

PRINCIPIUM

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Scientia ad Sidera
Knowledge to the Stars

Editorial

Welcome to the 22nd issue of Principium, the quarterly newsletter about all things interstellar from i4is, the Initiative for Interstellar Studies - and our US-based Institute for Interstellar Studies. And a special welcome if you are a new reader. Please tell us if we have your details wrong (info@i4is.org).

Our Introduction feature for Principium 22 is *Reaching The Stars in a Century Using Fusion Propulsion – A Review Paper based on the ‘Firefly Icarus’ Design* by Principium Deputy Editor Patrick J Mahon. Project leaders Robert Freeland and Michel Lamontagne are now delivering this study of a Z-pinch fusion propulsion probe as part of the Project Icarus Final Report.

Our front cover also celebrates this worthy successor to Project Daedalus, the pioneering BIS design study for an interstellar probe propelled by a fusion rocket. Another of Michel Lamontagne's talents is visualisation of the spacecraft the Firefly team has designed - here it is under construction and the details are described in *Michel Lamontagne and Our Front Cover Image*, inside the back cover.

Our back cover follows from the Gaia astrometry telescope shown in our last issue with an all sky survey showing the Milky Way Galaxy and its two satellite galaxies, the Magellanic clouds.

We have a review of the more exotic forms of propulsion in *Breakthrough Propulsion Physics: Leave the fuel tank at home* by Dan Fries and a book review of *Exoplanètes* by George Frangou, our first review of a book in French.

We are looking forward to October in Bremen and the annual gathering of the astronomical world, the International Astronautical Congress (IAC). We have a guide and timetable to i4is and interstellar at the conference, *Interstellar Papers*.

Our Interstellar News this time reports on events at our HQ including *Extreme Deep Space Exploration*, Rob Swinney, and *The Apkallu Initiative*, Kelvin F Long and several events for the rest of the year. We consider *Are we alone after all?* - based on conclusions by a team from the Future of Humanity Institute (FHI), Oxford University and report a different gloomy conclusion in Forbes magazine based on the hostile implications of nanocraft arriving at large fractions of c. Our star modeller, Terry Regan, has almost finished an i4is-commissioned set of models of the Andromeda probe - we report with pictures. We have an update

on Project Glowworm, our programme for testing a laser sail in space, and on papers deriving from our earlier Project Dragonfly. And we report the contents of a recent interstellar issue of JBIS, the Journal of the British Interplanetary Society.

This issue also has News Features on the astronomical elements of the 44th annual Asilomar Microcomputer Workshop, *Catching A Little Bit of Heaven*, by Robert Kennedy, and *Wormholes, Energy Conditions and Time Machines - at Marcel Grossmann* by Remo Garattini. And others reporting an *i4is Symposium and Lecture at HQ* and a debate - *Moon, Mars and beyond* at the Royal Institution. In *How far have we come?* our i4is colleague, Terry Regan, muses on the lifetime of his grandmother - who "saw it all" from the Wright brothers to the Moon landings. We have indeed come a long way.

The promised feature, *Nomadic Planets and Interstellar Exploration* by Marshall Eubanks of Asteroid Initiatives is postponed to P23. Next time we will also have more galaxy-scale thinking from Dmitry Novoseltsev (Дмитрий Новосельцев), *Engineering of new worlds - goals, motives and results*. Patrick Mahon will take us through an *Idiot's Guide to Project Daedalus*. We will, of course, have a *Report on the Bremen IAC conference*.

The Initiative for Interstellar Studies has long planned to create a membership scheme and we hope to have news of this in our next issue. We are proceeding cautiously so we have not yet fixed a launch date but we will announce the launch to all Principium subscribers before we make any formal public announcement.

Comments on i4is and all matters interstellar are always welcome,

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Reaching the Stars in a Century using Fusion Propulsion

A Review Paper based on the 'Firefly Icarus' Design

Patrick J Mahon

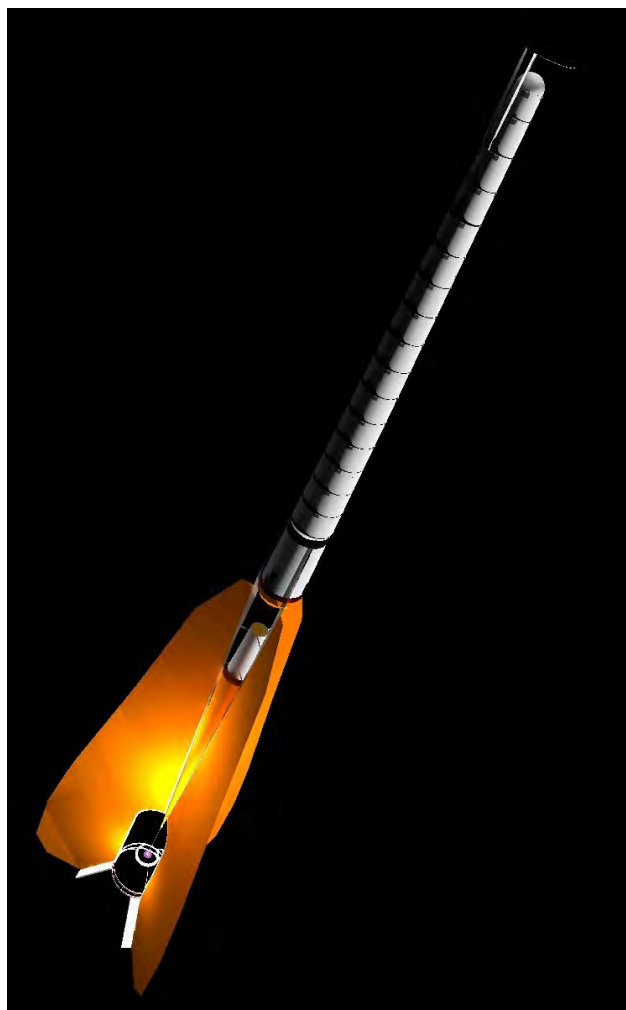
Fusion-based rocket propulsion remains our best current option to deliver substantial probe payloads to the nearest stars quickly. Project Icarus was founded by members of the British Interplanetary Society (BIS) and Tau Zero Foundation in 2009. It is now a joint effort by the BIS and Icarus Interstellar to build on BIS Project Daedalus using the knowledge and technology developed in the 30-40 years since that first thorough design study for an interstellar probe. Here our Principium deputy editor considers one of the more advanced designs within the Icarus Programme - the Z-Pinch propelled Firefly Icarus craft.

Abstract

If we are to launch unmanned probes that can reach and explore the nearest stars within a human lifetime, we will need to develop new propulsion technologies enabling much higher velocities than are possible at present. Nuclear fusion is one of the leading options, but it has yet to be achieved sustainably at a commercial scale.

Many different engineering approaches have been proposed for using nuclear fusion to propel a spacecraft. One such approach is Z-Pinch fusion, where a high current is driven through a plasma, compressing it sufficiently to initiate nuclear fusion. This is one of the approaches that has been explored recently by the Firefly team of the Project Icarus Study Group, led by Robert Freeland and Michel Lamontagne. Project Icarus follows-up Project Daedalus, the British Interplanetary Society's 1978 design for an interstellar probe.

This review paper, written at a technical level suitable for beginning undergraduates, considers in outline the physics and engineering of Z-Pinch fusion, and illustrates how this might work in practice through a case study of the 'Firefly Icarus' spacecraft design.



Firefly Icarus, perspective view at main engine shutdown
Credit: Michel Lamontagne, 2015

1. INTRODUCTION

The stars above us have interested humans in myriad different ways since the dawn of civilisation. However, a specific interest in the *astrophysics* of the universe beyond our own solar system seems particularly acute at present. This is partly due to the wealth of new science being done by space agencies around the world. For example, recent astronomical observations from the Kepler space telescope [1] have shown that many stars have planets in orbit around them, potentially including Proxima Centauri, our nearest star. If we want to know more, do we need to be able to master interstellar flight, so we can send probes to explore these distant stellar systems?

1.1. The justification for interstellar travel

Some will argue that we shouldn't try to send probes. After all, aren't we getting more than enough data from space-based telescopes? It's certainly true that our study of the stars has been revolutionised over recent years by observations from such instruments as Kepler, the Hubble Space Telescope and many others. However, remote observation does have its limitations. For example, our knowledge of the dwarf planet Pluto was increased by an order of magnitude by the New Horizons probe's flyby of the planet in July 2015. We can do a lot of science from *here*, but to answer some key questions, we will need to go *there*.

1.2. The main challenge to interstellar travel

The main problem with 'going there' is that the stars are an extremely long way away. Our nearest star, Proxima Centauri, is some 4.3 light years away from Earth. This is equal to 269,000 Astronomical Units, or AU, where 1 AU equals the average distance between the Earth and our own Sun (roughly 150,000 km). A quick calculation will show you that there are 63,240 AU in one light year; multiplying this by 4.3 gives you the answer above. To compare, Pluto orbits the Sun at an average distance of just under 40 AU – so our *nearest* star is around 7,000 times as far away as our solar system's *most distant* (dwarf) planet!

How long would it take for a probe to reach Proxima? The fastest spacecraft our species has yet produced is the Voyager 1 probe, launched in 1977 to survey Jupiter and Saturn. It left our solar system in 2012 and is currently travelling at 17 km/s (3.6 AU/year) [2]. If Voyager 1 was pointing towards Proxima, it would take some 74,000 years to get there.

That's clearly not a useful timeframe from the point of view of human scientists waiting for their results. Realistically, if a space probe is going to provide useful returns, it needs to do so within a reasonable human timeframe of decades or, at most, a century. To be clear, we're therefore talking about flight durations roughly 1,000 times shorter than it would take Voyager 1 to get to Proxima Centauri. Since $\text{time} = \text{distance}/\text{speed}$, we are going to have to find ways to accelerate probes to speeds three orders of magnitude higher than we can achieve today. Will that be easy or hard? The answer comes from a Russian space scientist born over 150 years ago.

1.3. The Tsiolkovsky Ideal Rocket Equation

Konstantin Tsiolkovsky was a schoolteacher who made great contributions to aerospace engineering in his spare time [3]. In 1903, Tsiolkovsky published the equation that now bears his name [4]. This shows how the final velocity that a rocket can reach is related to the velocity of its exhaust gases, the mass of fuel and oxidiser, and the mass of the spacecraft. The equation is derived in Box 1 opposite, and the final result is:

$$\Delta V = v_e \ln \left(\frac{m_0}{m_f} \right)$$

- where ΔV ('delta-V') is the change in the rocket's velocity, v_e is the velocity of the exhaust gases, m_0 is the initial, and m_f the final, mass of the rocket, so that $(m_0 - m_f)$ is the mass of the fuel plus oxidiser used to accelerate the rocket.

As Table 1 below demonstrates, the presence of the natural logarithm in the equation means that achieving a delta-V much greater than about three times the exhaust velocity is largely impractical, as the mass ratio (m_0/m_f) becomes so high (above twenty) that the rocket would be near impossible to build, as it would consist almost entirely of fuel and oxidiser. At the extreme, to achieve a delta-V five times the exhaust velocity would require that the fuel and oxidiser weigh nearly 150 times as much as the payload and rocket structure. Building a rocket structure light enough to achieve this mass ratio, whilst remaining strong enough not to collapse under the weight of the fuel, would be extremely challenging, if not impossible.

$\Delta V / v_e$	m_0 / m_f	$(m_0 - m_f) / m_f$
1	2.718	1.718
2	7.389	6.389
3	20.09	19.09
4	54.60	53.60
5	148.4	147.4

Table 1:
Implications of
Tsiolkovsky's
Ideal Rocket
Equation

In practical terms, a mass ratio of around 20 is a reasonable upper limit on what can normally be achieved. To take an example, for the Saturn V rocket which took men to the Moon, the lift-off mass (including fuel) was 2.8 million kilograms, of which 2.6 million kilograms was fuel and oxidiser. The non-fuel mass (m_f) was 220,000 kilograms [5]. The mass ratio was thus around 12.7.

What the Tsiolkovsky rocket equation demonstrates is that, for a given choice of fuel, with a given exhaust velocity, achieving a final velocity for the rocket of much more than around three times that exhaust velocity is essentially impractical. Now, the most energetic chemical fuel used today is hydrogen-oxygen, which produces an exhaust velocity of around 4,400 m/s (9,900 mph). Realistically, therefore, a rocket burning hydrogen and oxygen can accelerate to a final velocity of around 13,200 m/s (29,700 mph). This is sufficient to get us into Earth orbit (17,500 mph) or even to the Moon (25,000 mph). But it is equal to 0.0044% of the speed of light. At that speed it would take us 98,000 years to reach Proxima Centauri.

Application of Tsiolkovsky's Ideal Rocket Equation therefore demonstrates that chemical fuels are not suitable for interstellar travel via rocket within reasonable human timeframes of a few decades to a century, as the velocity of the exhaust products is far too low. What can we do instead?

1.4. Alternatives to chemical rockets

Many alternatives to chemical propulsion have been proposed in the interstellar travel literature – see, for example, [6], [7]. A brief list might include solar or laser sails, ion engines, nuclear fission-powered rockets, the Bussard ramjet and the antimatter rocket. However, almost all of these technologies have one or more drawbacks (typically either acceleration or thrust levels) which rule them out of contention for our present purposes, where we want near-term technologies that can achieve a mission duration of no more than a century.

Laser sails, which do not have to carry their own fuel on board and thus have the significant advantage of not being subject to the constraints of

Box 1: Deriving the Tsiolkovsky Ideal Rocket Equation

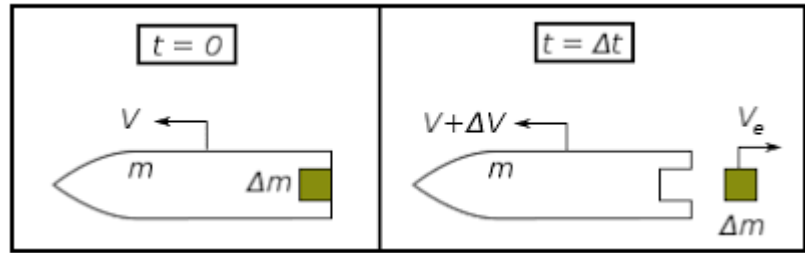


Figure 1: Idealised rocket firing (Image: Wikipedia)

Consider the rocket illustrated in Figure 1. At time $t = 0$, the spacecraft's momentum (measured in the rest frame) is $(m + \Delta m) v$

After an infinitesimal time period Δt , the momentum has changed to

$$m (v + \Delta v) + \Delta m (v - v_e)$$

Conservation of momentum enables us to equate these two terms. Expanding and simplifying, we reach

$$m \Delta v = \Delta m v_e$$

If we then multiply through by $\Delta t / \Delta t$, and take the limit as Δt tends to zero (noting that in the limit, $dm = -\Delta m$, as a positive Δm reduces m) and then integrate over the duration of the rocket firing, we obtain

$$\Delta V = -v_e \int (1/m)(dm/dt)$$

or

$$\Delta V = v_e \ln (m_0/m_f)$$

Tsiolkovsky's Ideal Rocket Equation, provide one potential option for sub-century travel to nearby star systems, and are under active investigation by such organisations as Breakthrough Starshot [8]. However, it is not immediately clear how a laser sail would decelerate into orbit when it arrived at its target – which is one of the constraints we will observe here (see section 2.4 below).

The most promising technology left on the table if laser sails are ruled out is, for many interstellar proponents, nuclear fusion.

2. NUCLEAR FUSION

2.1. Introduction to nuclear fusion

A detailed discussion of the physics of nuclear processes is outside the scope of this article. For those interested, a good treatment can be found in [9]. However, in brief, Einstein's famous equation $E = mc^2$ tells us that energy and mass are interchangeable, with very small amounts of mass being equivalent to very large amounts of energy, due to the conversion factor c^2 (roughly 9×10^{16} , or ninety thousand trillion): total conversion of one kilogram of mass would create 90,000 TJ (terajoules) of energy, equivalent to over two-thirds of the energy produced by the UK's largest power plant, Drax, in a whole year.

There are two different ways in which this energy can be harnessed usefully: nuclear fission, and nuclear fusion.

Nuclear fission is the process where an unstable heavy atomic nucleus, such as Uranium-235, decays into two lighter nuclei. This leads to a small reduction in overall mass, which is converted into energy that can be used peacefully in a nuclear power plant, or as the basis for a nuclear bomb. Nuclear fission is a tried and tested technology that has been used for both purposes for over fifty years.

On the other hand, nuclear fusion is the process where two light nuclei are brought together at sufficiently high temperatures and pressures, and for a sufficiently long time, that they are able to overcome the strong repulsive force between them and fuse together, forming a heavier nucleus. This process again leads to a small reduction in total mass, releasing energy. Many different nuclei can potentially be brought together in a fusion reaction, and this choice is vital as it determines what the fusion products are and how easy they are to use afterwards, whether for energy production or propulsion. The simplest example of relevance to spaceflight consists of the fusion of two nuclei of deuterium (an isotope of hydrogen consisting of one proton and one neutron). Half the time, the fusion reaction forms tritium (another isotope of hydrogen, this time comprising one proton and two neutrons) plus a proton; alternatively, it forms helium-3 and a neutron. In either case, the reaction products carry away the energy produced by the small reduction in overall mass.

Nuclear fusion is the process which powers all the stars in the Universe, so it is tried and tested on a stellar scale. However, humanity has not yet managed to create a self-sustaining fusion reaction

here on Earth which produces more energy than is needed to keep it going. Intensive research is being undertaken by several international collaborations, including one based at the Joint European Torus (JET) facility at the Culham Centre for Fusion Energy in Oxford, and the ITER (Latin "The Way") facility currently being constructed in southern France and due to become operational in 2025.

At the high temperatures required to enable fusion (typically tens of millions of degrees Kelvin), the fuel takes the form of an ionised plasma, with the positive nuclei separated from their atomic electrons. The key performance metric used to describe a fusion reaction is the so-called triple product, obtained by multiplying together the plasma density n , the plasma temperature T , and the confinement time τ . This triple product must exceed a minimum value for fusion to be self-sustaining.

2.2. Approaches to achieving nuclear fusion

There are two broad engineering approaches to achieving nuclear fusion in the laboratory:

- Magnetic Confinement Fusion (MCF) uses magnetic fields to confine the charged plasma, typically (although not always) within a ring doughnut-like toroidal container. The magnetic fields are necessary to ensure that the plasma does not touch the sides of the containment vessel, since at the temperatures required to initiate fusion any contact would lead to melting of the container and loss of containment of the plasma.
- Inertial Confinement Fusion (ICF) instead focuses powerful lasers onto a small pellet of the fusion fuel, such that the energy from the lasers heats and compresses the fuel, leading at the centre of the pellet to temperatures and pressures sufficient to initiate nuclear fusion.

Each of these approaches to fusion has been incorporated into detailed designs for an interstellar spacecraft: Project Daedalus and a range of designs in Project Icarus.

2.3. Project Daedalus

In the early 1970s, the BIS set up Project Daedalus to establish whether interstellar travel was practically feasible, or just the stuff of science fiction. The outcome of this ground-breaking volunteer-led project was a 1978 design [10] for an Inertial Confinement Fusion-powered unmanned starship that would send a 450-tonne scientific payload on a flyby mission past Barnard's Star, some 5.9 light years away and, at that time, seen as the most promising nearby star for scientific study.

2.4. Project Icarus

Project Icarus is a collaboration between the members of the British Interplanetary Society and Icarus Interstellar. It began in 2009 with the idea of updating the Project Daedalus design to take account of three decades of technological progress. The project has several specific goals of direct relevance to this article [11], [12]:

- (a) The design must use ‘current or near-future technology’;
- (b) The propulsion system must be ‘mainly fusion-based’;
- (c) The vessel must reach its destination within one hundred years of its launch; and
- (d) The mission is to fully decelerate a 150-tonne scientific payload into orbit around Alpha Centauri.

Given constraints (c) and (d) – of accelerating to reach, and then decelerating into orbit around, a destination 4.3 light years away within a century – this immediately gives us a minimum delta-V over the journey of 8.6% of the speed of light. We will need to check at the end of this article whether this constraint has been met.

One of the spacecraft designs that has been studied in detail by the Project Icarus Study Group is the ‘Firefly Icarus’ which is powered by a particular type of Magnetic Confinement Fusion known as Z-Pinch fusion [13]. It is this design that we will focus on in the rest of this article. To understand how it works, we first need some background on the concept of a Z-Pinch.

Box 2: Fleming’s right-hand and left-hand rules

Fleming’s ‘right-hand rule’ tells you the direction of the magnetic field generated by a (positive) current (eg in an electric wire, or a plasma).

Simply curl your right hand into a ‘thumbs-up’ sign, and point the thumb in the direction of the current. Your curled fingers indicate the direction of the magnetic field induced by the current – showing, for example, that the field curls around the current in an anti-clockwise direction if the current is travelling towards you.

Fleming’s ‘left-hand rule’ tells you the direction of the force generated by a (positive) current moving in a magnetic field. This time, hold out the thumb, first finger and second finger of your left hand, all at right angles to each other. Align your **F**irst **F**inger with the direction of the magnetic **F**ield, and your se**C**ond finger with the direction of the **C**urrent. Your thu**M**b will then point in the direction of **M**otion due to the induced force.

