PRINCIPIUM

The Newsletter of the Initiative for Interstellar Studies
Issue 16 | February 2017

ISSN 2397-9127

www.i4is.org

Scientia ad sidera
Knowledge to the stars

Editorial

Welcome to Principium 16, the quarterly newsletter about all things interstellar.

First, we welcome a new deputy editor, Patrick Mahon, who will be taking some of the load off the shoulders of both editor and Kelvin Long.

For our Guest Introduction this time we bring back our Executive Director, Kelvin F Long. Kelvin reflects on the most momentous project start of 2016, Breakthrough Starshot. He considers its significance both in the next few years and for the long-term future of interstellar exploration.

Interstellar News reports on our new, and very near future, Project Glowworm. We announce the new i4is website and upcoming membership scheme and report Kelvin's visit to NASA, Houston. We will be at the UK Space Conference in May-June 2017 and we are organising an Interstellar flight workshop in New York in June as we develop our Institute for Interstellar Studies, USA. We will also be addressing the Royal Astronomical Society and delivering another two week elective at the ISU, Strasbourg. And we celebrate another successful Starship Engineer course. More in the News section.

Given the announcement of the 2017 session we have held over further accounts of the May 2016 i4is/ISU course Interstellar Studies. We'll be reporting soon from this renewal of a major part of our work with the International Space University.

As promised last time we have a report from the Interstellar Challenge for London Schools 2016 and outline our plans for taking it to other parts of the UK, Europe and the world. We also report from our 2016 Starship Engineer course at the BIS in November.

There have been two major interstellar-themed films in the last few months, Arrival and Passengers. Arrival contemplates human (at times very human) reaction to the arrival of inscrutable aliens at multiple locations on Earth. Emotional, institutional and international reactions are all dealt with. Patrick Mahon contributes a suitably thoughtful review.

Passengers is both a larger and a smaller film than Arrival. It looks magnificent and its theme is nothing less than the first serious attempt to show how our species might migrate to the stars. But it is flawed both structurally and technically. John Davies, with input from i4is colleagues, contemplates a brave effort to "boldly go" to a new realism in this subject.

Our good friend, Professor Rachel Armstrong, has a new book, *Star Ark : A Living Self-Sustaining Spaceship*. This is an important book about sustainability on Earth as reflected in the proposition of a self-sustaining starship, containing both Rachel's own long-matured thinking and a series of contributions she has commissioned from architects, sociologists, designers, engineers, biologists, chemists, biochemists and artists. Kelvin Long reviews it in this issue of Principium, setting it in the context of pioneers as diverse as Richard Buckminster Fuller and Rachel Carson.

Stephen Ashworth has written our first Letter to the Editor. He expresses some reservations about the current movement to laser-push as the preferred first step to interstellar travel. Stephen is a critical friend of interstellar endeavours. I hope this letter to Principium is the first of many from Stephen and others. Constructive criticism is always welcome.

Alongside our elective contribution to the ISU Masters Degree, i4is experts also advise students on their projects. We describe this work with a particular focus on the achievements of the 2015-2016 year.

We celebrate the work of a new artist helping us to visualise our interstellar dreams. Efflam Mercier has contributed to a paper soon to be published by Andreas Hein, *Artificial Intelligence Probes for Interstellar Exploration and Colonization*. A selection of Efflam's images inspired by Andreas' vision are in a picture feature in this issue. And one of them provides our front cover this time.

Our rear cover is a magnificent starry panorama taken at the European Southern Observatory (ESO).

Comments on i4is and all matters interstellar are always welcome. Write to me!
John I Davies, Editor, Principium
john.davies@i4is.org

Keep in touch!

Join in the conversation by following the i4is on our Facebook page www.facebook.com/InterstellarInstitute

Become part of our professional network on LinkedIn www.linkedin.com/groups/4640147

And take a look at the i4is blog, The Starship Log www.i4is.org/the-starship-log

Follow us on Twitter at @I4Interstellar

And seek out our followers too!

