass: $$M_s = 2.\pi.R_m.(I/J_e)$$
- Braking distance: $$s_d = \frac{3}{2}\frac{V_0^2}{a_0}\left[1 - \left(\frac{V_f}{V_0}\right)^{2/3}\right]$$
- Braking time: $$t_d = 3\,\tau_0\left[\left(\frac{V_0}{V_f}\right)^{\frac{1}{3}} - 1\right]$$

Two Stage Fusion Rockets

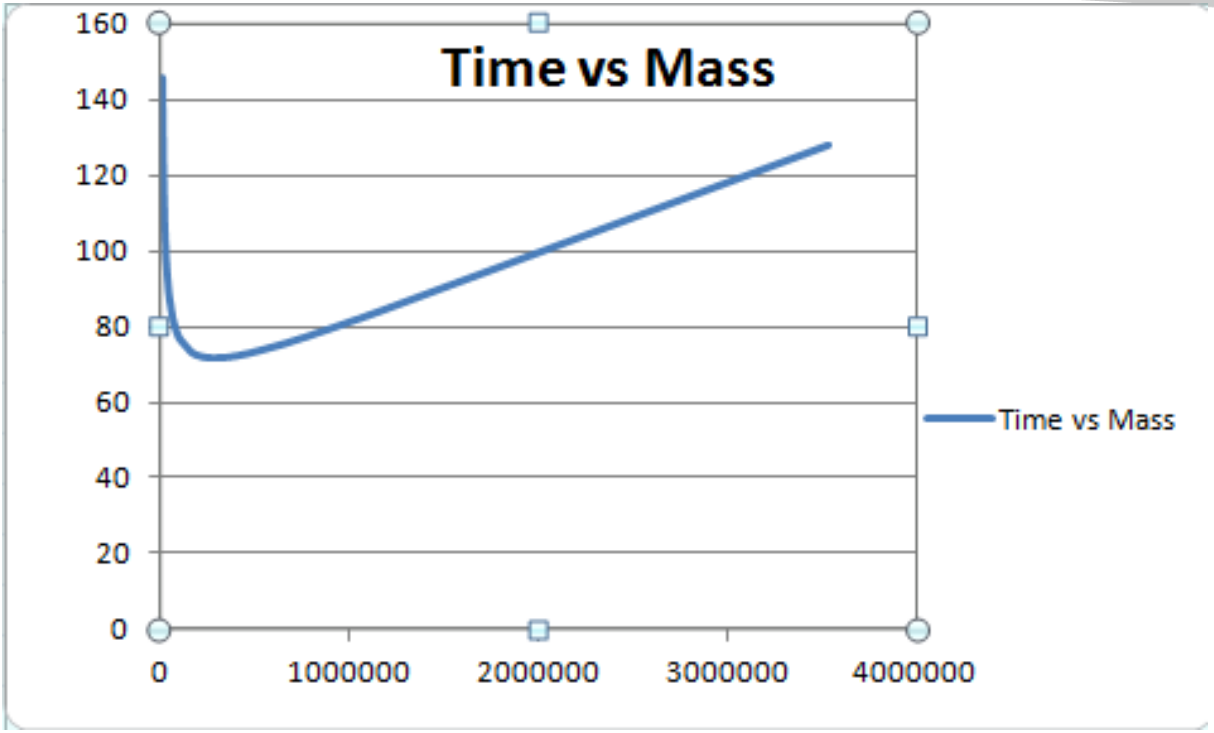


- Design work by Nathan Fowkes. Used with permission.
- Two Stage Fusion rocket concept.
- Based on “Project Daedalus” vehicle design, as it’s still the most well-defined interstellar fusion rocket.

Stage	Thrust (newtons)	Dry Mass* (kilograms)	Exhaust Velocity (metres/second)	Mass-Flow Rate (kilograms/second)	Fuel-Tank Mass-Fraction*
1	7.54E+6	1.4E+6	1.06E+7	0.72	0.0474
2	6.63E+5	9.31E+5	9.21E+6	0.0711	0.0527

*Dry mass, less main propellant tankage

- Fusion performance characteristics of the original "Daedalus" stages.
- Fuel-Tank Mass-fraction is a slowly varying function of the total fuel mass. Assumed constant over the relevant fuel mass range for this estimate.