The size of this force is then given by Ampère’s law: $\mathbf{F} = \mathbf{j} \times \mathbf{B}$, where $\mathbf{j}$ is the current vector, $\mathbf{B}$ is the magnetic field vector, $\mathbf{F}$ is the force vector, and $\times$ is the vector product operator.

3. THE Z-PINCH

A Z-Pinch occurs naturally when a large current passes through any medium. As shown in Figure 2 and described in more detail in Box 2, the current gives rise to a magnetic field in line with Fleming’s ‘right-hand rule’, and the magnetic field in turn generates an inward force on the current in line with his ‘left hand rule’.

In the case of a Z-Pinch, this leads to a pinch force which squeezes the current inwards. A naturally occurring example of this phenomenon is lightning, where the electrical discharge from cloud to ground ionises the air, creating a plasma, and then pinches it, producing both the visible lightning and the audible thunder.

The next question to answer is how much the current gets pinched by the magnetic field, and what the equilibrium condition is for such a situation.

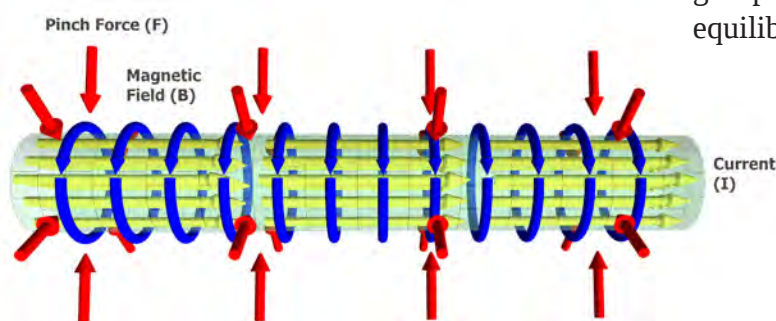


Figure 2: Geometry of an ideal Z-Pinch (Image: Michel Lamontagne)

3.1. Deriving the Bennett Pinch Relation

The equilibrium condition is determined by the Bennett Pinch Relation, first derived by Willard Harrison Bennett in 1934 [14], and re-derived in Box 3, by equating the magnetic pressure inwards to the outwards pressure of the hot plasma. The result is:

$$(1+Z) NkT = \mu_0 I^2/8\pi$$

What this tells us is that the higher the plasma current, I , the higher the product of the plasma density (N) and temperature (T) at equilibrium. Recalling from section 2.1 that these are two of the three factors which feature in the fusion triple product, we can see how a Z-Pinch of sufficiently high strength, running continuously for long enough, could conceivably create the right conditions to initiate nuclear fusion.

3.2 Practical problems with using a Z-Pinch to initiate fusion

Following Bennett's pioneering work, research on the use of a Z-Pinch to initiate fusion continued until the 1950s, when Kruskal and Schwarzschild published a paper describing potential instabilities in Z-Pinch plasmas [15]. This posed some serious questions for the viability of Z-Pinch fusion, and research on it stalled for forty years, until Uri Shumlak published a paper in the late 1990s, suggesting that these instabilities could be overcome through sheared axial flows (where adjacent layers of the plasma move parallel to each other, but at different speeds) of sufficiently high speed [16]. It is Shumlak's research that led the Project Icarus Study Group to consider Z-Pinch Fusion as a possible propulsion technology.

Box 3: Deriving the Bennett Pinch Relation

We derive the equilibrium condition for a Z-Pinch by equating the inward magnetic pressure (from Maxwell's equations) to the outward plasma pressure (from the Ideal Gas Law) for a cylinder of arbitrary radius r and length L .

At equilibrium, the inwards force F , squeezing the plasma together, is balanced by the pressure of the hot plasma trying to expand outwards. Since pressure = force/area, at a general radius r from the central axis, we have:

$$\text{Magnetic field strength inwards} = H = I/2\pi r \text{ (from Ampère's law)}$$

$$\text{Inward force due to this magnetic field} = F = j \times B = \mu_0 j \times H = \mu_0 I^2/2\pi r$$

$$\text{Outwards force at radius } r = \text{pressure} \times \text{area} = 2\pi r p$$

But the plasma pressure p is given by the Ideal Gas Law, $pV = NRT$, which can equivalently be written as $p = nkT$, where n = gas density (no. of gas particles per unit volume), k = Boltzmann's constant, and T = temperature). Equating the inward and outward forces at equilibrium, we have:

$$F_{\text{in}} = \mu_0 I^2/2\pi r$$

$$F_{\text{out}} = 2\pi r p = 2\pi r nkT$$

$$\mu_0 I^2/2\pi r = 2\pi r nkT$$

$$\mu_0 I^2/4\pi^2 r^2 = nkT$$

Finally, we convert n (the plasma 'gas' density per unit volume) into N (plasma density per unit length). Now, if a volume of radius r and length L contains X gas particles, then by simple geometry, $X = n \pi r^2 L = N L$. Substituting N for n , and noting that each ion in the plasma is accompanied by Z electrons (where Z is the atomic number), we finally have:

$$(1+Z) NkT = \mu_0 I^2/8\pi$$

4. Z-PINCH FUSION

Having established that a Z-Pinch can compress a plasma and raise its temperature, we now explore what happens if the conditions are extreme enough to initiate fusion. The mathematics of a fusing plasma in a Z-Pinch are complex, so I will simply reproduce two key results from [13] here.

4.1. Plasma temperature

As fusion proceeds, the plasma heats up and new energetic ion species are created. The equilibrium plasma temperature T_p is given by:

$$T_p = \mu_0 I^2 / (8\pi N_e (1 + Z_p))$$

Where $Z_p = \sum_i (N_i Z_i) / N$ is the weighted average atomic number of the various ions in the plasma. If the current I stays constant, the only way that T_p can increase is if N , the linear number density of the various ion species, decreases. This happens both because fusion, as the name suggests, takes two ions and joins them into one, halving their number density, and also because the speed of the ions through the pinch region increases, again reducing the number of them per unit length (ie their linear number density).

4.2. Exhaust velocity

The velocity of the exhaust leaving the fusion engine is given by:

$$V_{ex} = (2 P_{ex} / (dm/dt))^{1/2}$$

Where P_{ex} is the power remaining in the exhaust plume, once the various power losses (which include the power needed to accelerate, heat and compress the plasma, and the losses due to Bremsstrahlung radiation – explained in section 5.2) are taken into account, while dm/dt is the mass flow rate through the engine.

Using these equations, plus expressions for other relevant physical quantities including the radius of the Z-Pinch during fusion, the fusion reaction rate, and the mass flow rate, [13] models the performance of the Z-Pinch fusion engine, leading to the results presented in section 6 below.

5. PRACTICAL ISSUES

Any spacecraft, whatever its propulsion system, needs to be carefully designed to ensure that it will function effectively in the unforgiving environment of space. The general details of spacecraft design are outside the scope of this article; a good introduction can be found in [17].

However, the use of a Z-pinch fusion engine creates several specific engineering challenges for the spacecraft. In this section, we briefly outline the practical issues that will need to be overcome, drawing heavily on [13], where more detail can be found. In broad terms, they fall into three categories: (a) energy management; (b) radiation management; and (c) the consequences of these for spacecraft design.

5.1. Energy management

A Z-Pinch fusion drive requires a large electrical current to compress the plasma to a sufficiently high density to enable fusion. Freeland and Lamontagne calculate that the electrical system needs to supply 5 MA at 235 kV, implying a power of $P = I \times V = 1175$ GW. This is roughly one-third of the power consumption of the entire United States in 2005. The current itself is more than an order of magnitude larger than the highest current we can presently produce.

This creates three distinct energy management issues: (i) recapture of the energy from the fusion products in the exhaust plume; (ii) startup power; and (iii) cooling.

5.1.1. Energy recapture

Given their magnitude, we cannot expect to generate the required power levels in the usual way from a power plant onboard the spacecraft. The only realistic source of this power is by recapturing some of the surplus energy generated by the fusion reactor. This would be done by removing energy from the charged particles in the exhaust and feeding it back into the power system.

5.1.2. Startup power

Clearly, we cannot recapture energy from the fusion engine's exhaust plume before the engine has started. We therefore need a separate source of power to start the engine up. This will be provided by a set of capacitors which are charged up using the ship's primary power source, which in the Firefly design is a compact fission reactor.

5.1.3. Cooling

The need to reject excess heat is an issue for any spacecraft, given that the insulating properties of the vacuum of space mean that this heat cannot escape through conduction or convection, leaving radiation as the only option. For a spacecraft whose propulsion system relies on huge electrical currents to drive nuclear fusion, this problem is particularly acute.

As set out in the next sub-section, the spacecraft is designed so that most of the potentially damaging high energy radiation created in the fusion reaction can escape directly into space. This reduces the cooling requirements significantly. However, it is still necessary to cool several key parts of the ship, including the electrodes carrying power to the Z-Pinch drive, the magnetic nozzle which focuses the charged particles in the exhaust, and the support structure around the fusion engine.

To achieve the necessary level of cooling efficiency, Freeland and Lamontagne have chosen a phase-change radiator using Beryllium as the working fluid. This creates its own problems, since Beryllium has a high boiling point (2,743 Kelvin) and is extremely toxic to humans, but it has the advantage that Beryllium has the highest heat of vaporisation per unit mass of any element, at 33.0 MJ/kg, minimising the mass of working fluid needed to deal with a given heat load.

The working fluid is pumped through those elements of the ship that need cooling, where it changes from a liquid into a gas, then runs through pipes made from zirconium carbide (which can not only withstand the high temperatures involved, but also has a low probability of absorbing any passing neutrons and is resistant to radiation

damage) and is fed to carbon-carbon radiators, where the Beryllium gas turns back into a liquid as the excess heat is radiated away into space.

5.2. Radiation management

The Firefly Icarus engine is powered by the fusion of deuterium with deuterium. The choice of fuel was motivated by Project Icarus's terms of reference, and in particular the wish to be able to produce all the propellant on Earth (in comparison to the Project Daedalus engine, which required helium-3 mined from the atmosphere of Jupiter), as this significantly advances the timeframe within which the mission might become technically feasible.

However, the choice of D-D fusion leads to the creation of large amounts of radiation, including highly energetic neutrons which cannot be directed using electric or magnetic fields. In addition, the extreme conditions in the pinch region lead to the emission of Bremsstrahlung radiation in X-ray wavelengths. Since the pinch region is essentially a one-dimensional line, the neutrons and X-rays are effectively emitted cylindrically outwards.

This radiation flux is of such high energy that the inclusion of comprehensive shielding against it would be prohibitively expensive in mass terms. Instead, the Firefly designers have taken the opposite approach, designing the spacecraft so that the fusion engine is located as far as possible away from the payload and other radiation-sensitive parts of the ship. The design then allows the radiated neutrons and X-rays to escape into space without irradiating other parts of the ship. Shielding is then only required in the small area directly between the engine and the rest of the ship's structure.

5.3. Spacecraft design

Figure 3 is a schematic of the Firefly Icarus spacecraft design, illustrating how the various subsystems described above are integrated into the vehicle. Further details can be found in [13].

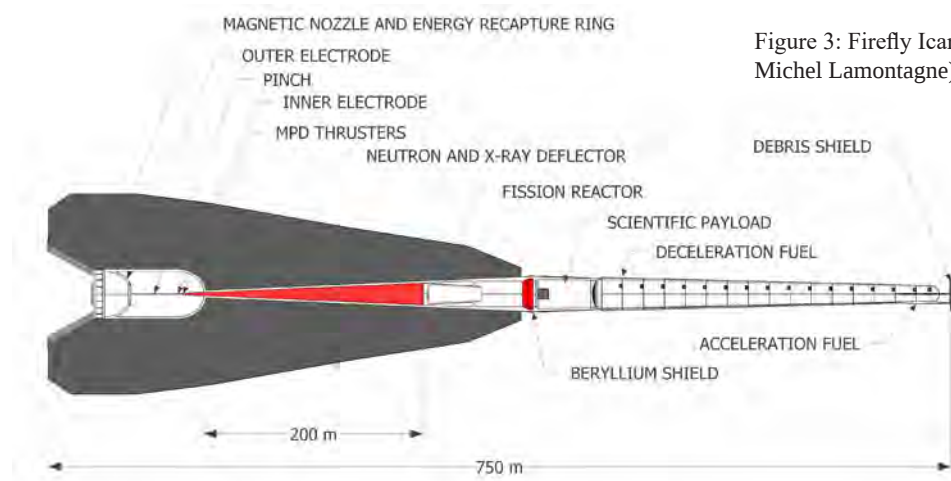


Figure 3: Firefly Icarus schematic (Image: Michel Lamontagne)

6. SUMMARY AND CONCLUSIONS

This paper briefly explains why chemical rockets are not up to the challenge of sending spacecraft to the stars in a reasonable timeframe, and why nuclear fusion is one of the leading alternatives. It summarises the logic behind the choice of Z-pinch fusion as the preferred propulsion technology for the Firefly Icarus interstellar spacecraft. Following an optimisation exercise, the Project Icarus Study Group have settled on a spacecraft with the following key design features [13]:

- Length = 750 metres
- Dry mass = 2,200 tonnes. This breaks down as follows:
 - radiators (1,600 t);
 - shielding (160 t);
 - payload (150 t);
 - miscellaneous structure (130 t);
 - magnetic nozzle/energy recapture (110 t); and
 - reactors (50 t).
- Wet mass = 23,550 tonnes. This includes:
 - Dry mass (2,200 t);
 - Fuel tanks plus pressurant (350 t); and
 - Fuel (21,000 t).
- Exhaust velocity (v_e) = 12,000 km/s (= 4% of the speed of light)
- Specific Impulse (I_{sp}) = $v_e / g = 1,200,000$ seconds
- Thrust = 600 kN

It's worth noting at this point that since v_e is 4% of the speed of light, the constraint set out in section 2.4 above, that the Firefly Icarus propulsion system be able to achieve a delta-V of at least 8.6% of c , should easily be satisfied, since according to the Tsiolkovsky equation, that only requires a mass ratio of $(m_0 / m_f) = \exp(\Delta V / v_e) = 8.58$, which is well within current capabilities.

The spacecraft could be constructed in Earth orbit, or alternatively at one of the Earth-Moon Lagrange points. The dry mass could be launched into Low Earth Orbit (LEO) on 17 of NASA's planned Space Launch System rockets (Block 2) or 20 Saturn Vs, so this aspect of the project is feasible with proven or near future launch capabilities [13]. The proposed mission profile would be as follows:

- the completed vehicle is towed to the far side of the Moon;
- it ignites its engines there (to avoid any radiation concerns back on Earth);

- it reaches 4.7% c after 10 years;
- it cruises at that velocity for 85 years;
- the spacecraft then turns through 180 degrees and fires the engine again for 5 years to decelerate it; and
- Finally, the spacecraft enters into orbit around Alpha Centauri after 100 years.

6.1. Areas for further study

Although the Z-Pinch fusion engine proposed for the Firefly Icarus spacecraft design is based on current or near-future technology, there remain several theoretical and practical issues which will require further study before the design can be said to be fully worked up. The three main challenges, as discussed by Freeland in [18], are:

- Energy recapture. As explained in section 5.1.1 above, the only realistic way to provide a Z-Pinch fusion engine with sufficient power to operate continuously is by recapturing energy from the jet of fusion products as they exit the engine. Research is needed on the best technology for achieving this.
- Plasma stability. As discussed in section 3.2 above, a Z-Pinch is subject to plasma instabilities which can potentially be overcome through a sufficiently rapid sheared axial flow. The Firefly Icarus engine design assumes that this is true in practice as well as theory, so that once fusion is initiated, the plasma remains stable indefinitely. This is currently being tested on a small scale by Uri Shumlak [19], but can only be fully verified experimentally by running a Z-Pinch fusion engine continuously – which requires a solution to the energy recapture problem discussed above.
- Theoretical analysis. The mathematical analysis of a Z-Pinch which was briefly presented in sections 3 and 4 above is not strictly applicable to a Z-Pinch once fusion occurs, as the analysis assumes adiabatic compression (ie compression where there is no gain or loss of heat). This is a valid assumption for the experimental tests of non-fusing Z-Pinches which have been carried out to date. It is not, however, valid for a continuous fusing plasma. A proper theoretical analysis will need to be developed in due course to support further experimental work.

6.2. Conclusion

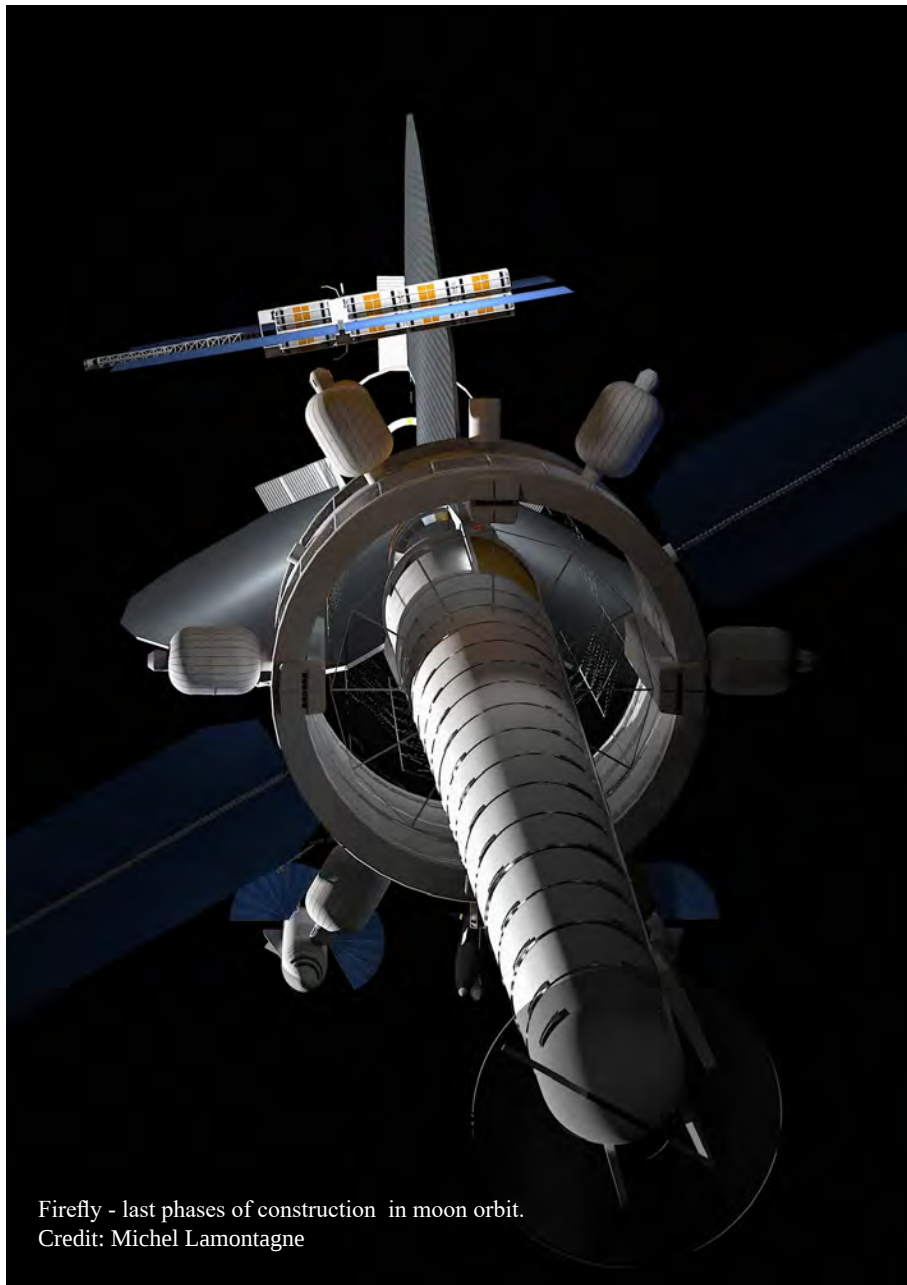
This paper hopefully demonstrates that although sending an unmanned probe to our nearest star is a highly ambitious undertaking, it is feasible with present day or near-term technologies. Just as importantly, I hope I have shown that the central issues involved are amenable to analysis by the average science undergraduate.

If this article has whetted your appetite for interstellar spacecraft design, I would encourage you to follow up the references (particularly [13]), read relevant books (eg [6], [7]) and consider attending one of i4is's Starship Engineer courses (see [20] for details). Finally, I would strongly recommend that you obtain a copy of the Project Daedalus report ([10], available from the BIS in an attractive hardback reprint edition), and the Project Icarus final report [21] upon publication.