Contact us on email via info@i4is.org.

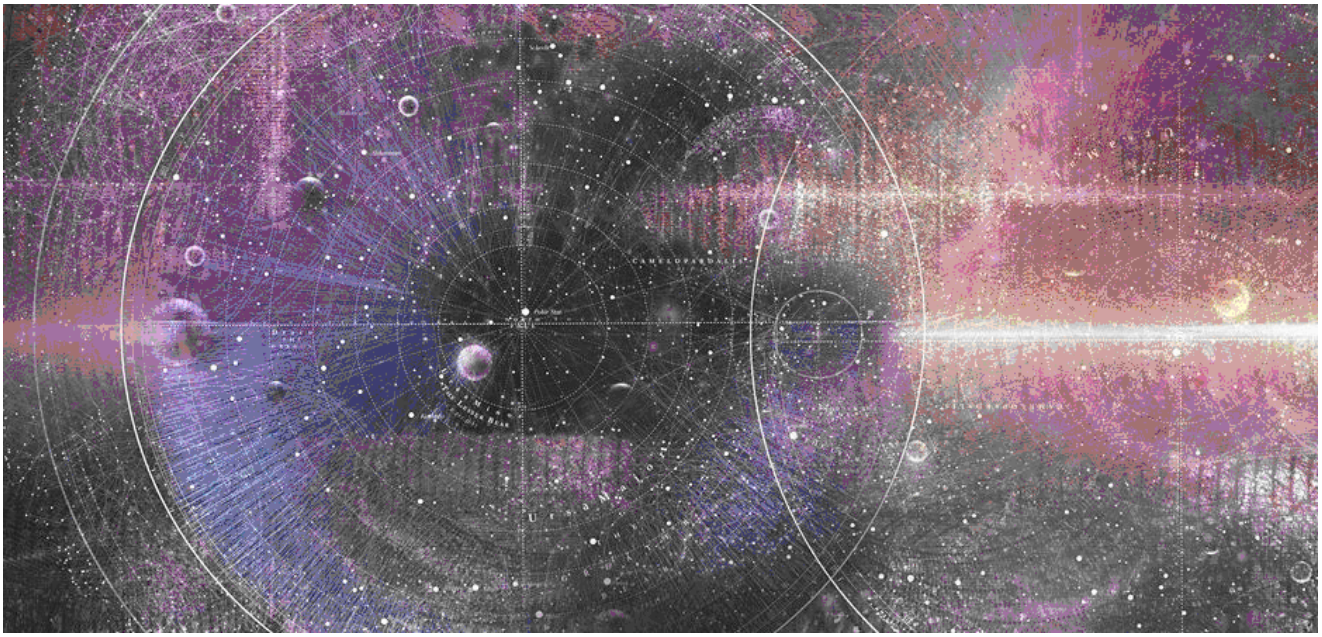
Back issues of Principium, from number one, can be found at www.i4is.org/Principium

The views of our writers are their own. We aim for sound science but not editorial orthodoxy.

AD ASTRA PROJECT STARSHOT

Kelvin F Long

INTRODUCTION - Kelvin F Long



In this article, the Executive Director of the Initiative for Interstellar Studies gives his personal perspective on the Breakthrough Initiative Project Starshot. Kelvin also serves on the Starshot Advisory Committee.