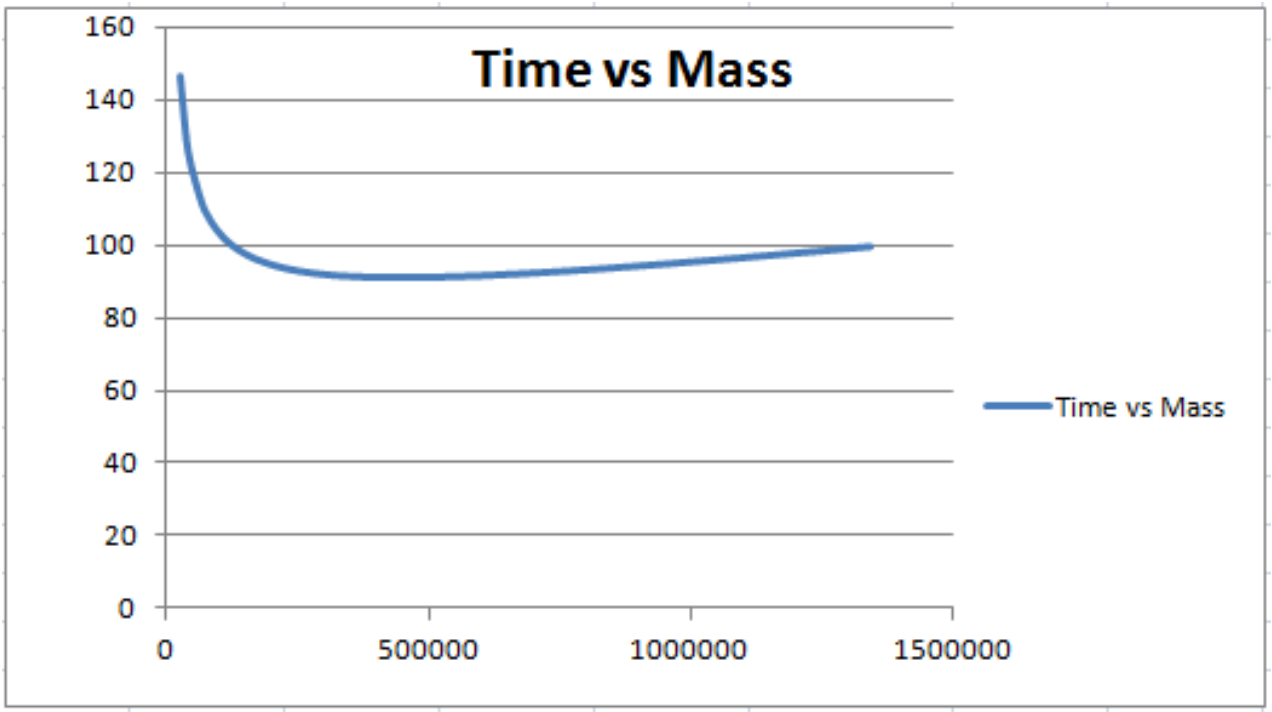


Highlights	Mission Time (years)	Initial Mass (tonnes)
Minimum Time Mission	71.58	281,181
Maximum Icarus	95.6	30,700

Stage	Thrust (newtons)	Dry Mass* (kilograms)	Exhaust Velocity (metres/second)	Mass-Flow Rate (kilograms/second)	Fuel-Tank Mass-Fraction*
1	5.67E+6	1.4E+6	7.98E+6	0.72	0.0474
2	5.00E+5	9.31E+5	6.944E+6	0.0711	0.0527

*Dry mass, less main propellant tankage

- Revision of the fusion physics, by Robert Freeland for Project Icarus, means a revision of the performance characteristics of the original "Daedalus" stages.
- Mass-flow rate and plasma nozzle efficiency (Bond & Martin estimated 97%) are kept the same. Nozzle efficiency needs to be revisited in future.