ACKNOWLEDGEMENTS

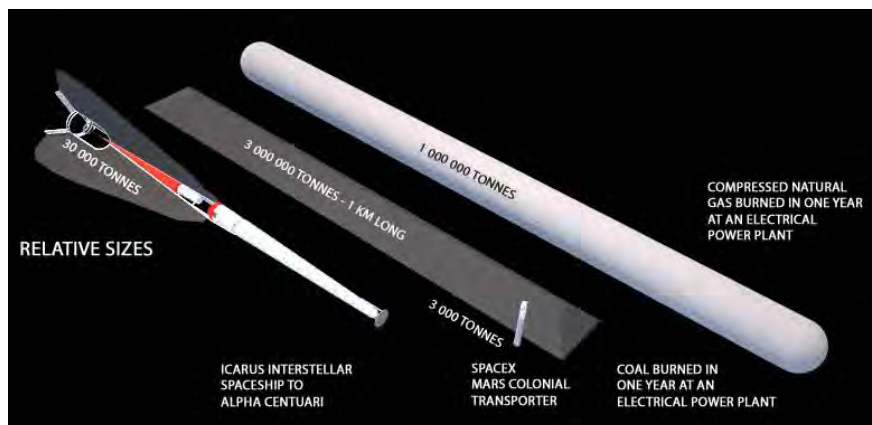
Particular thanks are due to Robert Freeland II and Michel Lamontagne, as the inspiration for this article comes from their excellent 2015 JBIS paper summarising the Firefly Icarus concept; I have drawn heavily on that paper and some of Michel's images within it here. Robert and Michel have also both been extremely generous with their help during the preparation of this article.

Thanks are also due to the members of the Project Icarus Study Group, especially Project Leader Rob Swinney, for allowing this article to be published ahead of the Project Icarus final report. I should additionally acknowledge helpful discussions with Principium editor John Davies, and with my son Andrew Mahon, a maths undergraduate who proved a willing and able test subject.



REFERENCES

1. NASA, "NASA Releases Kepler Survey Catalog with Hundreds of New Planet Candidates", www.nasa.gov/press-release/nasa-releases-kepler-survey-catalog-with-hundreds-of-new-planet-candidates (Last accessed 18 July 2018).
2. Jet Propulsion Laboratory, "Voyager Interstellar Mission", voyager.jpl.nasa.gov/mission/interstellar-mission (Last accessed 18 July 2018).
3. J Davies, "Tsiolkovsky – Interstellar Pioneer", i4is Principium, issue 20, pp.21-28 (Feb 2018), www.i4is.org/publications/principium (Last accessed 18 July 2018).
4. K E Tsiolkovsky, "The Investigation of World Spaces by Reactive Vehicles", Scientific Review, St. Petersburg, No.5, pp.45-75 (1903).
5. NASA, "Saturn V News Reference", history.msfc.nasa.gov/saturn_apollo/documents/Introduction.pdf (Last accessed 18 July 2018).
6. E Mallove & G Matloff, *The Starflight Handbook: A Pioneer's Guide to Interstellar Travel*, Wiley, 1989.
7. K.F. Long, *Deep Space Propulsion: A Roadmap to Interstellar Flight*, Springer, 2011.
8. Breakthrough Initiatives, "Breakthrough Starshot", breakthroughinitiatives.org/initiative/3 (Last accessed 18 July 2018).
9. W N Cottingham & D A Greenwood, *An Introduction to Nuclear Physics*, 2nd edition, CUP, 2008.
10. A Bond & A Martin, *Project Daedalus – The Final Report on the BIS Starship Study*, JBIS Supplement, 1978.
11. K F Long, R K Obousy, A C Tziolas, A Mann, R Osborne, A Presby and M Fogg, "Project Icarus: Son of Daedalus – Flying Closer to Another Star", JBIS, 62, pp.403-416, 2009.
12. R Obousy, "Project Icarus", in *Going Interstellar – Build Starships Now!*, ed. Les Johnson & Jack McDevitt, Baen Books, pp.219-232, 2012.
13. R M Freeland II & M Lamontagne, "Firefly Icarus: An Unmanned Interstellar Probe using Z-Pinch Fusion Propulsion", JBIS, 68, pp.68-80, 2015.
14. W H Bennett, "Magnetically Self-Focussing Streams", Phys. Rev. 45, pp.890-897, 1934.
15. M Kruskal and M Schwarzschild, "Some Instabilities of a Completely Ionized Plasma", Proc. Roy. Society A, 223, London, May 1954.
16. U Shumlak and N F Roderick, "Mitigation of the Rayleigh-Taylor Instability by Sheared Axial Flows", Physics of Plasmas, 5, 2384, 1998.
17. P Fortescue, G Swinerd and J Stark (eds.), *Spacecraft Systems Engineering*, 4th edition, Wiley (2011).
18. R M Freeland II, "Plasma Dynamics in Firefly's Z-Pinch Fusion Engine", paper given at the *Foundations of Interstellar Studies* workshop, New York, 13 June 2017.
19. U Shumlak, "Development of a Compact Fusion Device Based on the Flow Z-Pinch", arpa-e.energy.gov/?q=slick-sheet-project/flow-z-pinch-fusion (Last accessed 18 July 2018).
20. Initiative for Interstellar Studies, "Starship Engineer", www.i4is.org/what-we-do/education/starship-engineer (Last accessed 18 July 2018).
21. Project Icarus Study Group, "Project Icarus: A Starship Study", forthcoming.



The scale of energy. The Icarus Firefly compared to the volume and mass of coal and gas used in a year at a large electrical power plant of 1 GW electrical, of which there are hundreds in the United States alone. Firefly is a huge space vehicle, but it is small compared to the elements of today's energy infrastructure.
Credit: Michel Lamontagne

About Patrick Mahon

Patrick is a physicist working in the waste and recycling sector. He is a long-committed space enthusiast who enjoys the challenges of interstellar science and technology presented by i4is. He is a regular contributor to Principium and is its Deputy Editor.

69th International Astronautical Congress 2018

Interstellar Papers

Last time we brought you abstracts of papers by the Initiative for Interstellar Studies team (i4is.org/wp-content/uploads/2018/05/Principium21.pdf). Two papers we mentioned last time have been withdrawn - Adam Crawl on *Strategies for Complete Galactic Surveys* and Kelvin Long on *Project Icarus: Concept Design for an Inertial Confinement Fusion Drive Interstellar Probe*.

Principium editors John Davies and Patrick Mahon will be reporting from the Congress. Find us via twitter.com/I4Interstellar and at the British Interplanetary Society stand. More at - www.iafastro.org/events/iac/iac-2018.

Register for the Congress via www.iafastro.org/events/iac/iac-2018/

Timetable

Papers by the Initiative for Interstellar Studies team and others of interstellar interest. Details, including titles and authors, are as given on the IAC website.

Monday 1st October 15:15 Room: CCB London *Innovative and Visionary Space Systems*

iafastro.directory/iac/browse/IAC-18/D1/1/

Order	Mode	Paper title	Main author	Affiliation	Country
2	20	Evolving Asteroid Starships: A Bio-Inspired Approach for Interstellar Space Systems	Dr. Angelo Vermeulen	TU Delft	Netherlands

Monday 1st October 15:15 Room: CCB Roselius - *Space Agency Strategies and Plans*

iafastro.directory/iac/browse/IAC-18/A7/1/

Order	Mode	Paper title	Main author	Affiliation	Country
7	20	<i>Interstellar Probes: The Benefits to Astronomy and Astrophysics</i>	Mr. Kelvin Long	Initiative for Interstellar Studies	United Kingdom
8	20	<i>Long duration Genesis-type missions to exosolar planets</i>	Prof. Claudius Gros	University of Frankfurt am Main	Germany

Tuesday 2nd October 14:45 Room ÖVB 3 - SETI 1: SETI Science and Technology

iafastro.directory/iac/browse/IAC-18/A4/1/

Most papers this session but especially -

Order	Mode	Paper title	Main author	Affiliation	Country
1	20	The Breakthrough Listen Search for Intelligent Life: the first SETI results and other future projects.	Mr. J. Emilio Enriquez	UC Berkeley / Radboud University Nijmegen	United States
2	15	An update the Australian activities of Breakthrough Listen	Dr. Daniel Price	U.C. Berkeley	United States
3	15	SETI radio surveys of the distant Universe	Prof. Mike Garrett	University of Manchester	United Kingdom

Tuesday 2nd October 18:00 – 19:00 Room: DLR Hall - Plenary Highlight Lecture 1

www.iafastro.org/events/iac/iac-2018/plenary-programme

The Growing Role of Artificial Intelligence in Space Exploration

Steve Ankoo Chien, Senior Research Scientist, JPL/Caltech will be "...describing a number of success stories highlighting the tremendous impact of Artificial Intelligence.." and "...how AI is critical to future mission concepts [including] an interstellar mission to explore distant solar systems."



Public Day, Wednesday 3 October, 12:00 - 18:00

Public free admission to
exhibition and special event
"space is big - space is public"
(13:30 Space Safety, 14:30 live
link to the International Space
Station) [www.iac2018.org/
program/public-day](http://www.iac2018.org/program/public-day)

Subject to change

Thursday 4th October 13:15 Room: IP Hall - Interactive Presentations - 16th IAA Symposium on Visions and Strategies for the Future

iafastro.directory/iac/browse/IAC-18/D4/IP/

Order	Mode	Paper title	Main author	Affiliation	Country
4	10	space internetworking service based on DTN for interplanetary Internet	Mr. Longfei Li	Xi'an*	China
5	10	Technologies for the First Interstellar Explorer: Beyond Propulsion	Dr. Anthony Freeman	JPL	United States
6	10	Tethered Slingshot Maneuver in the Three-Dimensional Space	Dr. Alessandra Ferreira	UNESP - São Paulo State Uni.	Brazil
10	10	CubeSat Sundiver for Interstellar Precursor Missions	Dr. Martin Lades		Germany

* Xi'an Microelectronics Corporation (CASC) Technology Institute, China Aerospace Science and Technology Corporation (CASC)

Thursday 4th October 13:15 Room: IP Hall Interactive Presentations - IAF Space Exploration Symposium

iafastro.directory/iac/browse/IAC-18/A3/IP/

Order	Mode	Paper title	Main author	Affiliation	Country
33	10	adaptive in-situ resource utilisation (isru) for long term space exploration	Mr. Satinder Shergill	Cranfield University	United Kingdom

Thursday 4th October 14:45 Room: ZARM 5 New Missions Enabled by New Propulsion Technology and Systems

iafastro.directory/iac/browse/IAC-18/C4/6/

Order	Mode	Paper title	Main author	Affiliation	Country
10	15	The Interplanetary Crossbow: Technology and Architecture Description for an Interplanetary Laser-Sail System for the Use of small Payloads.	Mr. Kelvin Long	Initiative for Interstellar Studies	United Kingdom
11	15	Advanced Propulsion system for searching Exoplanets	Mr. Mridul Jain	University of Petroleum and Energy Studies	India

Friday 5th October 09:45 Room: Bremen 1 - Strategies for Rapid Implementation of Interstellar Missions: Precursors and Beyond

iafastro.directory/iac/browse/IAC-18/D4/4/

Order	Mode	Paper title	Main author	Affiliation	Country
1	10	IN-SITU INVESTIGATION OF THE INTERSTELLAR MEDIUM	Prof.Dr. Robert F. Wimmer-Schweingruber	University of Kiel	Germany
2	10	Near-Term Interstellar Probe: First Step	Dr. Ralph L. McNutt, Jr.	Johns Hopkins University Applied Physics Laboratory	United States
3	10	Decelerating interstellar probes with magnetic sails	Prof. Claudius Gros	University of Frankfurt am Main	Germany
5	10	Characterization of a Non-Stationary Spherical Inflated Light Sail for Ultra-Fast Interstellar Travel by Using Commercial 3D Codes	Mr. Dario Riccobono	Politecnico di Torino	Italy
6	10	Project Glowworm: Testing Laser Sail Propulsion in LEO	Mr. Zachary Burkhardt	International Space University (ISU)	United States
7	10	Using Graphene Interstellar Solar Photon Sails: Sensitivity Studies for Pico-Probes and Arks	Prof. Gregory Matloff	New York City College of Technology	United States

The paper Laser-powered Electric Propulsion for Interstellar Precursor Missions, Ms. Ana Cristina Baltazar Garduño of International Space University (ISU) has been withdrawn

Friday 5th October 09:45 Room: ZARM 2 - Small Spacecraft for Deep-Space Exploration

iafastro.directory/iac/browse/IAC-18/B4/8/

Order	Mode	Paper title	Main author	Affiliation	Country
16	10	a minimal chipsat interstellar mission: technology and mission architecture	Ms. Wenjing Hu	International Space University (ISU)	France

Friday 5th October 13:30 Room: Bremen 1 - Space Resources: Technologies, Systems, Missions and Policies

iafastro.directory/iac/browse/IAC-18/D4/5/

Order	Mode	Paper title	Main author	Affiliation	Country
11	10	exploring potential environmental benefits of asteroid mining	Dr. Andreas Makoto Hein	Ecole Centrale de Paris	France
14	10	a techno-economic analysis of asteroid mining	Dr. Andreas Makoto Hein	Ecole Centrale de Paris	France

Friday 5th October 13:30 Room:CCB Scharoun

iafastro.directory/iac/browse/IAC-18/E1/2/

Order	Mode	Paper title	Main author	Affiliation	Country
5	15	Space Studio West London – A Project Based Learning Model for Space Education	Mr. Satinder Shergill	Space Studio West London	United Kingdom

News Feature

i4is Symposium and Lecture at HQ

Patrick Mahon

On 1 June, i4is held a half-day symposium, followed by an evening lecture, at our headquarters in Charfield, Gloucestershire, to mark the start of a series of lectures and talks intended to communicate the broad range of i4is's work and interests to our members and supporters, as well as a wider audience. Patrick Mahon reports from our Interstellar Space, The Mill. All pictures by Kelvin Long.

The event was opened by i4is President Kelvin F Long, who welcomed everyone and invited those who had not visited before to spare a moment before the end of the day to examine the huge variety of space-related items to be found throughout the building.

Current and Proposed Space Telescope Missions

i4is Deputy Director Rob Swinney began by explaining why it's worth the trouble and expense of launching telescopes into space. There, they are free of the problems caused by

Earth's atmosphere, which is opaque to some wavelengths of electromagnetic radiation, and which distorts the quality of the images available (due to atmospheric convection) even for those wavelengths that can get through.

Rob summarised the missions of the current generation of space telescopes, including Hubble (which covers visible radiation), Spitzer (infra-red), Chandra (X-rays), Kepler (exoplanet hunter) and Gaia (astrometry), before moving on to consider future missions that

are currently on the drawing board or in preparation. These include the James Webb Space Telescope (successor to Hubble), ATLAST (successor to the James Webb), PLATO (successor to Kepler) and Ariel (successor to PLATO). Rob finished by musing on the relative strengths and weaknesses of space telescopes in orbit around the Earth, versus probes sent towards their target. Although sending a probe to, for example, Alpha Centauri will be an enormous undertaking, the potential justification can be quickly understood. Go onto the



I4is space symposium Rob kicks off - space telescopes post Hubble

NASA website and compare the images of Pluto captured by the New Horizons spacecraft, during its 2015 flyby of the dwarf planet, with the much lower resolution of the best pictures of the planet that were available prior to that flyby, supplied by the Hubble Space Telescope orbiting the Earth. Space telescopes can do a lot, but sometimes you just have to go there.

system for recycling air and water (although even these are not true closed-loop systems), but they require a constant stream of resupply craft to be sent up to the ISS, carrying food and other consumables. Since this will clearly not be possible with an interstellar mission, we need to do something different. Simple mathematics tells you that just getting better at recycling is not

science fiction novel – ‘Aurora’ by Kim Stanley Robinson – which explores the problems encountered by a generation starship that takes 170 years to travel to Tau Ceti, and only just makes it there intact.



Patrick Mahon
sustainability and
space resource
utilisation

Sustainability and Resource Utilisation in Space - keeping resources in use

Patrick Mahon works in the waste and recycling sector, so within this he takes a special interest in sustainability in space. The central idea was that our current approach to recycling is not up to the job of sustaining any form of medium to long duration manned interstellar spaceflight. If you consider the technologies in use on the International Space Station, they have an effective

the answer for long duration missions: if you recycle 90% of your materials every year, which is much better than any country on Earth manages at present, after 50 years you will have just half a percent of your resources left. His proposed solution was to move to a circular economy, a concept based on the long-term restorative capacity of the Earth on which we all depend. He finished the talk by illustrating some of the broader sustainability challenges we may face, by referencing a recent

Proposal for a Trans-Neptunium object mission design study

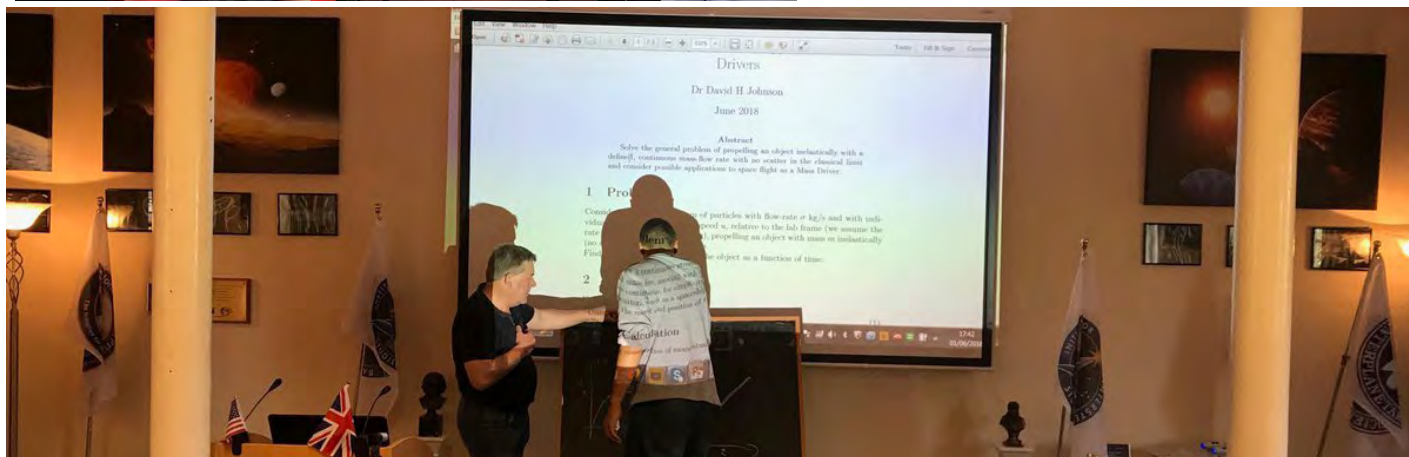
The third presentation was given by Kelvin Long, who surveyed the various current projects focused on missions to Alpha Centauri and noted two things about them: first, that they all lie on (and sometimes beyond) the boundary of what's currently feasible; and second, that there's a lot of science and exploration to be done between the orbit of Neptune and our next nearest



Stephen Ashworth - a strategic goal for humanity on earth and in space in 2061

A strategic goal for humanity on Earth and in space by 2061

The fourth and final presentation in the afternoon symposium came from Stephen Ashworth. He told us that his talk had started life as a blog post a couple of years earlier, at the time of Tim Peake's six-month mission to the International Space Station, and focused on the impact that Artificial Intelligence, or AI, is likely to have on the future of humanity. Stephen's key point was that the future is unknowable, but that doesn't mean we can't consider the most likely scenarios and decide what we need to do as a species in



Terry Regan and David Johnson discuss mass drivers

star system. Kelvin thinks we should be looking to expand our technical capabilities in a step-by-step fashion by starting with some Interstellar Precursor Missions. He gave a couple of examples – NASA's Prometheus probe (a cancelled project to develop nuclear-electric propulsion), their Jupiter Icy Moons Orbiter (JIMO, also cancelled), and ESA's Laplace (another mission to the Jovian moons) – before putting forward his own proposal, called DART. This stands for Direct Astronomical Reconnaissance Technology. This spacecraft would use nuclear-electric propulsion to first visit a dwarf planet such as Eris, then move on to a Trans-Neptunian Object, then head for the Oort Cloud, and finally travel on towards the

Interstellar Medium. Kelvin ended his talk by suggesting that DART could be an ideal project for i4is to take forwards as a detailed design study.

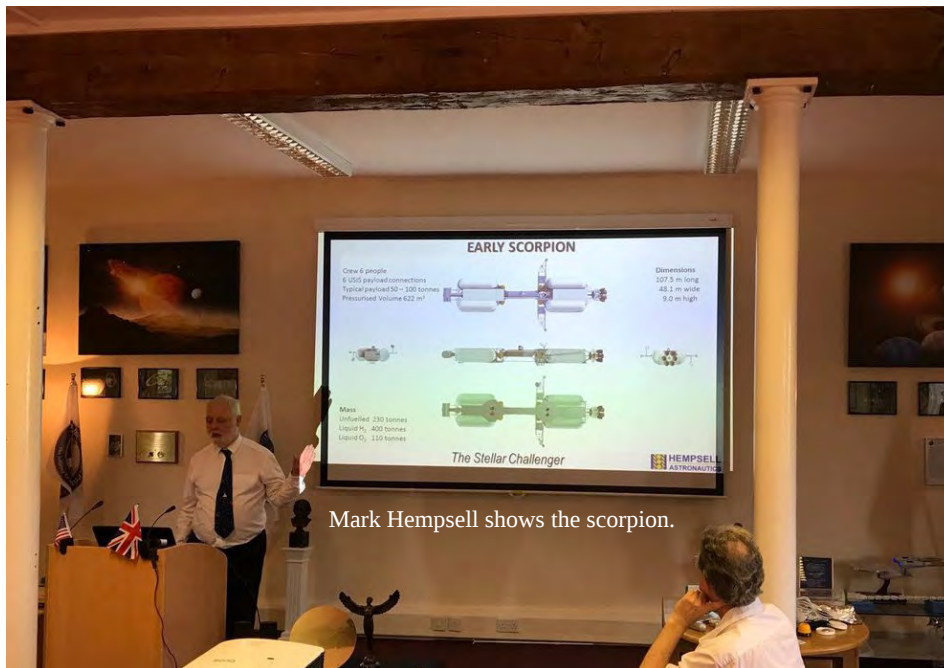
A coffee break gave attendees time to quiz the first three presenters further about their topics.