As we seek to send our voyagers to those incandescent lights in the night sky as a plethora of diamond sparkles, it is worth reflecting on our philosophical approach to the exploration of space. There are two ways to accomplish things in space flight. The first is to build only on what we have accomplished to date and to set all programmatic goals based on an extrapolation of existing achievements. Because this is an incremental method, I shall call this the 'ad astra incrementis' (to the stars incrementally) approach to space exploration. The second approach is to declare a stretch goal, accepting that there are many unknowns along the way and that there is no full certainty of success. Because this is a direct path method, I shall call this the 'ad astra' (to the stars) approach to space exploration. One is a conservative and low risk philosophy, and the other is a high risk but potentially high gain philosophy, in that it jumps you forward towards a big vision. In fact, I would go so far as to say that one is past-oriented and the other is future-oriented. In the early 1960s President Kennedy also used an 'ad astra' approach by declaring that:

"We choose to go to the Moon!...We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win…"

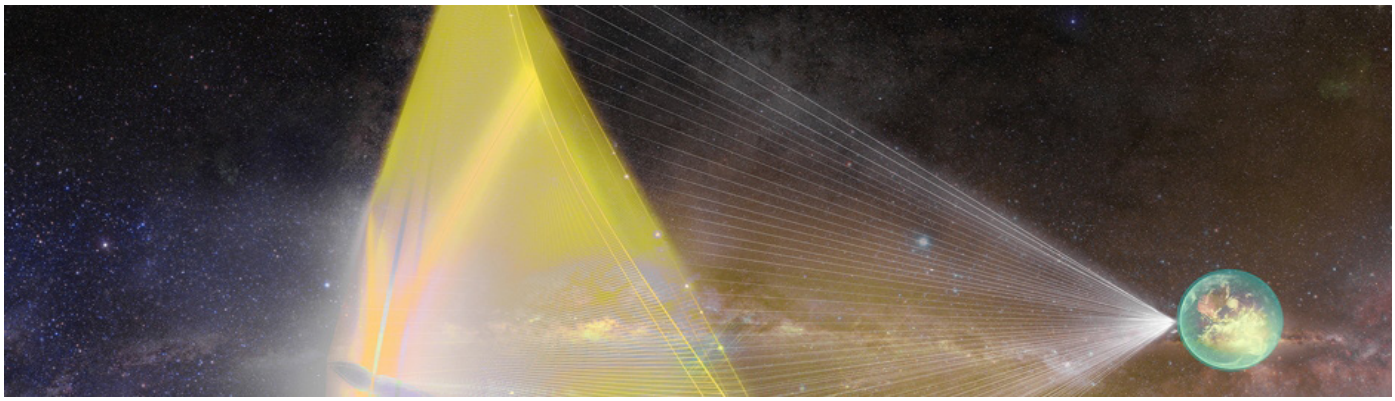
I was not born when that speech was made, but I encountered it for the first time in 1989 during a visit to a museum exhibition to celebrate the 20th anniversary of the Project Apollo moon landings. For me, a young man still in school, my exposure to that vision was life changing and a personal epiphany. There was something intoxicating about the optimism of it, and I knew from this moment that America was a special country, where people can dream of travelling to the Moon…and then they go there. That experience is incredibly empowering and years later, after a long period of self-discovery and education, I made it my mission in life to contribute similarly to the next big challenge of humankind, travelling to those distant stars that adorn the Cosmos, like camp-fires in the night, constantly taunting us to go and see what is there.

Over the years, I have been a part of creating many space projects and indeed space companies, in both the United Kingdom and the United States. All of these had some interstellar focus where appropriate, and like a bowman with his arrow, I was trying to point the way towards an optimistic future where humanity can perfect itself as it embarks on one of the greatest journeys since the migration out of Africa all those many hundreds of thousands of years ago. My hope was that, one day, someone with the resources and capacity to make interstellar flight a reality would notice all those efforts across the world and thus say *okay, we choose to go to the stars, not because it is easy, but because it is hard*. That day happened on the 12th April 2016 and I am immensely proud to be a part of such an inspirational endeavour that promises a new era of hope.