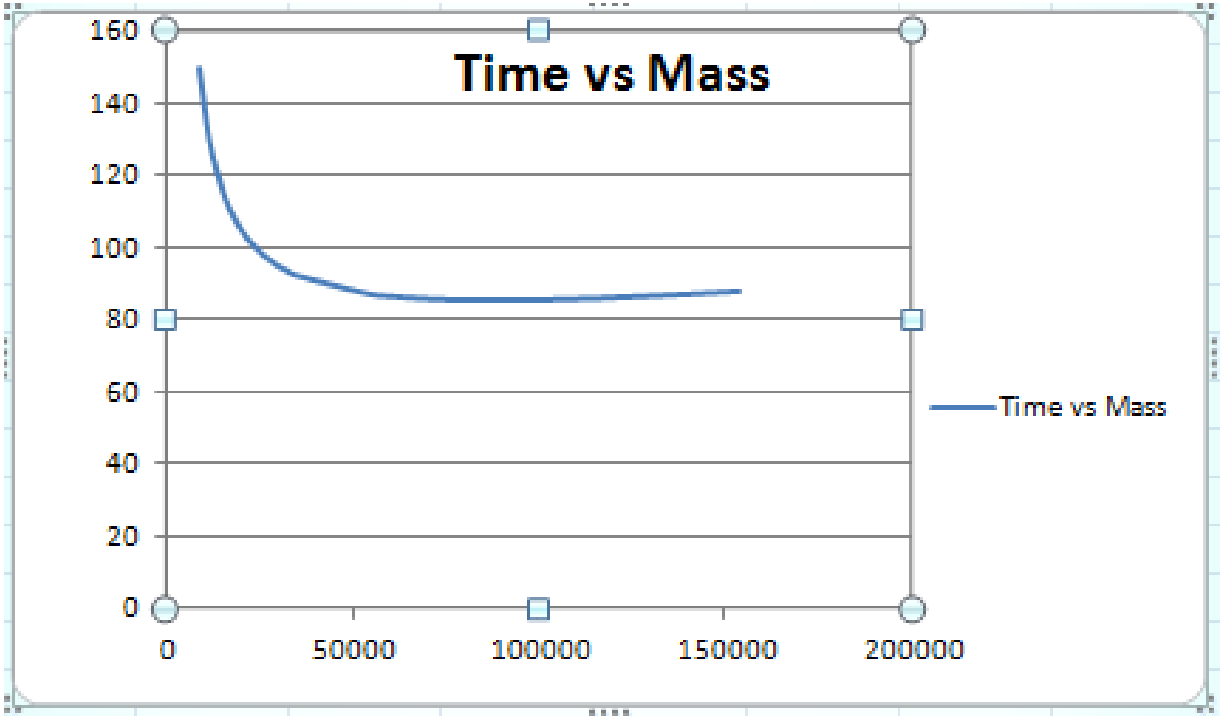


Highlights	Mission Time (years)	Initial Mass (tonnes)
Minimum Time Mission	91.0835	446,300
Maximum Icarus	95.6	180,200

The Interstellar Medium

- The Interstellar Medium is mostly hydrogen & helium atoms or ions. About 1% of all other elements in gaseous or dust form.
- ISM is relatively thin near the Sun due the so-called “Local Bubble” – a region of expanding hot, thin gas.
- Between here and Alpha Centauri there seem to exist somewhat higher density “cloud” with 100,000 – 200,000 particles per cubic metre.
- An astrosphere – a star’s magnetosphere – has been detected around Alpha Centauri A & B, but its properties are as yet unknown.
- An ISM density of 100,000 particles per cubic metre is assumed for this study.

Mag-Sail Performance



Highlights	Mission Time (years)	Initial Mass (tonnes)
Minimum Time Mission	85	93,100
Maximum Icarus	95.6	28,600

Conclusions

- Mag-sails potentially provide an effective means of reducing overall mission mass for fusion starships.
- Requires sufficiently low density superconductor wire. Recent observation of possible Room-Temperature superconductivity in water-doped graphite suggests it will eventually be available.
- Future study will examine protection of the Mag-Sail from ISM dust particles via magnetic deflection, due to the charge on the dust.
- One physics uncertainty is the efficiency of the coupling between the artificial magnetosphere and the plasma flow. Needs more experimental work as simulating all the relevant physics brings computers to their knees.

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