Derivation of Equation for Application to Mass Drivers

Dr David Johnson, who happens to be Kelvin's brother, presented a paper he had recently written on the mathematics of a mass driver. This was probably quite hard work for anyone in the audience who hated maths at school, but David's patient derivation of his final equation was an enjoyable challenge.

order to maximise the likelihood of the future we most prefer coming true. Stephen illustrated this idea by discussing several of the scenarios for humanity's future relationship with robots and AI that have been proposed in fact and fiction, ranging from dumb robots through to deadly 'Terminators' and beyond. He concluded by asking who would get to ask and answer these questions in future: us, the robots, or both of us?

The symposium concluded with an hour's break for discussion, refreshment and to investigate the space exhibits and memorabilia on display throughout the building.



Mark Hempzell shows the scorpion.

The Stellar Challenger – a concept study

The evening lecture was given by the President of the British Interplanetary Society, Mark Hempzell. Mark explained that after a long and exciting career as an aerospace engineer, he was now dividing his time between consultancy, his work with the BIS, and writing the 'Scorpion Voyages' series of four science fiction novels, in the sub-genre known as 'hard SF' where the stories are based on rigorous and sound science and engineering principles. He noted that he had recently spoken on this subject at the BIS Mars symposium in late February, and had also published two papers about these ideas in JBIS (in the January and December 2017 issues). Two short stories based in the same story universe as

the forthcoming novels can also be found in the recently published BIS anthology 'Visionary II'. His talk on this occasion was focused on the design of one particular vehicle that will feature in the second novel: a manned vehicle to explore the outer reaches of our solar system, right up to and through the heliopause, and into the interstellar medium beyond. He



BIS President Mark Hempzell discussing the Scorpion Voyages

described the vehicle in some detail, pointing out that it would be launched in pieces, sent up over 25 launches of the Skylon spaceplane and assembled in orbit. Propulsion was based on Alan Bond's 'Serpent' hybrid thermonuclear arcjet engine design (see the November 1972 issue of JBIS for details). Mark summarised the mission profile and the payload of scientific instruments to be carried, which includes a novel arrangement of four identical secondary probes, launched from the main spacecraft in a stacked arrangement that enables the fourth one to go further than

the other three, reaching 1000 AU in a century. His conclusion was that a Thousand Astronomical Unit (TAU) mission was feasible using present day or near-term technology, and so this spacecraft passes the feasibility test and will feature in his novels. Mark's fascinating talk elicited many detailed questions from the audience, and the meeting finally drew to a close at 7:15 pm.

Conclusion

This event was a great illustration of the benefit to be derived from i4is having its own headquarters building. The day provided attendees with an excellent opportunity to hear a varied series of talks on interstellar subjects and discuss the issues with interested colleagues. Several more such events are in preparation, and we look forward to seeing many of you at them. If you're interested in the topics covered in Principium, I'd strongly encourage you to come along to a future event if you can.

Patrick Mahon is Deputy Editor of Principium.

News Feature

Debate: Moon, Mars and beyond at the Royal Institution

John Davies

On 17 July this year the Faraday Theatre of the Royal Institution of Great Britain (the RI) hosted a debate "Moon, Mars and beyond". The debate was organised by BIS staff and volunteers. This was a near full house - evidence that this topic is a live one with considerable public interest. This report gives just a taste of a historic debate which will be reported in more detail in the BIS magazine, *Spaceflight*.

The theatre of the RI is a historic room. It is the famous raked amphitheatre where scientists and other creative people have come to share their ideas for over 200 years. This is the venue for the BBC Christmas Lectures - these Royal Institution Christmas Lectures were first held in 1825; many delivered by Michael Faraday. They were televised by the BBC as early as 1936. Three experts addressed the question of where we should next send people.

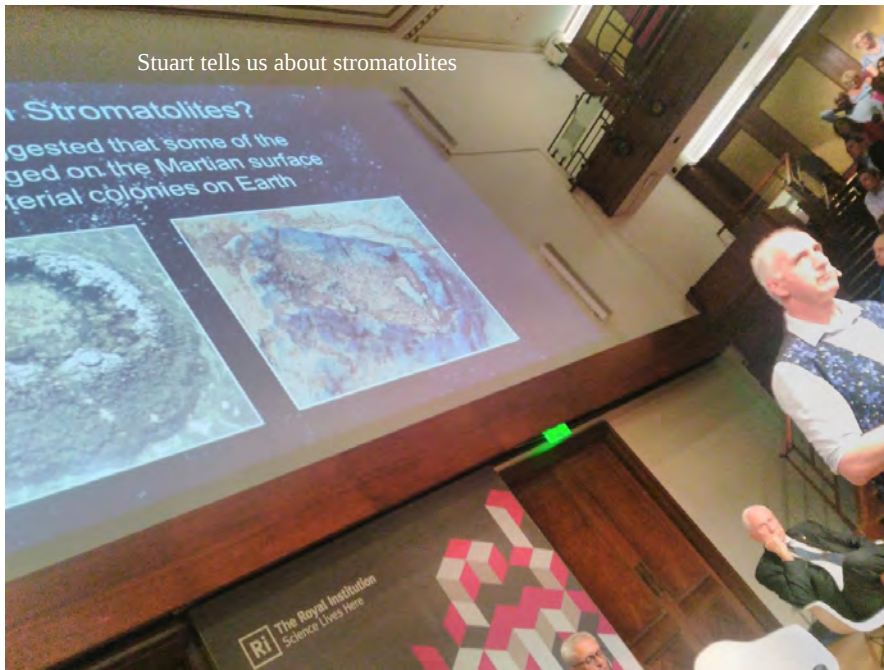
Colonel Al Worden advocated reaching out beyond Mars and ultimately to the stars. Al is an American astronaut and engineer who was the Command Module Pilot of Apollo 15, the fourth lunar landing mission in 1971. He is one of very few astronauts who have been outside a spacecraft beyond Earth orbit. He became Senior Aerospace Scientist at the NASA Ames Research Center and went on to other senior roles in NASA and elsewhere. He formally opened the i4is HQ in 2017 - see Principium Issue 19 November 2017, 'The Interstellar Space'. I can personally testify that Al Worden is one of the most charming and interesting people you could meet. More about him

on - www.alworden.com. Chris Welch advocated a return to the Moon. Chris is Professor of Space Engineering at the International Space University (ISU) in Strasbourg, France. He is a vice president of the International Astronautical Federation, a board member of the

British Interplanetary Society (BIS) and is a member of the editorial board of the peer-reviewed Journal of the BIS (JBIS). He is Director of the Master of Space Studies Programme at the ISU. Chris is a good friend of the Initiative for Interstellar Studies. He is a



Al emphasises *Billions of stars* to the audience in the historic Faraday Theatre

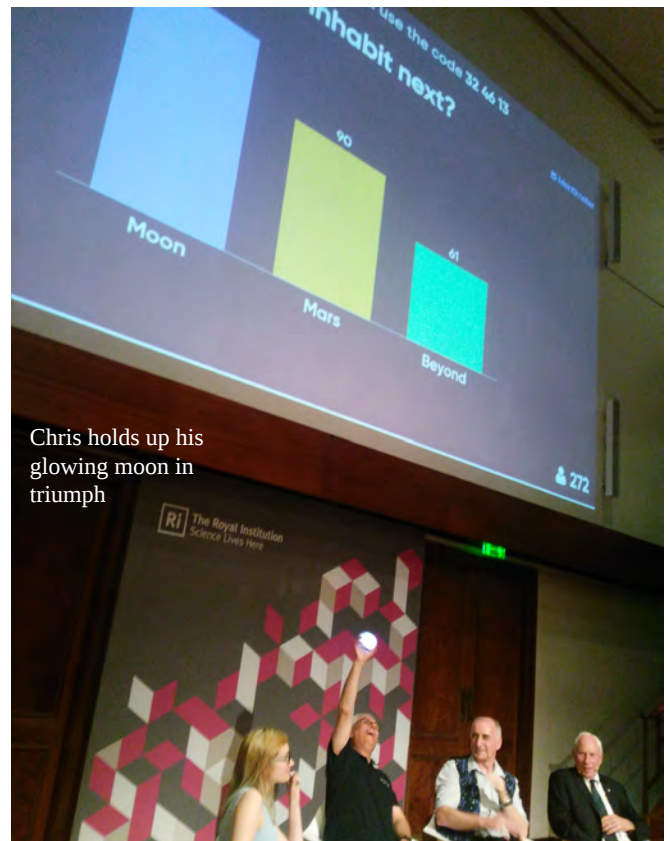


Stuart tells us about stromatolites

member of our advisory board. He works with a number of i4is experts who support interstellar-related Masters projects at the ISU, notably the world ship project "Astra Planeta", and has commissioned i4is to deliver two-week elective programmes in interstellar studies at ISU Strasbourg. More about him on -www.isunet.edu/prof-christopher-welch.

Stuart Eves advocated going straight to Mars. Stuart is currently a technical consultant for Vaeros Ltd. From 2004 he was Lead Mission Concepts Engineer at Surrey Satellite Technology

Limited. Stuart is a Fellow of the Royal Astronomical Society, a Council Member of the British Interplanetary Society, and he currently chairs the government/industry Space Information Exchange forum. In 2017 he published a book "Space Traffic Control" which advocates and explains how we can achieve greater resilience for satellite systems. Chris Welch stressed the practicality of a return to the Moon. Stuart Eves pointed out the larger scope for human endeavour on Mars. Al Worden gave us the vision of going further and inspired us with his personal experience of being well beyond the Earth.



Chris holds up his glowing moon in triumph



Alistair Scott hands Al Worden his FBIS

In the end the Moon received the most support with Mars second and the Beyond option gaining a respectable minority of votes. The evening closed with BIS past president Alistair Scott presenting Al Worden with his Honorary Fellowship of the British Interplanetary Society, in recognition of his services to astronautics.

John Davies is the editor of Principium

Interstellar News

John Davies and Patrick Mahon with the latest interstellar-related news

Events at the Mill

i4is HQ hosted several events since we last reported:

Public Presentation: Extreme Deep Space Exploration - A personal perspective by Rob Swinney - 27 July 2018

Some people are working on how we might really travel to the stars in the near future. Rob Swinney, i4is, Fellow of the BIS, Project Leader of Project Icarus and former RAF squadron leader discussed the likely methods and means in a way understandable to all. In the near future will it be giant nuclear rockets or miniature beamed sails; will it be some private adventurer or nation state – or take some unified world organisation; or will the driving force be peace or war?



Rob mirrors our Icarus statuette.



The Apkallu Initiative logo was designed by Kelvin F Long and executed by our old friend, the artist Alex Storer. The iconography is complex but some of the most striking features are the Great Pyramid of Giza representing the liberal arts such as architecture, the three symbols in the lower part of the square are Cuneiform for the number 100,000 to represent 100,000 years, which is the duration for which the artefact must be designed to last. The object in the centre is a dodecahedron, the faces containing elements of a range of disciplines. This is just a tiny selection -for more details look on the Apkallu Initiative website.



Kelvin shows an early preservation of culture, the Pyramids

The Apkallu Initiative: A Project to build a Minilithic Artefact to Preserve the Knowledge of Human Civilization into Deep Time In the Event of Global Cataclysm by Kelvin F Long - 29 June 2018.

This major new initiative by Kelvin has attracted wide interest. More at - www.apkalluinitiative.com.

More events elsewhere in this issue of Principium and future Mill events later in this News.

Are we alone after all?

A distinguished group of researchers has reached a startling and perhaps depressing conclusion. Anders Sandberg, Eric Drexler and Toby Ord of the Future of Humanity Institute (FHI), Oxford University, have published *Dissolving the Fermi Paradox*, arxiv.org/abs/1806.02404. They have evaluated the degree of confidence we can place upon the terms in the Drake equation and found much to doubt. They believe that they have found uncertainties that span multiple orders of magnitude. Running an initial Monte Carlo simulation on the parameters of the Drake equation they found an empty galaxy 21.45% of the time. In other words, one in five galaxies would have no civilisations at any given time. With further detailed analysis of probabilities they conclude:

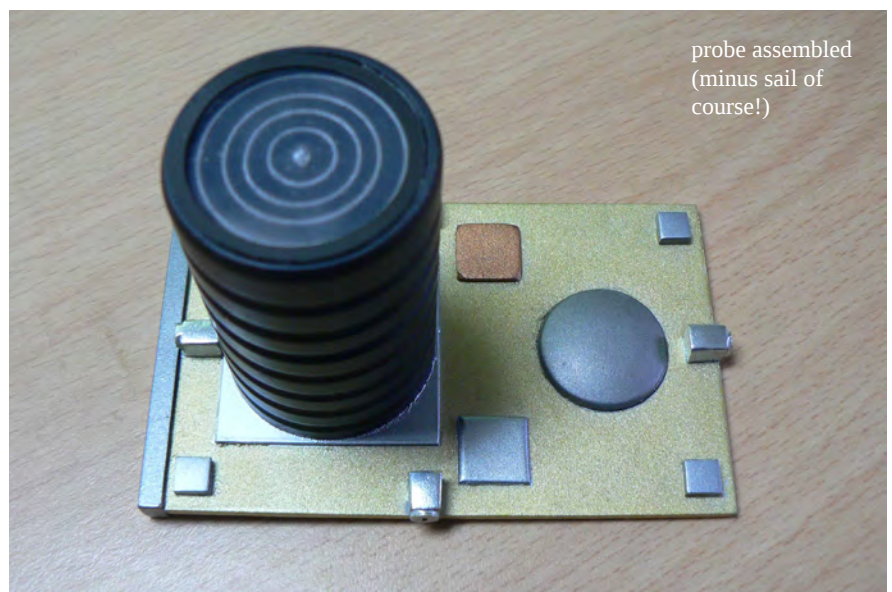
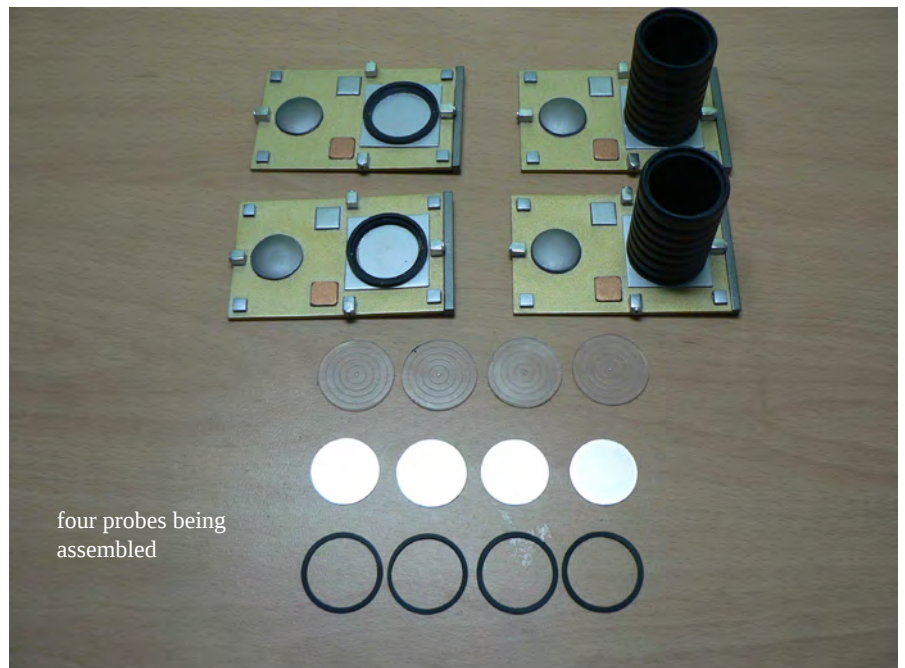
"... we find a substantial probability that we are alone in our galaxy, and perhaps even in our observable universe (53%–99.6% and 39%–85% respectively). 'Where are they?' - probably extremely far away, and quite possibly beyond the cosmological horizon and forever unreachable."

One possible explanation for the Fermi Paradox is, of course, that civilisations tend to destroy themselves. If Sandberg et al are correct then this argument is not required - which does not, of course, mean that we, the sole sentient species in existence, will not do so!

Anders Sandberg is a researcher at the FHI with a long-established interest in matters interstellar, www.fhi.ox.ac.uk/team/anders-sandberg. Eric Drexler is an engineer most famous for his 1986 book *Engines of Creation: The Coming Era of Nanotechnology* www.fhi.ox.ac.uk/team/eric-drexler. Toby Ord is a moral philosopher with a recent interest in questions of human extinction, www.tobyord.com.

More modelling genius from Terry

Our star modeller, Terry Regan has almost finished an i4is-commissioned set of models of the Andromeda probe as proposed in our 2016 study (i4is.org/what-we-do/technical/project-dragonfly/andromeda-probe) published as *Initial Considerations for the Interstellar (Andromeda) Probe: A Three Day Study* (arxiv.org/ftp/arxiv/papers/1708/1708.03556.pdf). Here are some early shots of his most recent work. Picture credits - Terry Regan



TVIW Symposium: The Power of Synergy

Our friends at the Tennessee Valley Interstellar Workshop (TVIW) are holding a symposium at Oak Ridge, Tennessee, on October 23-25, 2018. They aim to help us get on the stairway to the stars by exploiting small near-earth asteroids, establishing a permanent self-sustaining moon base, and completing the first human round-trips to Mars. Leaders from NASA, DOD, DOE, ORNL, industry, and academia will discuss synergistic new technologies that can enable this.

More at tviw.us/tviw-symposium-on-the-power-of-synergy.

Project Glowworm update

Project Glowworm is our R&D programme for testing a laser sail in space. We have made progress on developing the chipsats, to which the laser sail will be attached. In order to develop the chipsat technology, we currently have two international teams (Drexel University and TU Munich) actively working on chipsat prototypes. The idea is to develop and launch these chipsats quickly into space. We aim at a development and launch cycle of under one year (i4is.org/the-attosat-manifesto). Such a short cycle would allow us to mature the technology quickly. This would allow us to build and launch a chipsat with a laser sail within the next two years or so, which would be a necessary objective for testing laser sail propulsion in space. We are currently looking at various opportunities for sending the chipsats into space, for example, putting them on SunCubes, small 3x3x3 cm cube-sized spacecraft. Things are moving rapidly and the Glowworm team is confident that we will have first conceptual designs for the chipsats within the next two months. We continue to seek participation and ideas in this project, which is likely to transform the world of space exploration!

Interstellar in JBIS

The Journal of the British Interplanetary Society (JBIS) Volume 71, No 2, February 2018 is a wholly Interstellar Issue including -

Searching for E.T.- A Universal Units Proposal, Eugene Terry Tatum

Computing the Minimal Crew for a multi-generational space journey towards Proxima Centauri b, Frédéric Marin &

Camille Beluffi

Worldship Ethics: Obligations to the Crew, James S J Schwartz

The Social Dynamics of Science, Exoplanetary Environments and the Drake Equation, Douglas A Van Belle

The Global Catastrophic Risks Connected with the Possibility of Finding Alien AI During SETI, Alexey Turchin

JBIS is available via www.bis-space.com/what-we-do/publications.

Project Dragonfly papers

i4is Project Dragonfly was our first major laser-push endeavour. Dragonfly papers published so far are -

Perakis, N, Schrenk, L E, Gutmiedl, J, Koop, A, & Losekamm, M J (2016). *Project Dragonfly: A feasibility study of interstellar travel using laser-powered light sail propulsion*. Acta Astronautica, 129, 316-324.

Perakis, N, & Hein, A M (2016). *Combining magnetic and electric sails for interstellar deceleration*. Acta Astronautica, 128, 13-20.

From the i4is Andromeda Study- Hein, A M, Long, K F, Fries, D, Perakis, N, Genovese, A, Zeidler, S & Cress, B *The Andromeda Study: A Femto-Spacecraft Mission to Alpha Centauri* (2017). submitted to JBIS.

Upcoming HQ events

The i4is HQ hosts these events in the rest of 2018 -

Wed 15 - Sun 19 Aug, *Starship Engineer Summer School*

Fri 28 - Sat 29 Sep, Lecture: *Holographic Photon Sails*, Prof Greg Matloff & C Bangs

Sat 20 Oct, Symposium on the *Philosophy of Extraterrestrial Intelligence in the Universe*, Kelvin F Long and others.

Fri 30 Nov, Lecture, Prof Carl

Murray, Cassini mission.

Fri 14 Dec, Xmas Social and lecture, David A Hardy, *Starships in Space Art*.