The Initiative for Interstellar Studies had already been collaborating with some of the Breakthrough Starshot leadership team in early 2016, since we gave some input on what was possible technologically, and some of the output from this was discussed in Principium issue 15 under the project name Andromeda and our existing laser-sail effort Project Dragonfly. But it all became real when the Russian entrepreneur and physicist Yuri Milner backed the possibility of an interstellar flight with the launch of Project Starshot. He was joined in this initiative by the American entrepreneur Mark Zuckerberg (founder of Facebook, the most successful online social network) and the British physicist Stephen Hawking (black holes, Hawking radiation and cosmology). These three people constitute the Board of the Breakthrough Initiatives. Leading the project is the Executive Director Pete Worden, former Director of NASA Ames Research Center, a retired US Air Force Brigadier General, and the recipient of the NASA Outstanding Leadership Medal for the 1994 Clementine mission to the Moon. Heading the Advisory Committee is Professor Avi Loeb, Frank B Baird Jr. Professor of Science at Harvard University. These people join this endeavour, because they are not only inspired by the vision, but also because they believe it is possible in theory. I have had the honour of meeting them and all of them are inspirational in their dedication to the goal. Placing themselves at the forefront of the wave of human expansion into the Cosmos – they are leading the charge independent of what national government space agencies are doing and by this they are showing exemplary leadership.

To understand the challenge ahead, let us deconstruct what the Project Starshot has to achieve.

Yuri Milner and Stephen Hawking at the Breakthrough Starshot announcement, April 2016.



The project aims to send a gram-scale probe (a StarChip) to the nearest stars in 20 years (at 20% of the speed of light, c) and return data from the local exoplanets to Earth. Due to the recent announcement of an Earth-mass exoplanet around Proxima b, we can assume that for now this is the likely first target and it is at a distance of 4.2 light years. This is a distance of 397 trillion ($\times 10^{12}$) km or 267,000 Astronomical Units, where 1 AU is the mean distance between the Sun and Earth. The fastest deep space probes to date are the Voyager probes, which are travelling at around 17 km/s or 3.5 AU/year. To reach the distance of Proxima b in only 20 years would require a speed of around 13,350 AU/year or 63,330 km/s (>20% c) which is approximately 4 orders of magnitude faster. A larger velocity also means more energy and therefore more power.

The propulsion architecture chosen for this mission is a laser sail. The equations for laser-beam propulsion power are well understood and are a function of the system mass, sail reflectivity and the rate of acceleration. The Starshot acceleration period is about 10 minutes, which implies an acceleration of 10,000 g. If we assume a perfectly reflective sail material, to accelerate a 1 gram payload up to 20% c requires a power of at least 15 GW. Breakthrough Starshot plans to use a 50-100 GW beam, although the beamer is to be ground based, to avoid the necessity to build up large space-based infrastructure and thus an inevitable programme delay before a first launch was possible.

There have been several historical proposals for the use of laser-sail beaming in the literature. One of the first advocates of this technology was the American physicist Robert Forward. In a paper published in the late 1970s (which was also presented to the US Congress), he argued that such a mission was possible by the year 2000. In the 1980s he published a series of papers exploring laser-sail interstellar missions and he called his concept 'Starwisp'. But the problem was that his calculations showed that such a mission would require very large architecture. His calculations for a 1,000 ton vehicle using a 3.6 km sail diameter required a 1,000 km diameter (560,000 tons) Fresnel lens in order to keep the laser beam collimated for long enough to ensure the required pressure and thrust profile on the sail. His payload would reach a velocity of 34,000 km/s or 11% of the speed of light, after being accelerated at 0.36 m/s² for 3 years. The probe would cruise to the nearby stars in 37 years. The mission would require a power of around 65 TW and this was for a flyby mission (no stopping).

The NASA physicist Geoffrey Landis has done further research which built on the earlier work by Forward and adopted similar architectures. In particular, Landis came up with mission scenarios for sending probes into the Kuiper belt (~100 AU), the Oort Cloud (~10,000 AU) and for interstellar flybys. For these three mission scenarios, Landis aimed for cruise velocities of 100 km/s, 3,000 km/s and 30,000 km/s (10% c) respectively, which would require powers in the GW range.