Straight Shooting Required?

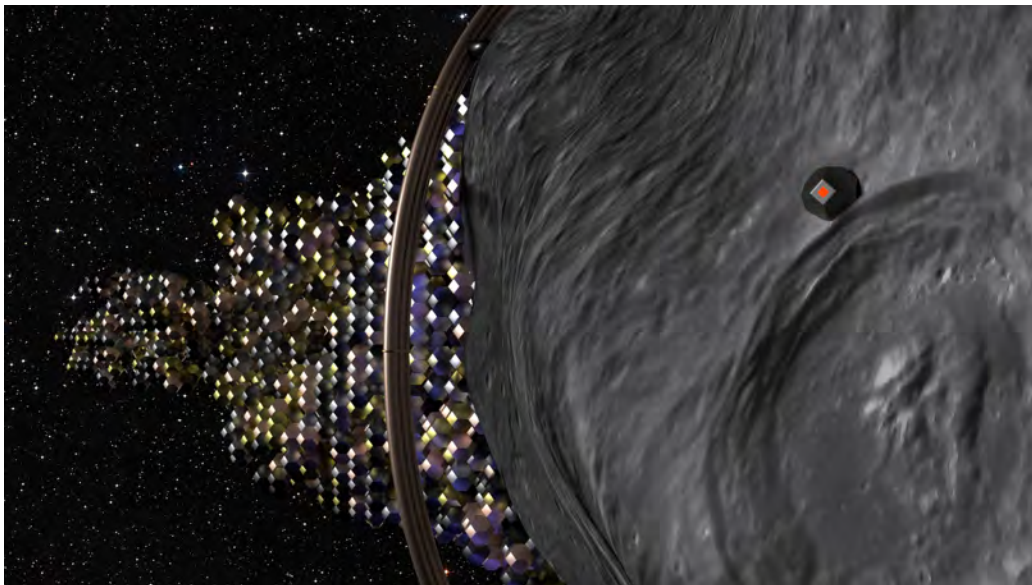
Science writer Ethan Siegel strikes a cautionary note in Forbes magazine, 7 August 2018, *Is Humanity About To Accidentally Declare Interstellar War On Alien Civilizations?* (www.forbes.com/sites/startswithabang/2018/08/07/is-humanity-about-to-accidentally-declare-interstellar-war-on-alien-civilizations).

He says "Imagine yourself on a world not so different from Earth, orbiting a star not so different from our Sun." and asks us to consider our reaction if a 1 gram spacecraft arrived at 20% of the speed of light thus impacting with the same energy as the Chelyabinsk meteorite. A fleet of them would look like enemy action. He quotes Hawking, "If aliens ever visit us, I think the outcome would be much as when Christopher Columbus first landed in America, which didn't turn out very well for the Native Americans". Can we devise and trust mechanisms to provide terminal guidance for a laser propelled nanocraft or even slow it down (see "*Slow down!*": *How to park an interstellar rocket in our last issue*, P21)?

But Harvard Professor Avi Loeb, chair of the Breakthrough Starshot advisory board, refutes this (www.forbes.com/sites/thelabbench/2018/08/16/why-humanity-probably-wont-accidentally-start-an-interstellar-war-with-an-alien-civilization) and Paul Gilster of Centauri Dreams and the Tau Zero Foundation, also comments www.centauri-dreams.org/2018/08/17/the-breakthrough-starshot-opportunity.

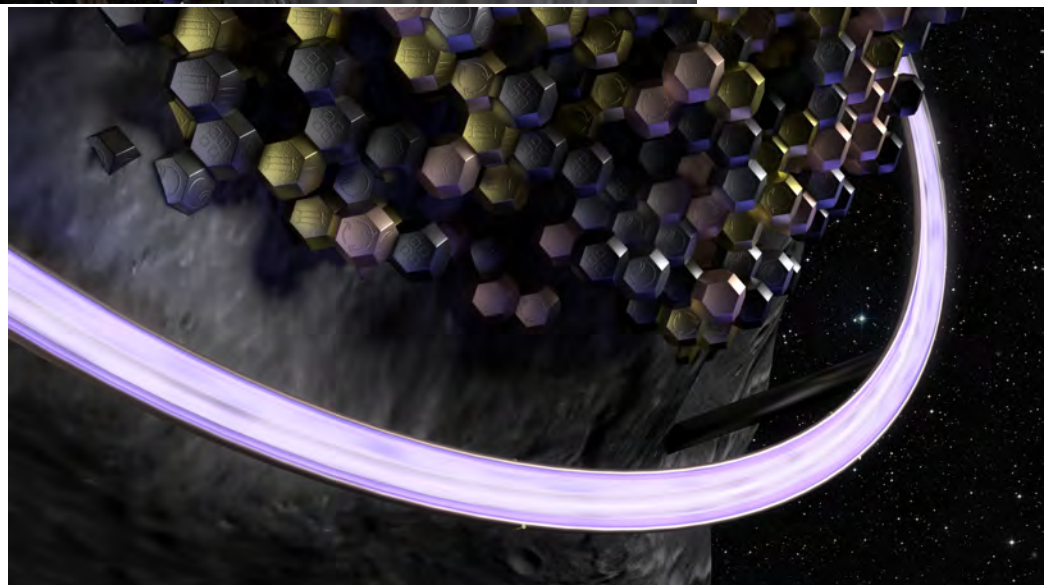
Picture Feature: Images from the TU Delft Starship Team - DSTART

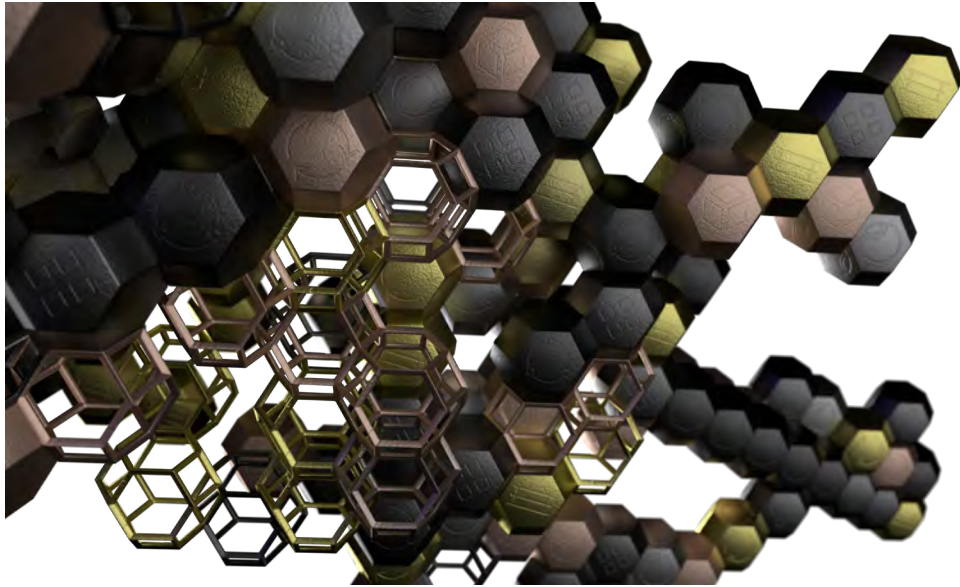
We look forward to the paper *Evolving Asteroid Starships: A Bio-Inspired Approach for Interstellar Space Systems* from the TU Delft Starship Team at the IAC in Bremen in October. Much more about this gathering of the astronautical clans elsewhere in this issue. As a prelude, here are some images imagined by the team, provided by Angelo Vermeulen. You may recall our P21 front cover image from the same source.



EAS (Evolving Asteroid Starships) by DSTART (2018) overview closeup by Nils Faber

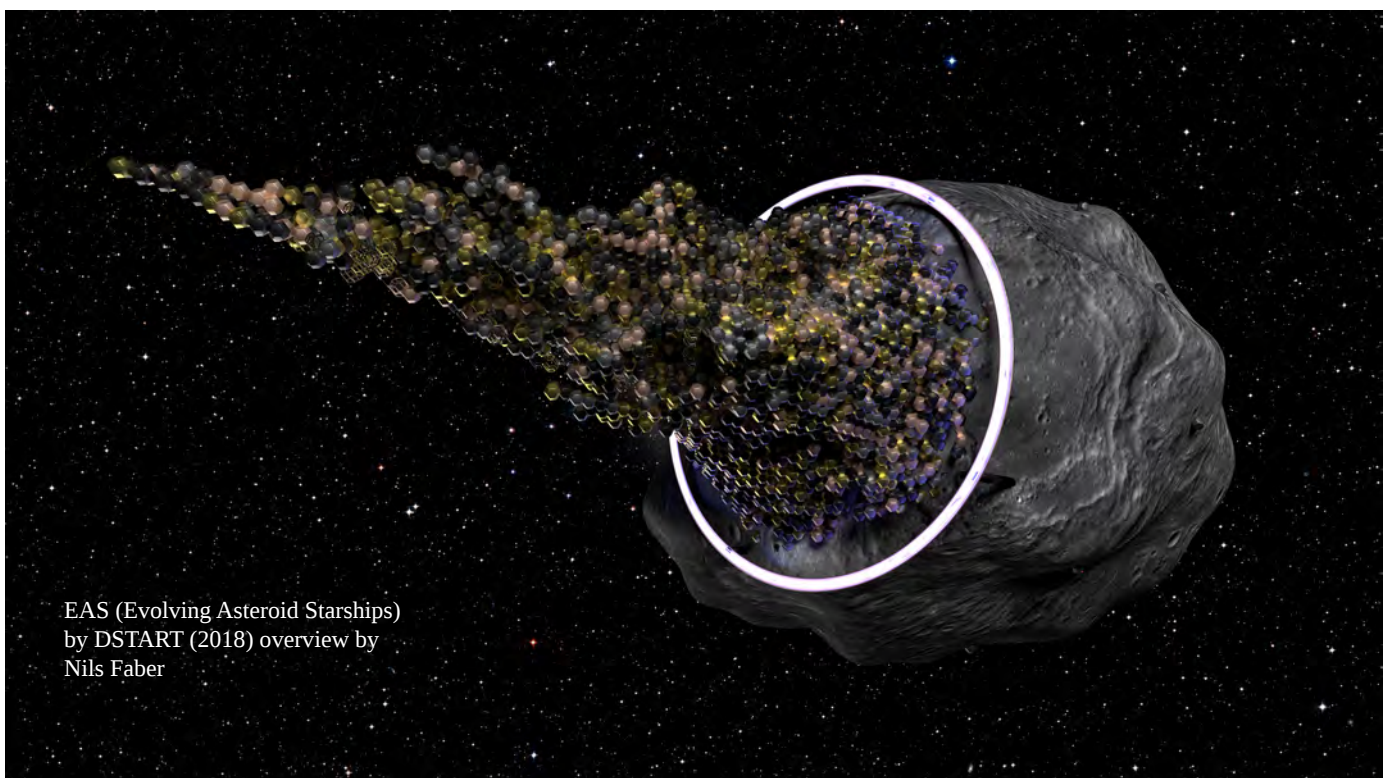
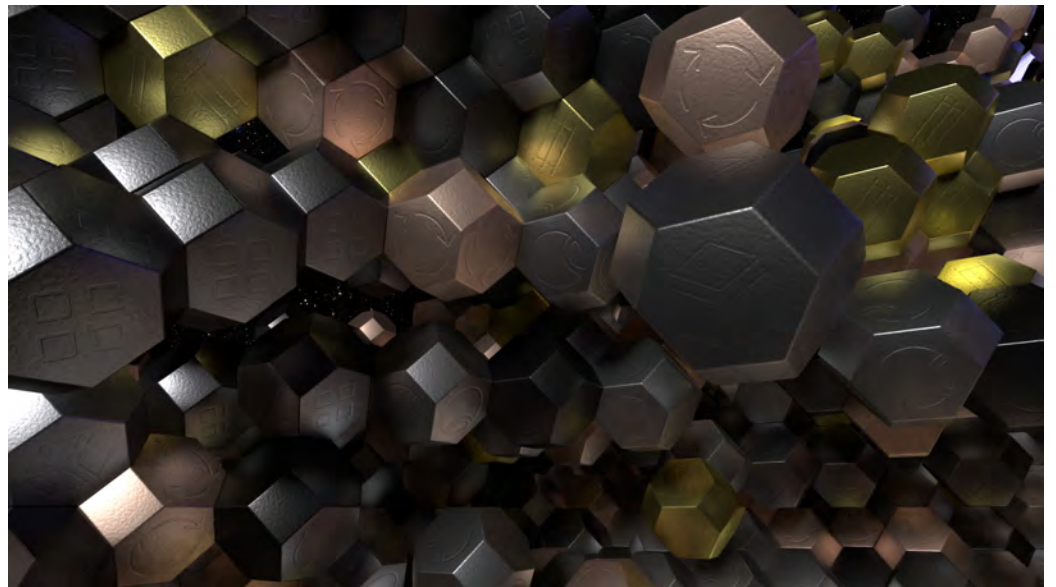
EAS by DSTART (2018) overview detail by Nils Faber





EAS by DSTART
(2018) construction
by Nils Faber

EAS by DSTART
(2018) modules -
image by Nils Faber



EAS (Evolving Asteroid Starships)
by DSTART (2018) overview by
Nils Faber

News Feature: Catching A Little Bit of Heaven

i4is-US at the Asilomar Microcomputer Workshop

Robert G Kennedy III

i4is-US President Robert G Kennedy III ran the forty-fourth Asilomar Microcomputer Workshop, April 25-27, 2018. He reports on the interstellar theme *Catching A Little Bit of Heaven* which was a major part of this unique and venerable conference. All images are Robert's unless otherwise stated.



figure 1: Group
Picture, 27 April 2018

For those readers who don't know me yet, I'm president of the "American branch" of i4is (www.I4IS.us) and also general chair of the historic Asilomar Microcomputer Workshop (www.amw.org).

AMW is a small, sequestered, off-the-record, invitation-only, technology conference, held annually in the spring in Pacific Grove, California. It was founded in 1975 as an IEEE technical workshop, initially sponsored by the Western Area Committee of the IEEE Computer Society. IEEE (Institute of Electrical and Electronic Engineers) itself was formed in 1963 from the amalgamation of the American Institute of Electrical Engineers and the Institute of Radio Engineers. IEEE is now the world's largest association of technical professionals with more than 400,000 members in 160 countries around the world.

AMW has always been a general, broad-topic conference—perhaps the general conference formula is the reason it has survived, thrived, and is still relevant today. It is intense, sometimes going 48 hours straight, always from Wednesday thru Friday afternoons. The participants are among the most remarkable people on the planet. To observe the 30th AMW in 2004, my colleague Ted Laliotis wrote (see www.amw.org/AMW1975-2018.pdf):

The intentional lack of written proceedings and the exclusion of general press representatives (“marketdroids”) was perhaps the most distinctive characteristic of AMW that made it so special and successful. This encouraged the scientists and engineers who were at the cutting edge of the technology, the movers and shakers that shaped Silicon Valley, the designers of the next generation microprocessors, to discuss and debate freely

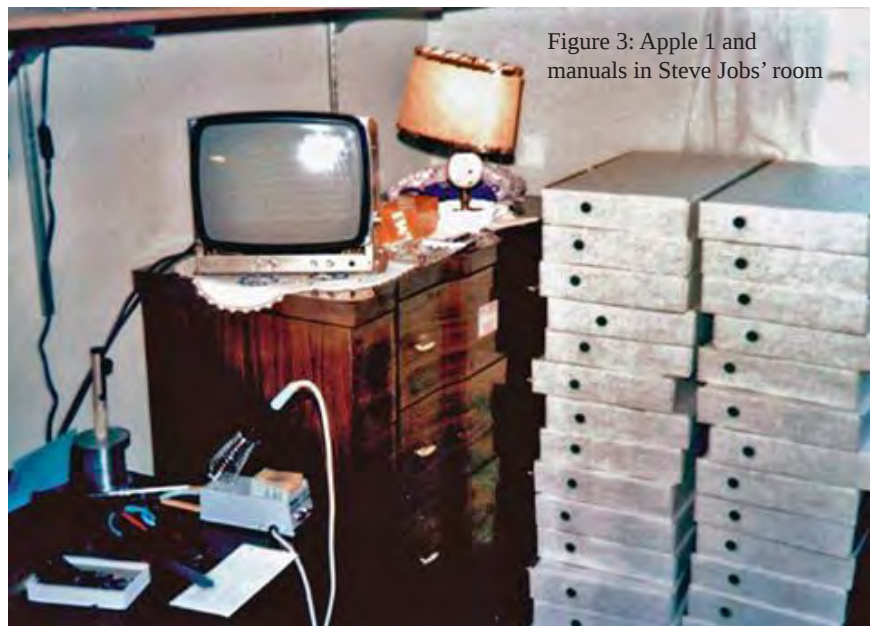


Figure 3: Apple 1 and manuals in Steve Jobs' room

the various issues facing microprocessors. In fact, many features, or lack of, were born during the discussions and debates at AMW. We often referred to AMW and its attendees as the bowels of Silicon Valley, even though attendees came from all over the country, and the world.

Another characteristic that made AMW special was the "required" participation and contribution by all attendees. Every applicant to attend AMW had to convince the committee that they had something to contribute by speaking during one of the sessions or during the open mike session. In the event that someone slipped through and was there only to listen, that person was not invited back the following year. Another hallmark of AMW is the famous/notorious Thursday-night anything-goes open session aka “RAT talks” (for “**Rich** Asilomar Tradition”).

The AMW has had a notable influence on history. Many important innovations came out of the AMW or were first discussed there, eg reduced-instruction-set-computing or RISC which is now the standard for virtually every operating system in the world. Amusing anecdote: Participants at the second Workshop in 1976 played a critical role in what became the Apple, when, during the “Open Mike” session, a Mr Paul Terrell who was there to speak about “Future of the Neighborhood Computer Store” was instructed from the podium to take a phone call at the pay

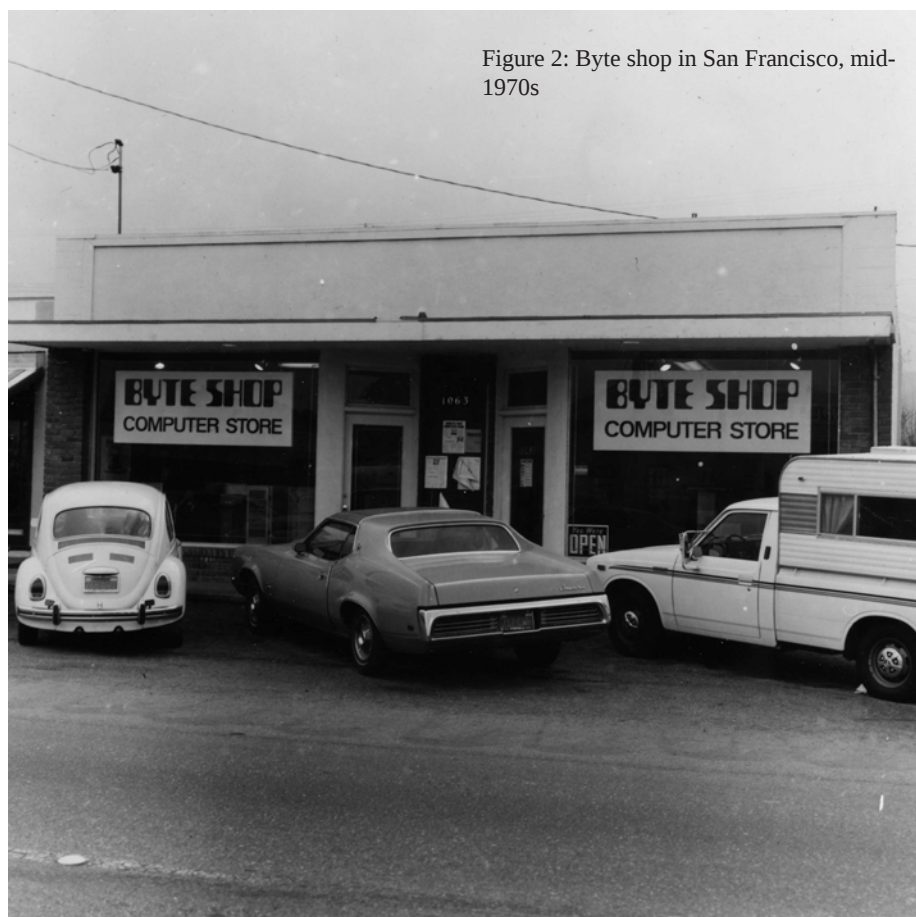


Figure 2: Byte shop in San Francisco, mid-1970s

Defense Language Institute (DLI), where American soldiers go to learn foreign tongues. The applicability to SETI is obvious, which is perhaps one reason why the SETI Institute is also in Silicon Valley.

Therefore, in keeping with the principle that the hallmark of a great event is ending with a bang, we organized the closing session at AMW#44 to be about the recent work and portfolio of i4is-US. Building on the outstanding cooperation in November of 2017 (see Principium #20) in regard to 1I/Oumuamua, we titled the session, “Catching A Little Bit of Heaven”, led by Dr T Marshall Eubanks of Asteroid Initiatives LLC. Your humble narrator (YHN) opened with a brief backgrounder on "Interstellar Interlopers: Getting Ready for the Next Surprise", making the case that the potential science return (summarized below) was worth on the close order of US\$10 billion to get, about what one of NASA’s “flagship missions” (such as Galileo, Cassini, Hubble, or Webb) cost in today’s currency. Marshall then presented “Such a Long Long Time to Be Gone, and a Few Milliseconds to Be There: Exploration of Passing Interstellar Asteroids”. Our own Dan Fries (PhD candidate at Georgia Tech) closed with, “Interstellar

Capabilities: Why the Biggest Laser is Not Big Enough”. This finale was a great success which “blew the audience away” as intended. For that, I am indebted to Marshall and Dan.

A precis of Marshall’s outstanding presentation is below, followed by Dan’s:

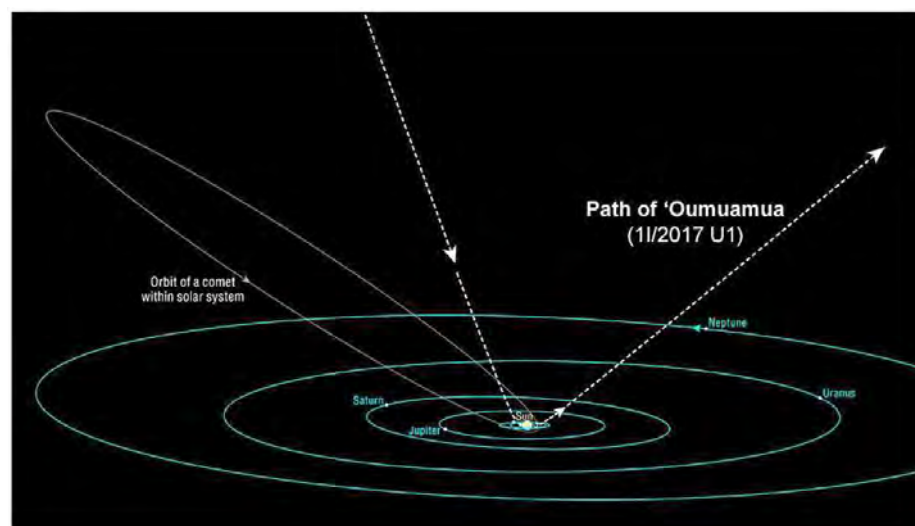
Summary of talk by T Marshall Eubanks, PhD.

Marshall discussed what we can learn about interstellar asteroids, such as the recent 1I/Oumuamua, from measuring their velocity, and went on to consider the prospects for a potential probe mission to the object. Incoming v_{∞} (“vee-at-infinity”) in both magnitude and direction provides a strong clue as to galactic source population. The Sun and most of the nearby stars are in the galactic thin disk, with an rms velocity of ~ 30 km/sec and only small velocity out-of-plane components. Objects from other populations may also speed through the galactic disk, with typical RMS velocities of ~ 50 to 100 km/sec for objects from the thick disk, and ~ 300 km/sec for objects from the galactic halo. Possible intergalactic asteroids and comets would be expected to have velocities relative to the Sun > 500 km/sec. All the higher velocity objects should have near random inclinations, and thus

relatively large velocities out of the galactic plane.

1I (nicknamed “One Eye” by Marshall, and “Oo-La-La” by me) has a vee-at-infinity of 26.3 km/sec, on both ingress and egress from the solar system, quite consistent with it being a long term resident of the galactic thin disk, but much too small for it to be a thick disk or halo object. Nevertheless, this is substantially faster than the fastest human spacecraft to date, Voyager 1, which has a $v_{\infty} = 16.86$ km/sec. Getting the velocity to catch 1I is not easy, and requires sending a fairly large spacecraft close to a large mass (either the Sun or Jupiter) for an Oberth Maneuver. The probe would mass 5745 kg, close to that proposed for a SLS-launched Europa Clipper spacecraft, and perform a gravity assist to pass within 10 solar radii. Two solid fuel stages would fire sequentially close to the Sun, delivering a total delta-vee of 4.489 km/sec for the Oberth maneuver close to the Sun. A Saturn flyby would still be needed to get the probe out of the plane of the solar system. Third stage will be permanently attached to the probe, and to be used for terminal encounter, delivering a total possible 0.815 km/sec to power a close flyby.

Figure 5, 1I/Oumuamua Almost Got By Us—It Was Only Detected After Perihelion
Credit: T Marshall Eubanks, Asteroid Initiatives LLC



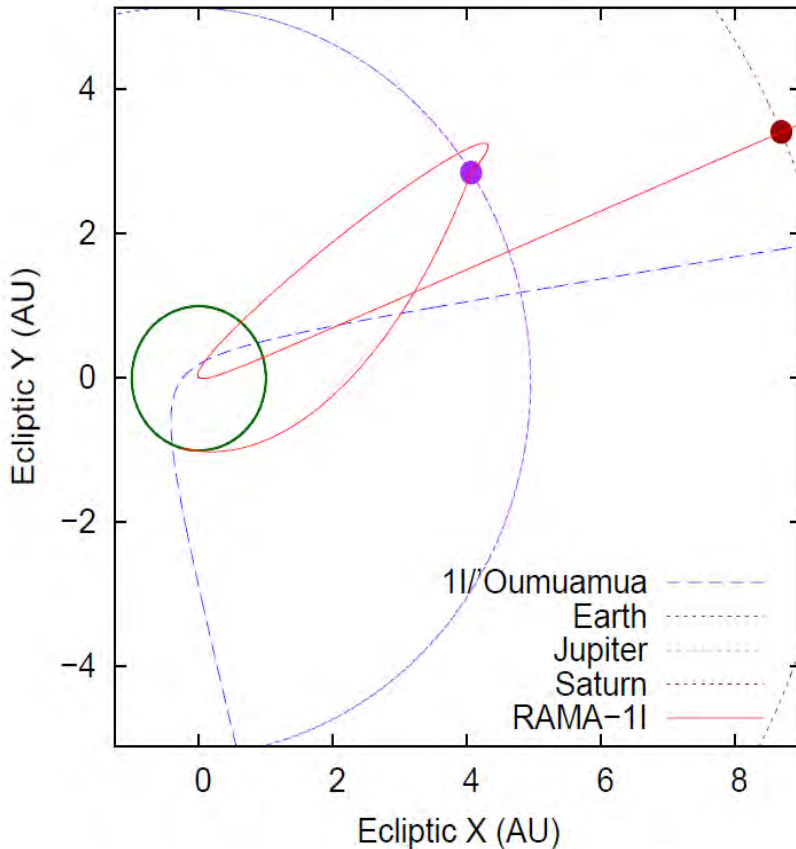


Figure 6, Top View of Probe's ("RAMA-11") Path thru Solar System Inside Saturn Orbit
Credit: T Marshall Eubanks, Asteroid Initiatives LLC

If launched in March 2022, the 1I flyby would be in early 2043 at a distance of about 146 AU from Earth, with a payload about the size of New Horizons, 500 kg. One-Eye's 2.2-hour rotation period implies an effective bulk density of ~ 2.3 grams/cm³, or 2.3 times water.

The scientific goals for the exploration of the One-Eye are:

1. Determine the chemical composition of the 1I surface and shallow interior, establish whether the surface of 1I consists of silicate rock, refractory organic material, nickel/iron, or other materials, and thus place 1I within the context of the formation of exoplanetary systems.
2. Determine the stellar processes active in the formation of 1I and, if possible, whether it was formed in a large star forming region (as was the solar system), a small stellar nursery,

or in some other fashion (such as in a supernova remnant).

3. Determine whether complex organic molecules survive on or near the 1I surface, their relation to organic molecules found in the interstellar medium, and whether the 1I history includes pre-biological or even biological processes.
4. Determine the general morphology and geology of 1I, and search for any satellites or rings.
5. Determine the rotation period of 1I, the inclination of its rotation pole, its actual elongation and thereby set constraints on its internal structure and density variations.
6. Determine the exposure age of the 1I surface, both from an observation of surface craters and from chemical analysis of radiation induced breakdown

of molecules on the 1I surface.

7. Determine or constrain the intrinsic 1I magnetic field.

Determine the 1I-solar wind interaction.

At >100 AU from the Sun, 1I will have an absolute magnitude of ~ 22 magnitude, very dim. A probe with a sufficiently large navigation telescope to search for that would only detect 1I at a distance of 1.5 million km. 1I will not be detected until the spacecraft is a few hundredths of an AU away, a day or two at best from the fast flyby. Because round trip flight time is about 28 hours at 100 AU, the probe will have to find the target, maneuver close, and execute the flyby, all without help from Earth. Current propulsion technology cannot muster the delta-vee to soft-land a probe on One-Eye. Sampling can be done with a small impactor (~ 10 kg), which would cause an energized plume that the main spacecraft (or a sub spacecraft) could sense, to determine elemental and molecular compositions. Assuming 30 m-thick target, impact will take ~ 1 millisecond, and the prompt plume flare will last tens of milliseconds. After 21 years of travel, much of the excitement would be over in <100 milliseconds. (That's a 10-billion-to-1 ratio.)

Truly, "a long, long time to be gone, and a short time to be there."

Summary of talk by Dan Fries

Dan's presentation was beautiful, graphics-rich and filled with high concepts. He began with the big picture, making the case for Why Interstellar? Answer: because it's something bigger than ourselves, making this seemingly outlandish field a most human endeavor.

He showed where the human race is now, where it might want to be, and what's in between those two states.

A desirable end-state (that one might describe as having the hallmarks of a Kardashev Type I civilization) would feature

- access to unlimited energy,
- FTL travel and communication,
- economy of abundance in every respect,
- control of all four fundamental forces and matter on the molecular level,
- expansion of the human consciousness,
- peace and prosperity.

The in-between bit includes

- cislunar development and beyond such as space-based solar power, moving industry off-world, space elevator(s), asteroid mining,

- colonizing other worlds in the Solar System,
- early interstellar probes such as BIS's Project Daedalus, and the current effort in Breakthrough Starshot (also in Silicon Valley).

Among these grand schemes, Dan showed projects and activities specific to i4is: laser sails (e.g., our Project Dragonfly), asteroid mining (gleaned from our NIAC proposal), chipsats (eg Project Glowworm).

Notably (to me), Dan explicitly

drew attention to avenues of scientific inquiry that are neglected in the space community (since it tends to be dominated by "rocket-heads"—my expression, not Dan's). These so-called "soft" life and social sciences, plus humanities, are just as interesting, tough, and potentially rewarding to investigators as traditional "hard" science and engineering. (I was most gratified to hear this, since i4is-US has made it a strategic objective to pay attention to these underserved areas as well as citizen science.)

In this way, by presenting an overview of the entire space ecology interspersed with applicable specific examples of our work, Dan demonstrated how something as seemingly far-off as interstellar travel and exploration is relevant and worth getting started on now, even by those of modest means. This argument is one that this particular audience has a unique ability to appreciate, given their perspective on the social revolution caused by microprocessors and formative influence in it.



RGK gives the Vulcan salute at the group picture from Asilomar this April

About Robert Kennedy

Robert G Kennedy III, PE, is President of i4is-US. He is a New Yorker who has settled in Oak Ridge, Tennessee, where i4is-US is incorporated. In his "day job" he is active in geothermal development in Ethiopia, Tanzania and Uganda and in energy-efficiency, renewable-resource business development and public energy policy in his home country at local, state, regional and national levels. He has worked for the Space Subcommittee of the United States House of Representatives on commercial remote sensing and military satellite communications. He was a technical/political consultant to the film "Deep Impact". He has also significant expertise in nuclear engineering. You may recall from Principium 19 that he was able to show a transplutonium production rod to the discoverer of Plutonium (and a few other elements), Glenn T Seaborg, in 1994, just a few years before the death of that finest of nuclear chemists.

BOOK REVIEW: Exoplanètes

George Frangou

(Belin 2018, www.belin-editeur.com/exoplanetes)

Engineer, innovator and entrepreneur George Frangou returns to his first love, astrophysics, in this review of a new book, *Exoplanètes*, by Dr David Fossé, deputy editor of *Ciel & Espace*, the bimonthly of l'Association française d'astronomie (AFA). He enthusiastically recommends this book to all who can read French and hopes it will soon be available in English translation.

About David Fossé and Illustrator Manchu

Astrophysicist Dr David Fossé, is the deputy editor-in-chief of the magazine *Ciel & Espace*.

His areas of research include the study of extrasolar planets, cosmology and black holes and the history of science.

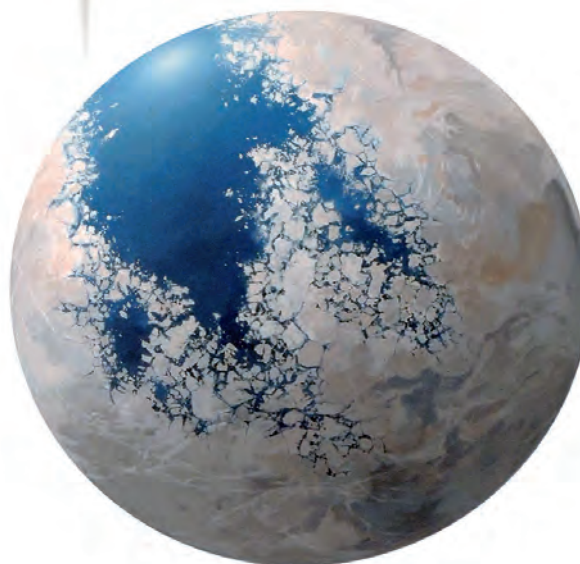
Exoplanètes illustrator Manchu has over 500 novel covers to his credit and has won prestigious artistic SF prizes. His attention to scientific rigour in art makes him the perfect illustrator for this book.

Scope

On 9 January 1992, radio astronomers Aleksander Wolszczan and Dale Frail announced the discovery of two planets orbiting the pulsar PSR 1257+12. This discovery was confirmed, and is generally considered to be the first definitive detection of exoplanets. When in 1995 51 Pegasi b was discovered orbiting a main-sequence star astronomers were confronted with a world that should not exist at all; a planet twice as big as Jupiter and its year lasts just 4 hours! 20 years later, we have discovered about 4,000 extrasolar planets and we think there are several hundred billion in the Galaxy. The diversity of these distant worlds is immense:

David Fossé
Peintures de Manchu

exoplanètes



Belin:

Credit: Belin

further reading

Another two of the most recent books on exoplanets are -

Exoplanets*, by astronomer Michael Summers and physicist James Trefil explore very similar subjects to David Fossé and Manchu's book. The authors provide concise and clear expositions of the methodologies for obtaining the new knowledge, along with the proper caveats that separate the degrees of certainty from varying hypotheses that the data suggests.

* *Exoplanets, Diamond Worlds, Super Earths, Pulsar Planets, and the New Search for Life beyond Our Solar System*, Michael Summers and James Trefil, 2018, www.penguinrandomhouse.com/books/549299/exoplanets-by-michael-summers-and-james-trefil/9781588346254

The Exoplanet Handbook, by Michael Perryman emphasises the interconnection between the various fields and provides extensive references to more in-depth treatments and reviews. The Handbook ties all these avenues of research together across a broad range of exoplanet science.

* *The Exoplanet Handbook (2nd edition)*, Michael Perryman, 2018, www.cambridge.org/gb/academic/subjects/physics/computational-science-and-modelling/exoplanet-handbook-2nd-edition?format=HB

ocean planets, super-earths, hot jupiters and rocky terrestrial worlds - and David Fossé's book does an excellent job of classifying them and describing them with sufficient scientific rigour and evidenced-based research.

Written in French, *Exoplanètes* is quite a technical book and could be included in the reading list for astrophysics and astronomy undergraduate degrees. It has a reasonable glossary of terms and has numerous references and citations in the bibliography. It is an excellent treatment of the prevailing body of knowledge in the ever-growing Exoplanets discipline.

David's passion for the subject and his desire to inform the world about 'what's out there', drives him to explain the subject he loves, in a way that also engages a non-technical readership making it an exciting, inspirational read! Manchu's well thought-through illustrations convey the scientific rigour alongside the artistic license which is a hallmark of his work. His illustrations are nothing short of stunning.

The book is written in four parts. Part One deals with the realm of the gas giants, following 51 Pegasi b, the first planet discovered around another sun in 1995. Following this the "Hot Jupiter" has long been the dominant category amongst the giants. Part Two examines Super Earths like Kepler-442 b and Mini-Neptunes sometimes known as gas dwarfs or transitional planets. The chapter on Ocean Planets with its description of Kepler-22 b is particularly notable. Probably the most enthralling part in the book, Part Three, 'Earths!', examines terrestrial type planets. With a view to seeking possible extraterrestrial life, a portrait is provided of the closest exoplanet to our solar system, Proxima b,

orbiting within the habitable zone of the red dwarf star Proxima Centauri, and Trappist-1f, a likely rocky exoplanet with a massive high pressure and temperature water-steam atmosphere, orbiting within the habitable zone around the ultracool dwarf star Trappist-1 39 light-years away from Earth in the constellation of Aquarius. Part Four is a detailed technical section describing the methods for exoplanet detection including orbital transit, radial velocity, gravitational microlensing and planetary chemical composition using spectral analysis. The final part also includes a section on the convergence of Dr Fossé's scientific thinking and Manchu's imagination behind the illustrations in the book.

Exoplanètes Highlights

Planets with three suns, metallic or diamond planets. Not only is the plurality of worlds a reality, but it is an absolute extravagance! We know enough today to understand how exoplanets are different from what we understood in the past, when we did not have the means to see them. Manchu and David Fossé, combine great scientific rigour and imagination making it possible for the reader to travel to these strange new worlds of the gas giant, "super-Earth" and "mini-Neptune", and exo-Earth.

Amongst the classifications, I have highlighted four summarizing the most exciting and interesting planets with illustrations. The four are The Ocean planet [Kepler-22 b], Evaporating Gas Giant HD 209458 b, terrestrial planet Kepler-186f (SETI 1b) and pulsar planet PSR B1257+12. The highlights also help emphasize the impact and importance of *Exoplanètes* as a scientific work worthy of the international astrophysics community!

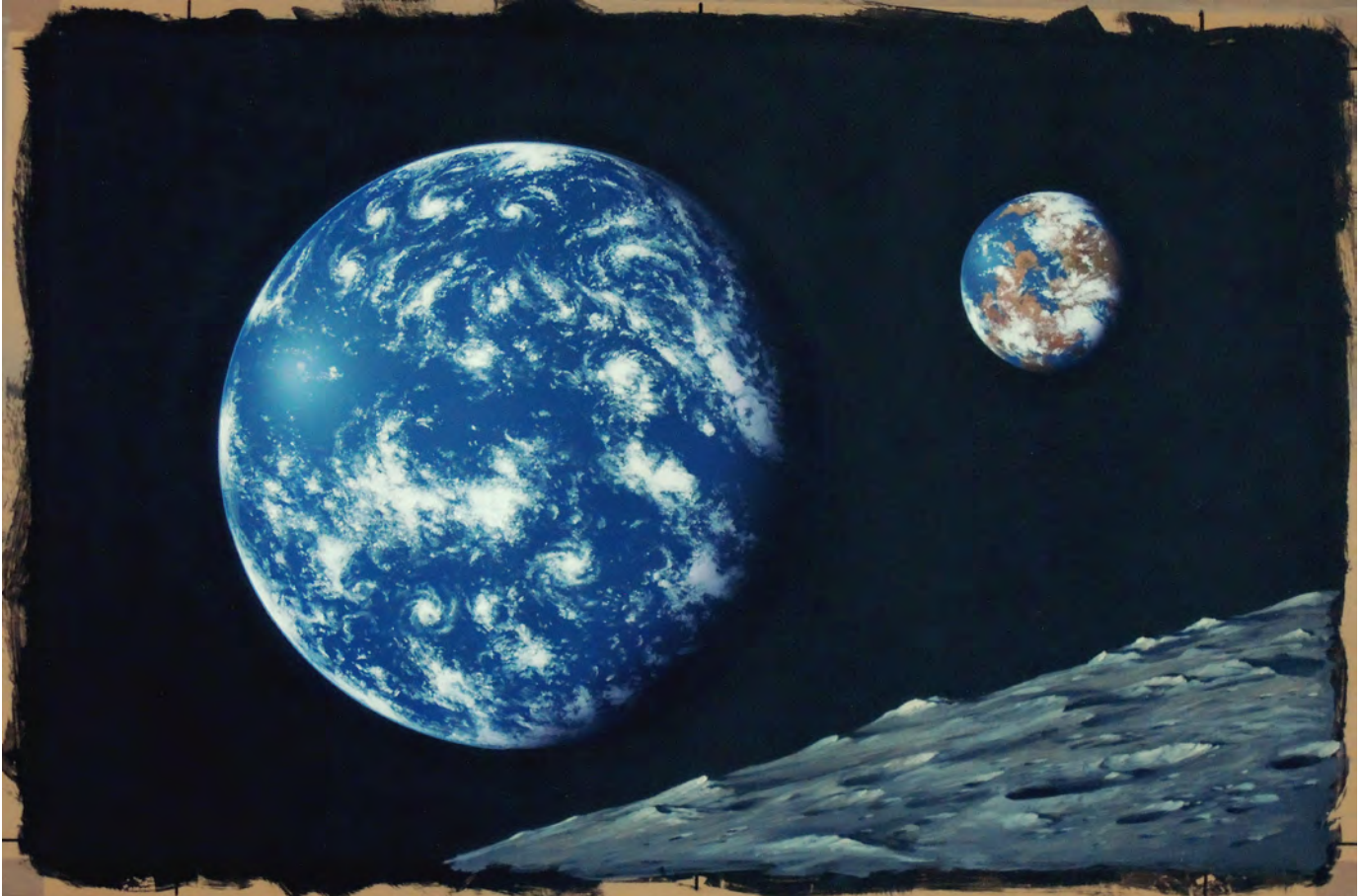


Figure 1: An ocean planet and two of its satellites. Credit : Manchu/D Fossé (Exoplanètes, Belin 2018)

The Ocean Planet [KEPLER-22 b]

Kepler-22 b turns in 290 days around a star, Kepler-22, of 0.97 and 0.98 mass and magnitude (relative to the Sun).

If it is completely covered with water as the models suggest, it will be a big blue planet. David Fossé and Manchu surrounded it with two imaginary satellites but whose existence is plausible from 0.7 and 0.5 terrestrial radius (radii respectively).

We might speculate that life could have appeared more easily on one of these satellites than on the planet itself.

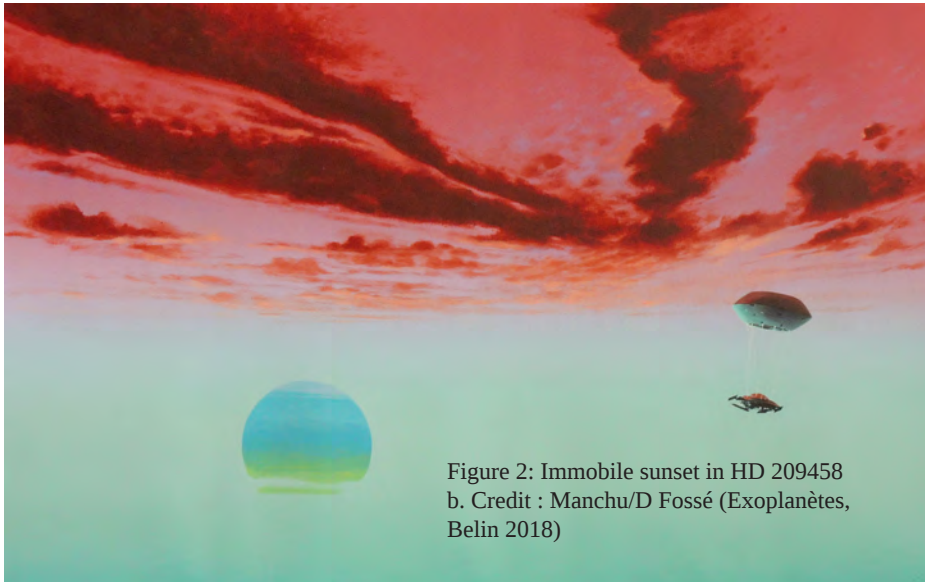


Figure 2: Immobile sunset in HD 209458 b. Credit : Manchu/D Fossé (Exoplanètes, Belin 2018)

Evaporating Gas Giant [HD 209458 b]

A sunset on HD 209458 b. On this exoplanet, the sun does not actually set, it remains perpetually fixed in the sky. It is also much bigger than the sun seen from the earth. The brown clouds are made of drops of iron or glass. The colours of the sky are inspired by a modelling from the French astrophysicist Alain Lewis.

Our Earth's Exoplanet Sister [SETI 1b]

Kipping & Teachey 2016 suggest that advanced civilizations could cloak their presence, or deliberately broadcast it, through controlled laser emission. Such signatures could be readily searched in the archival data of transit surveys. The transit method is presently the most successful planet discovery and characterization tool at our disposal. When SETI1 b, seen from the Earth, begins or finishes its transit, its inhabitants emit powerful laser beams in our direction for fifteen minutes.

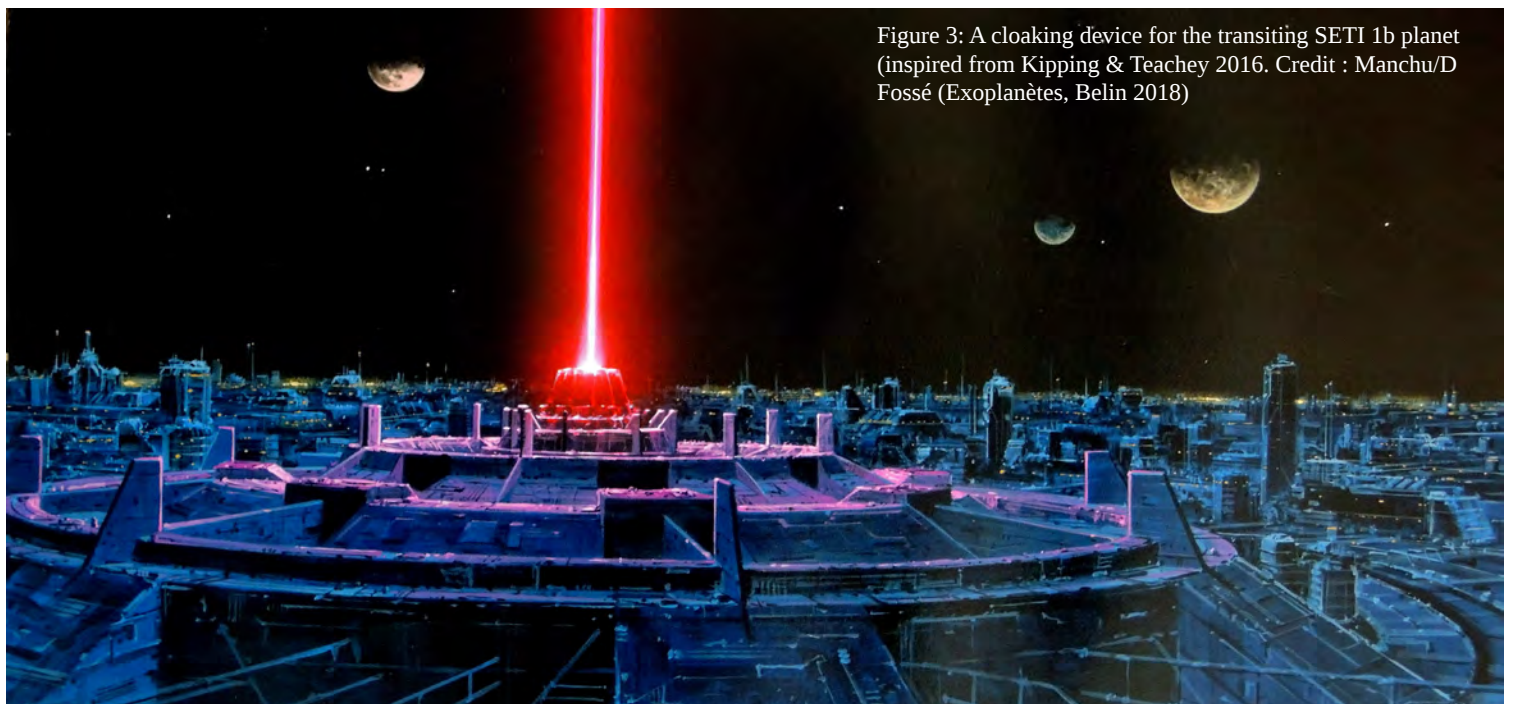


Figure 3: A cloaking device for the transiting SETI 1b planet (inspired from Kipping & Teachey 2016. Credit : Manchu/D Fossé (Exoplanètes, Belin 2018)

Pulsar Planet [PSR B1257+12]

The pulsar has a planetary system with three known extrasolar planets, named "Draugr" (PSR B1257+12 b or PSR B1257+12 A), "Poltergeist" (PSR B1257+12 c or PSR B1257+12 B) and "Phobetor" (PSR B1257+12 d or PSR B1257+12 C), respectively. They were both the first extrasolar planets and the first pulsar planets to be discovered; B and C in 1992 and A in 1994. PSR B1257+12, previously designated PSR 1257+12, alternatively designated PSR J1300+1240, also named Lich, is a pulsar located 2,300 light years from the Sun in the constellation of Virgo.

The X-ray output of the pulsar Lich feeds a very intense aurora borealis in much of the world's high (hypothetical) atmosphere.



Figure 4: Fluorescent minerals on a pulsar planet. Credit : Manchu/D Fossé (Exoplanètes, Belin 2018)

Final Words

Whether you are simply interested in Exoplanets or an astrophysics student, I highly recommend this book, which should be made available in the English language at least for a wider world audience. It will be well worth it.

About George J Frangou

George has more than thirty years in business and academia. He is a Physicist, Engineer, innovator, technological entrepreneur and founder of multiple companies based on original patented ideas. With 13 patents and peer-reviewed papers, George is the inventor of three distinct technologies Artificial Precognition for AI and robotics, Information Density Holography and Video Precognition. George holds a BSc in Astrophysics and a MSc in Wireless and Optical Communications from Queen Mary University of London (www.qmul.ac.uk). He has also done postgraduate work in Information Visualization at Imperial College London and in Industry and Business at the University of Warwick. His credentials include CEng, FIoD, FRSA. He is a fellow of the British Computer Society, with recognised eminence in machine learning.

Breakthrough Propulsion Physics: Leave the fuel tank at home

Dan Fries

Dan Fries looks at the more exotic end of current propulsion experiments. The Mach Effect thruster and the EM Drive have that quality of "by your bootstraps" technology. But researchers in Europe and the USA are very seriously involved in examining them and measuring thrusts which are tiny but potentially useful and may be scalable.

While more and more interest exists in utilizing resources outside of our planet's protecting atmosphere, one of the biggest problems remains unsolved: the efficient moving of large masses from Earth and in between stellar bodies. So far, we have relied mostly on Newton's third law in this endeavor, pushing mass out of the back of a rocket at high velocities to generate thrust and impart momentum onto an object in a vacuum. Unfortunately, the laws of physics put stringent limitations on such systems and we end up with spacecraft whose total mass is almost completely made up from stored propellant. For example, flying to the edge of the solar system from a low earth orbit using an ideal liquid hydrogen-liquid oxygen rocket, would require about 85% of the spacecraft mass to be propellant, thus making this approach highly impractical for the utilization and colonization of our entire solar system. While there is room for improvement with options such

as electrical propulsion, nuclear driven engines, photon rockets, and alternative fuels (including anti-matter), it is very likely that we will never bridge interstellar distances unless we come up with radically new propulsion concepts.

An alternative approach is presented by so-called propellantless propulsion concepts, where the idea is to produce thrust without expelling a reaction mass. Examples of such a concept based on well-established physics are some forms of beamed propulsion such as laser and microwave sails. However, beamed propulsion still requires some sort of array emitting the momentum carrying rays pushing the target spacecraft forward. Of course, this means that the propulsive capability decreases rapidly with distance from the array and the spacecraft is dependent on the array to be functioning and within reach. Two other concepts, based on more exotic and less well-understood

physical principles, that have been attracting a lot of attention recently are the Mach Effect as well the EMDrive Thruster. Both thrusters are operating on the principle of conversion of electricity into a directed force, capable of accelerating an object attached to the thruster. Such a thruster, if operational, would revolutionize the way we approach space travel. Nonetheless, preliminary results and the underlying working principles should be viewed with a healthy amount of skepticism. For many scientists, such a device violates known laws of physics, most prominently the conservation of energy and momentum. Moreover, independent repetition of the experiments is required to ascertain positive thrust measurements and working principles. In the light of this exciting progress and the need to involve a larger community of researchers, we should take a closer look at the Mach Effect and EMDrive Thrusters.

Mach Effect Thruster

The Mach Effect Thruster (MET) proposed by James Woodward (California State University Fullerton) uses Mach's principle to generate a force in an object that is undergoing mass-energy fluctuations [1]–[3]. The Mach principle states that the distribution of mass and energy in the rest of the universe, and their gravitational interaction with a body, determines the inertia of that body during acceleration. Thus, generating mass or energy fluctuations in a body would allow one to manipulate the inertia of that body. Both experimental evidence and theoretical explanation attempts have been presented for the MET. Woodward's theoretical work attempts to use the non-linear Hoyle-Narlikar theory, which describes gravitation in the framework of electromagnetic radiation reaction theory. A purely linear theory would fail to capture the seemingly instantaneous interaction of particles with the rest of the universe postulated by the Mach principle. The Hoyle-Narlikar theory is fully Machian and reduces to Einstein's theory of gravitation in the limit of matter density distributed as a smooth fluid. It allows for both retarded and advanced waves, the latter of which are a concept used to describe entanglement and instantaneous-like information exchange between particles in the universe (see also emitter and absorber theory in electrodynamics). The advanced waves, in fact, would still be travelling at the speed of light, c , but backwards in time.

The result is the so-called “Woodward mass fluctuation formula”,

$$\nabla^2 \phi = -\nabla \vec{g} = 4\pi G \rho + \left[-\frac{1}{m^2} \left(\frac{\partial m}{\partial t} \right)^2 + \frac{1}{m} \frac{\partial^2 m}{\partial t^2} \right]$$

where ϕ is the gravitational potential, and ρ is the stationary mass density. The first term on the right-hand side corresponds to the contribution to the gravitational field by the properties of a body at rest while the second term in square brackets corresponds to a time varying density or mass. Following the approach by Tajmar [1], integrating over the volume yields for the mass fluctuation term,

$$\Delta m_0 = -\frac{1}{4Gc^2 \rho_0} \frac{\partial P}{\partial t}$$

where $\partial P / \partial t$ is a time-varying power input into the body. Tajmar's derivation of this term uses the weak-field approximation to general relativity and Sciana's inertia model, arriving at the same general results as Woodward. The fact that a time varying power input might correspond to the

temporal variation of a body's mass also follows from the fact that energy content and mass are directly linked by Einstein's relation $E = mc^2$. Nonetheless, the effect predicted by Mach's principle is orders of magnitude larger than this relation suggests. This variation in mass finally results in a net force acting on the body, if the driving power is configured correctly.

In recent experiments, the time varying power input is realized using stacks of Piezo disks (PZT), as illustrated in Figure 1 and Figure 2. Applying a voltage to this stack results in an expansion of the stack, which can be translated into an acceleration and to first order -

$$\partial P / \partial t = \partial(Fv) / \partial t \approx m_0 a^2$$

- where a is the acceleration of the Piezo stack. The experimental results to date show thrust signals on the order of $2 \mu N$ for input powers around 200-300 W (~ 400 Vpp) and a driving frequency of ~ 39 kHz [2].

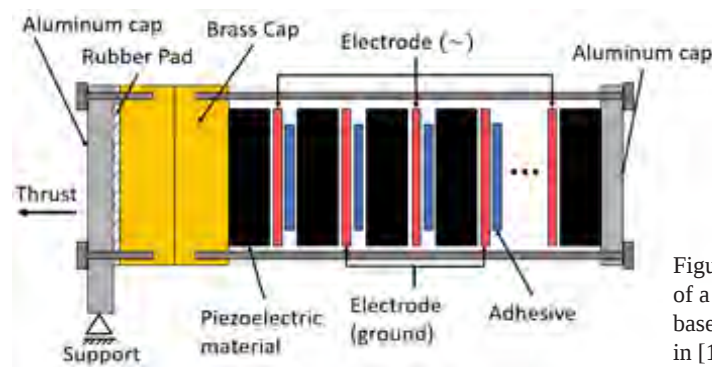


Figure 1: Schematic of a MET prototype, based on the sketch in [1].

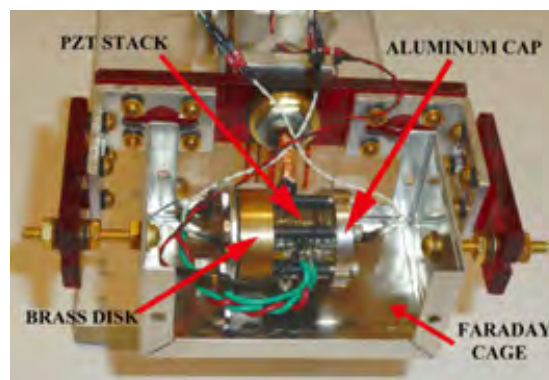


Figure 2: Photograph of a MET test article by Woodward's group Credit [2].

EmDrive

A radio frequency (RF) resonant cavity thruster, also called EmDrive, has been proposed as another concept of reaction mass-less propulsion. The concept was originally proposed by Roger Shawyer [4] and got more attention recently when Harold “Sonny” White (NASA Johnson Space Center) announced that his team had successfully completed the most sophisticated measurements to date, reporting net thrust produced by a working prototype [5]. The basic principle of the thruster has a magnetron feeding microwave energy into a tapered waveguide, as shown in Figure 3. The overall length of the waveguide, or cavity, is such that resonance occurs at the magnetron operating frequency. It is not clear which physical mechanism in this setup would result in a net thrust, but several explanations have been proposed. Shawyer’s explanation of the

working principle of the EmDrive is that the group velocity of the electromagnetic waves at the larger end section is higher than the group velocity at the smaller end section, resulting in a differential in radiation pressure and a net force. However, this was criticized as violating the laws of electromagnetism and conservation laws. Harold White has suggested the EmDrive could be an example of a quantum vacuum thruster. Such a thruster, also referred to as Q-thruster, would provide a reaction propulsive force extracting work from virtual particles originating in quantum vacuum fluctuations of the zero-point energy field (the latter being analogous to a pilot-wave). Arguments against this kind of explanation are again violations of conservation laws and the questionable existence of a “quantum vacuum virtual plasma” providing the reaction mass necessary for a net force.

Other proposed explanations include the “Modified Inertia Hubble-scale Casimir effect”, photon leakage, the Mach effect, and the warping of space-time. In their experimental work, White et al [5] report that “a dielectrically loaded, tapered RF test article excited in the transverse magnetic 212 (TM₂₁₂) mode ... at 1937 MHz is capable of consistently generating force at a thrust-to-power level of 1.2 ± 0.1 mN/kW with the force directed to the narrow end under vacuum conditions”. They used a copper frustum loaded with a disk of polyethylene as dielectric medium on the smaller end and measured a maximum forward thrust of $1.9 \pm 6 \mu\text{N}$ at an input power of 80 W using the setup in Figure 4. The corresponding maximum reverse thrust was $74 \pm 6 \mu\text{N}$, while the null-tests showed only the thermal signal and no impulsive element.

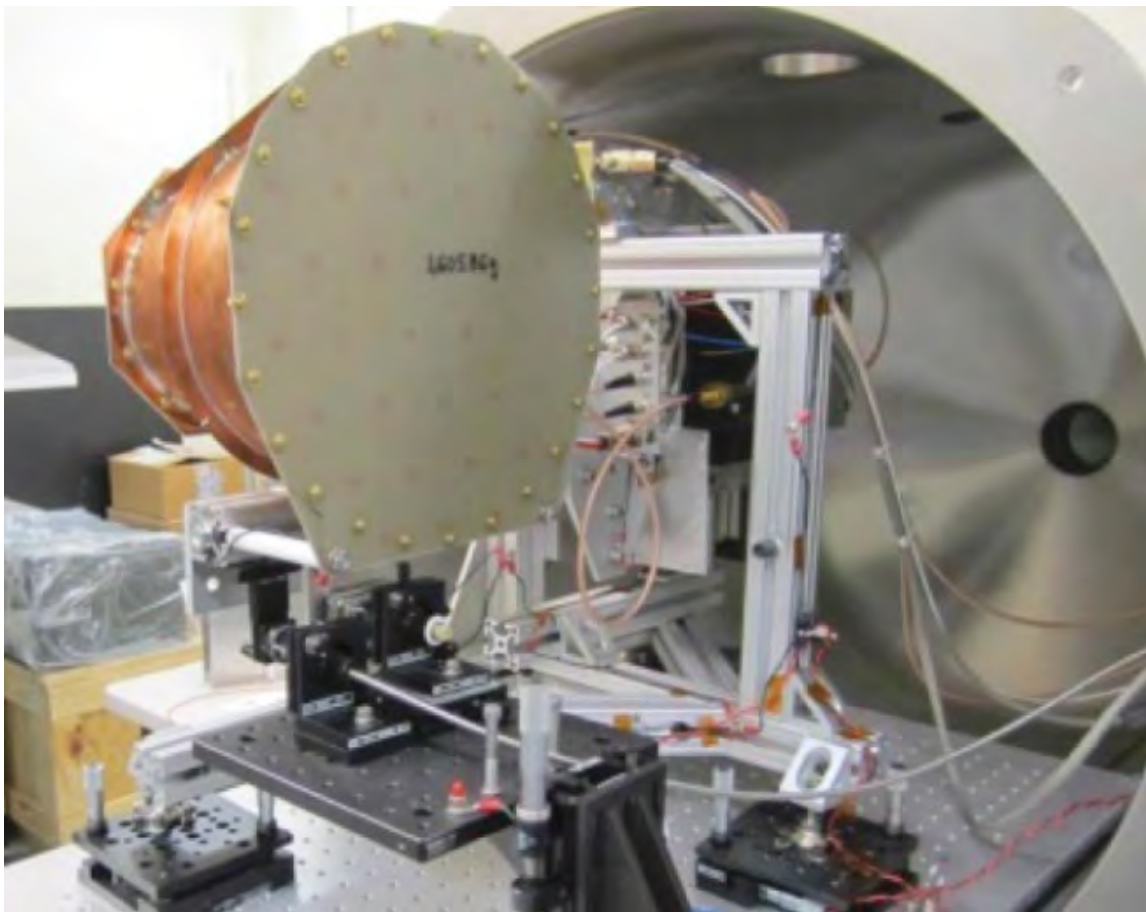


Figure 3: Prototype resonant cavity thruster built by NASA's Advanced Propulsion Physics Laboratory. Credit [5]

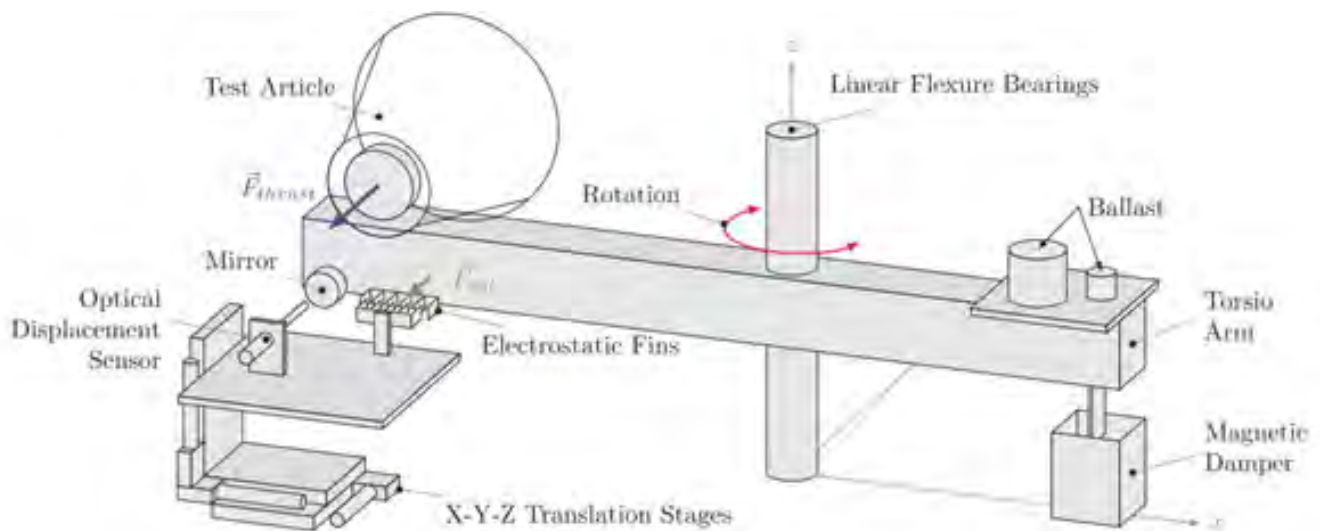


Figure 4: Simplified representation of the torsion pendulum setup used by White et al. Credit [5].

Testing the limits

Although some of the results surrounding the presented propellantless drives seem ground-breaking, measuring thrust in the μN range is extremely difficult and the methods are by no means free from controversy. One major factor is that experiments measuring such small forces are extremely sensitive and it is difficult to account for all possible sources of error. Factors possibly influencing measurements include, but are not limited to, the vacuum conditions, the occurrence of harmonic oscillations, electromagnetic interference, calibration method and reliability, external vibrations (traffic, seismic activity, oceans), thermal expansion, and outgassing. Thus, the dissemination of results and the report of experimental details is extremely important, to judge whether claims of new physical mechanisms to generate force are believable, or whether additional measurements and precautions are required. Moreover, independent testing of hypothesis and repetition of results is required to confirm hypothesis and measurements. Very recently, the research group around Martin Tajmar

at the Technical University of Dresden has published first results from their “SpaceDrive Project”. The project’s goal is to contribute to the development of breakthrough space propulsion systems. As a first development milestone, the research group is attempting to reproduce findings and further eliminate possible sources of error relating to both the EMDrive and the MET [6]. To get an idea of the effort going into the testing of the working principle of these thrusters one only has to look at the TU Dresden’s testing equipment. They use a torsion balance with sub micro-Newton resolution that has been continuously improved over four years of research. The displacement measurements are achieved optically, and the entire setup is placed into a vacuum chamber which is vibration isolated from its environment. The balance arm and thruster-electronics in the vacuum chamber are electromagnetically shielded, the position of the test article can be fine adjusted using stepper motors, and two different calibration techniques for the torsion balance are used. Finally, the experiment’s temperature is continuously monitored, liquid metal contacts are used to supply the entire setup with power and data signals, harmonic

oscillations are damped, and data acquisition is automated as much as possible. In addition, sophisticated test procedures are employed to ensure steady-state measurements and compensate for effects which could cause spurious thrust measurements.

To assess results reported for the EMDrive, the group at TU Dresden built a microwave cavity with the same inner dimensions as White et al [5] and theoretically similar thrust characteristics. Interestingly they found that the thrust they measured (about double of what was measured by White et al) was not produced by the microwave cavity but more likely by an interaction between the earth’s magnetic field and the current flowing to the device’s amplifier. Apparently, no experimental test to date has taken this interaction into account and shielding of the microwave cavity and amplifier is not reported anywhere. This finding necessitates reassessment of existing data, further modifications of the test setup, and additional measurements, as at these experimental scales the interaction is capable of completely masking any potential

thrust produced by the EMDrive. Testing a MET, the team behind the SpaceDrive Project used a thruster directly supplied by Woodward and Fearn (whose work was mentioned earlier in the article). During this series of measurements, the thruster was actually mounted inside an electromagnetically shielded box and shows the characteristics one would actually expect for a functioning propulsive device. That is, a thrust force of 0.6 μN (at 150 W of input power or 150 Vpp) which reverses its direction when the thruster is turned 90° and disappears when turned 180°, ie parallel to the torsion balance arm. Nonetheless, further testing of their equipment revealed some anomalous thrust measurements, indicating that some electromagnetic interaction or thermally induced expansion is still masking real thrust values which are expected to be much smaller. Thus, while the results are not final, they provide extremely important additional data points and pave the way to conclusive results and explanations.

Where does this leave us?

It is clear from the above that the laws of physics are not always straightforward in their interpretation, leaving room for the possibility to find previously unknown propulsion concepts that go beyond classical combustion-based rocket engines. The devices reviewed at this stage provide thrust to input power ratio of $\sim 0.02 - 1.2 \text{ mN/kW}$, as compared to 50 mN/kW in the case of an ion thruster. Thus, at this point the biggest advantage of the examined propellantless drives would clearly be the enormous mass savings. However, it has also become apparent that such breakthroughs do not come without a cost. It takes time and larger groups of people willing to derive and re-derive the governing scientific principles, to run and re-run the experiments and to evaluate and re-evaluate the results, until it is clear whether a proposed technique works and, more importantly, how it works. Only then can we hope to scale the technology up and to obtain the necessary means to do so. And that, we certainly want to do, if we hope to brave the sea of stars. Of course, the MET and EmDrive are not the only breakthrough space propulsion concepts being considered, however, reviewing each one of them in more detail would go beyond an article like this. The interested reader could look into Space-Time-Engineering (Warp drive), anti-matter catalyzed fusion propulsion, and photon rockets.

References

- [1] M. Tajmar, "Mach-Effect thruster model," *Acta Astronaut.*, vol. 141, no. September, pp. 8–16, 2017.
- [2] H. Fearn, A. Zachar, K. Wanser, and J. Woodward, "Theory of a Mach Effect Thruster I," *J. Mod. Phys.*, vol. 06, no. 11, pp. 1510–1525, 2015.
- [3] H. Fearn and J. F. Woodward, "Experimental Null Test of a Mach Effect Thruster," *J. Sp. Explor.*, vol. 2, no. 2, 2013.
- [4] R. Shawyer, "A Theory of Microwave Propulsion for Spacecraft," 2006.
- [5] H. White et al., "Measurement of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum," *J. Propuls. Power*, vol. 33, no. 4, pp. 830–841, 2017.
- [6] M. Tajmar, M. Kößling, M. Weikert, and M. Monette, "The SpaceDrive Project - First Results on EMDrive and Mach-Effect Thrusters," *Sp. Propuls. Conf.*, no. May, 2018.

About Dan Fries

Dan is performing experimental research on combustion in incompressible and compressible turbulence for a PhD at Georgia Tech (www.gatech.edu). He has a degree in Aerospace Engineering from the University of Stuttgart and is interested in all things space exploration and propulsion. Within i4is, he is a member of the i4is Technical Committee and leads our work on Project Glowworm.

News Feature

Wormholes, Energy Conditions and Time Machines

- at Marcel Grossmann: the third time
Remo Garattini

i4is Senior Researcher Remo Garattini is a regular attendee at the annual Marcel Grossmann conferences on General Relativity (GR) and gravitation. He reports here on how this area of research is leading to some startling conclusions about areas of physics hitherto regarded as at the edge of known science.

The Marcel Grossmann conference has now reached its 15th edition, MG15, in Rome. For those of you who are not familiar with this meeting, I have to say that this is the biggest and most famous conference about General Relativity (GR) and gravitation in the world. One particular aspect connected with GR is the subject of interstellar flight. I have long been interested in this area (Editor's note: For example see Remo's guest introduction in Principium Issue 9 May 2015). At the Marcel Grossmann conference (MG) this argument has not been discussed in the sense that an i4is member could contribute, but....almost! Indeed, at MG15, for the third time MG hosted a special parallel session dedicated to "Wormholes, Energy Conditions and Time Machines".

As far as I know, the first time that the subject of wormholes was proposed was in 2006 at the Berlin MG12 and the chairman was Mark Hadley. In Berlin I presented for the first time my idea of "Self-Sustained Traversable Wormholes", namely a wormhole which can exist using its own quantum fluctuations forming a Zero Point Energy (ZPE). In Berlin I had the opportunity to meet Francisco Lobo with whom a collaboration began and at MG14 and the recent MG15 in Rome, it was Francisco Lobo who organized the parallel session on Traversable Wormholes. At MG14, we had the honour to have Matt Visser and Sergey Sushkov as speakers: the former gave a talk about Buchert averaging and energy conditions, while the latter gave a talk about

Marcel Grossmann Meetings on general relativity

www.icra.it/mg/mg15/

Since 1975, the Marcel Grossmann Meetings (on Recent Developments in Theoretical and Experimental General Relativity, Gravitation, and Relativistic Field Theories) have been organized in order to provide opportunities for discussing recent advances in gravitation, general relativity and relativistic field theories, emphasizing mathematical foundations, physical predictions and experimental tests. The MG meetings were founded in 1975 by Remo Ruffini and Abdus Salam with the aim of reviewing developments in gravitation and general relativity with major emphasis on mathematical foundations and physical predictions.

See also - en.wikipedia.org/wiki/Marcel_Grossmann

Exact Wormhole Solutions with Nonminimal Kinetic Coupling. I should also mention the presence of another active scientist in this subject area: Jutta Kunz who gave a talk about Properties of Rotating wormholes at MG14, while at MG15, she gave a talk about Wormholes Immersed in Rotating Matter. Last but not least, I have also to point out that at MG15, we had another honour: Kirill Bronnikov was with us and he gave a talk about Dynamic wormholes from nonlinear electrodynamics. For those of you who are not familiar with this author, Kirill Bronnikov is one of the pioneers of traversable wormholes, with Homer Ellis. Indeed, the simplest traversable wormhole proposal appeared in the famous paper written in 1987 by Michael S Morris and Kip S Thorne, entitled “Wormholes in spacetime and their use for interstellar travel: a tool for teaching general relativity” published in the American Journal

of Physics - also known as the Ellis-Bronnikov wormhole. At MG14 Francisco Lobo had the initiative to invite all the speakers in the parallel session to produce a book published by Springer entitled “Wormholes, Energy Conditions and Time Machines”. This is the most recent collection of papers about traversable wormholes and all the related arguments. In this book, in the Warp Drive chapter, there also is a contribution from Miguel Alcubierre written with Francisco entitled Warp Drive Basics. In 2012 and 2015, in Turin, two conferences on similar subjects were held. The conference title, in both years, was “The Time Machine Factory”. Of course, even in these two conferences, the traversable wormhole issue has been considered. With this list of contributions and conferences, it seems that all I am saying is nothing but pure advertising. In a sense it is, but as I wrote in Principium Issue 9, the subject

of traversable wormholes and therefore interstellar flight cannot be considered “Science Fiction” anymore: it is SCIENCE, in the strict sense of the word. To convince ourselves about this, it is sufficient to do a query using the term Wormhole in - inspirehep.net. The result is 1561 records - from 1960 to today (July 2018). If we refine the query to the term Traversable Wormhole, the result reduces to only 151 records. The reason is simple: the term wormhole includes everything: Euclidean wormholes, foamy wormholes, etc, while the term traversable wormhole is specific to the Morris-Thorne wormhole. To conclude, the research subject of traversable wormholes, warp drive, etc, has had and has now a large impact on the scientific community. This means that the “future civilization” invoked by Carl Sagan in the novel “Contact” is approaching.



About Remo Garattini

Remo completed his first degree in Theoretical Physics at the University of Milan and later completed his PhD at the Mons-Hainaut University in Belgium with a thesis on Space Time Foam with Professor P Spindel and R Brout as supervisors. He has a permanent research position at the University of Bergamo, Faculty of Engineering. His research activities are in Quantum Gravity and Quantum Cosmology (Inflation, Dark Energy, Space Time Foam) and the Casimir effect. He is editor in chief for Astrophysics and Cosmology of the MDPI Journal “Entropy” (www.mdpi.com/journal/entropy) and Guest Editor for Galaxies and Quantum Reports of MDPI - which delivers scholarly open access publishing (www.mdpi.com/about). In April 2017, Remo was qualified by the Italian Abilitazione Scientifica Nazionale (ASN - rio.jrc.ec.europa.eu/en/library/national-scientific-qualification-asn) to be Associate and Full Professor in Theoretical Physics.

How far have we come?

Terry Regan

Terry Regan, modelmaker and practical engineer, muses on the long life of his grandmother, Florence Hammond (1896-1982). Prompted by looking at some pictures of her in her youth, he notes that she was around from before the dawn of powered flight until well into the space age.

Terry Regan recalls his grandmother's saying "you'll sooner do that as fly to the moon". Being born before the Wright Brothers flew and living till after Apollo 11 (50 years ago next July) she in fact saw it happen. Here's her time-line and some pictures.

Florence Hammond - Born December 17th 1896



Right to left: Florence Hammond (Aged 4), Reginald Hammond, Essie Hammond.

Aged 4, Ferdinand von Zeppelin first flies a Zeppelin Dirigible 02/07/1900.

Aged 7, The Wright Brothers first flight 17/12/1903.

Florence Hammond aged 16, 3rd from the left (the serious one).



Aged 14, World's first jet propelled aircraft.

Aged 22, First Atlantic flight.

Aged 30, 1926 John Logie Baird demonstrates Television.

Aged 31, John Logie Baird transmits a Television signal from London to Glasgow.

Aged 41, Hindenburg disaster.

Aged 43, Igor Sikorsky flies a helicopter.

Aged 50, V2 rocket blows the roof off her house 55 Hazelmere Gardens.

Aged 53, The sound barrier is broken.

Aged 63, Russia launches first Earth satellite, Sputnik.

Aged 65, First man in space, Yuri Gagarin.

Aged 73, Apollo 11 Moon Landings, Flossie never uses the phrase "you'll sooner do that as fly to the moon" ever again.

Aged 80, Concorde flies supersonic.

Aged 86, Flossie dies having been born before the Wright brothers flew and watched the first man to set foot on the moon live on TV.



Florence Hammond aged about 19.

NEXT ISSUE

Engineering of new worlds - goals, motives and results

Nomadic Planets and Interstellar Exploration

An Idiot's guide to Project Daedalus

Report on the October IAC conference

**We'd love to hear your thoughts on Principium,
the Initiative or interstellar flight in general.**

**Email - info@i4is.org - or come along to
Facebook(InterstellarInstitute),
Twitter (@I4Interstellar) or
LinkedIn to join in the conversation.**

Michel Lamontagne and Our Front Cover Image

Our front cover image this time was created by Michel Lamontagne. Michel is one of the two principal developers, with Robert Freeland, of the Firefly design for Project Icarus. Michel is a French Canadian living near Montreal. He works as a mechanical engineer, mainly in building systems: plumbing and HVAC. He's been a member of Icarus Interstellar for five years, mostly working on the report for the Icarus project, of which the Firefly study will be a major part.

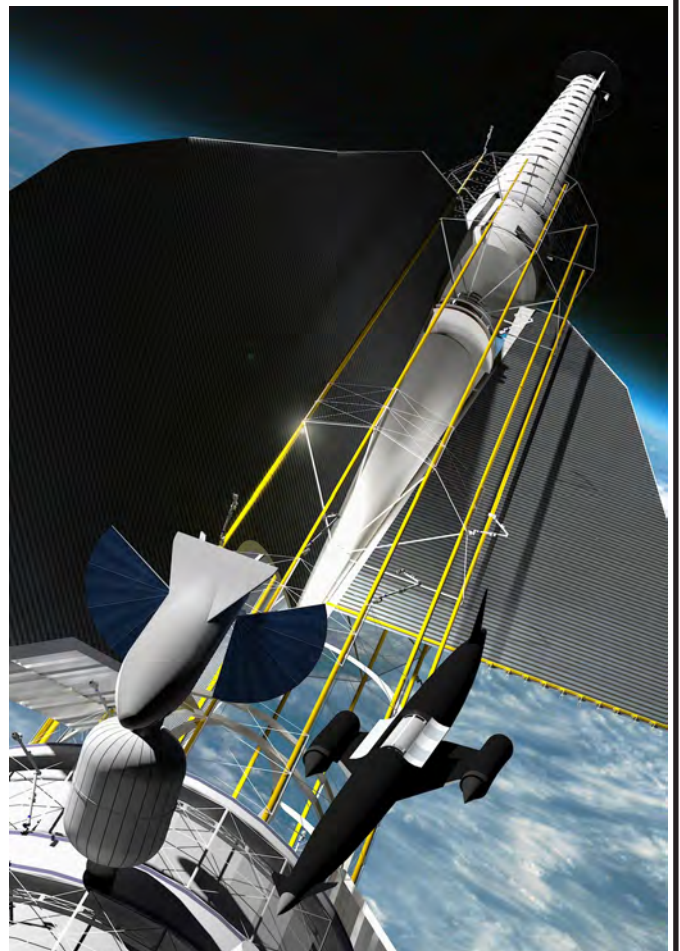
The image shows the Firefly Interstellar probe being assembled in low Earth orbit. In the lower left you see part of a large habitat, with two contra-rotating modules for crew, workers and visitors.

There is a Skylon SSTO vehicle (Reaction Engines) coming in to dock, and a BFR (SpaceX) with extended solar panels docked to a Bigelow inflatable habitat module. The yellow elements are structural beams, also serving to anchor enclosures where building work is going on. A number of spiderfabs (Tethers Unlimited) are working on one of the radiators. The payload and fuel extend to the top right. The ship is practically finished, and will soon be towed out to a lunar orbit for fueling and launch.

The image was done using Sketchup 2018 for the modeling and Twilight Render V2 for the photorealistic rendering. A bit of post processing was done on Photoshop Elements 14. The background Earth is a stock photo from NASA.

As you will see, Michel is an artist as well as an engineer. He mostly did comics in his earlier years; you can find example of this earlier work (up till 2014) on the web site: sites.google.com/site/bdespace/Home - use the side menu for most images.

His more recent work is on Deviant Art: www.deviantart.com/michel-lamontagne/gallery/



Mission

The mission of the Initiative for Interstellar Studies is to foster and promote education, knowledge and technical capabilities which lead to designs, technologies or enterprise that will enable the construction and launch of interstellar spacecraft.

Vision

We aspire towards an optimistic future for humans on Earth and in space. Our bold vision is to be an organisation that is central to catalysing the conditions in society over the next century to enable robotic and human exploration of the frontier beyond our Solar System and to other stars, as part of a long-term enduring strategy and towards a sustainable space-based economy.

Values

To demonstrate inspiring leadership and ethical governance, to initiate visionary and bold programmes co-operating with partners inclusively, to be objective in our assessments yet keeping an open mind to alternative solutions, acting with honesty, integrity and scientific rigour.

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*The Initiative for Interstellar Studies is a pending institute, established in the UK in 2012 and incorporated in 2014 as a not-for-profit company limited by guarantee.
The Institute for Interstellar Studies was incorporated in 2014 as a non-profit corporation in the State of Tennessee, USA.*



**Scientia ad Sidera
Knowledge to the Stars**

*Front cover: Firefly Icarus starship final assembly in low earth orbit, Credit Michel Lamontagne. More details inside rear cover.
Back cover: Gaia's sky in colour - our Milky Way Galaxy and neighbouring galaxies. Measurements of nearly 1.7 billion stars from second Gaia data release, April 2018. Credit: ESA/Gaia/DPAC.*