So like other interstellar propulsion architectures, laser-sails looked very challenging. All of this also means that lots of money would be required to fund such missions and the best estimates at the time would likely put the cost in the trillions of dollars.

Yet Robert Forward had a perspective on this too:

"Travel to the stars will be difficult and expensive. It will take decades of time, GW of power, kg of mass-energy and trillions of dollars….interstellar travel will always be difficult and expensive, but it can no longer be considered impossible".

There are three fundamental problems with all previous mission architectures using laser-sail based systems. These are:

1. Necessity for large space-based infrastructure. This not only pushes out the lead time over many decades, but it also requires low cost access to Low Earth Orbit (LEO), which is only just emerging within the space commercialisation industry with

goals to reduce the cost down as low as $1,000/kg.
2. Excessive power requirements through a single beamer and associated energy source, from the Sun for example, and how that is engineered.
3. Long duration beaming times, of the order of years.

All of the above implies large costs too. This is all on top of the high materials technology requirements such as the need for highly reflective but low absorption materials.

There are many things that distinguish the approach of the Breakthrough Starshot project. But I want to cite four key issues for attention:

1. Placing the beamer on the ground, and not relying on collimation lenses. We have much experience of large ground based observatories, and this includes laser telescopes. This also avoids the need for large space-based architectures as a prerequisite for first launch.
2. Adopting a phased array power beaming system. This is made possible by progress in laser-optics over the last few decades and the adoption of phase locking techniques to combine an array of lasers into a single focussed beam.
3. Moving to low mass payloads, which means that rapid accelerations are achievable in minutes. These low mass payloads are made possible by the astonishing progress in micro-electronics and the advances in materials sciences and nanotechnology.
4. Existing trends in critical technology which predict a continued rise in laser power and a continued decrease in the laser cost ($/W) which makes a Starshot mission affordable 20 years from now. Interplanetary and interstellar mission scenarios will be in the $billions to $10s billions cost range, instead of the $trillions predicted under previous mission architectures.

Nobody is claiming that the goal that Project Starshot has set itself will be easy to achieve. For sure, the programme of work contains many difficult technical physics and engineering challenges. Indeed the public announcement of the project was accompanied by a list of 19 challenges that the Breakthrough Initiative team would like the world's scientists to contribute towards solving.

To mention a few of them, they include -

- Surviving the journey given the presence of interstellar ions and dust in space.
- Giving sufficient pressure to the sail to propel it to the required velocity whilst not vaporising the sail material when the laser beam couples its energy to the surface.
- Maintaining pointing accuracy of the beam towards its target destination during the boost phase.
- Controlling any 'jitter' of the probe from the laser beam which could result in large deviations in final destination.
- Packing sufficient micro-electronics on the StarChip to facilitate any science goals and local command and control systems.
- Manufacturing sail materials with the appropriate material properties.
- The problem of sending information back, including images, over many light years distance, via radio or laser communication systems.

All of these are technically hard science problems, but they are also tractable with some effort. In general, we have a good grasp of the physics and mathematics, but it is the engineering that needs further work. Much of this was discussed by one of the Project Starshot leading scientists, Professor Philip Lubin in his paper for the Journal of the British Interplanetary Society *Directed Energy for Relativistic Propulsion and Interstellar Communication*s, P. Lubin et al. (2015), JBIS, 68, pp.172-182.

As a final note, I want to also say a few words on what I think is the true future of laser-sail propulsion. This is a space-based system as originally envisaged by Robert Forward. I advocate this eventual architecture, as part of a longer term goal, for the following reasons.

Firstly, a space-based beaming platform can also be used for powering satellites, space stations, large mass vehicles for solar system travel and even lunar/Earth based power grids.

Second, in order to propel human missions to the stars, the mass of the payload will go up significantly from that adopted by the Starshot project, and is likely to be in the region of millions of Mtons to Gtons. This also means that the power requirements will grow proportionally with the mass. It is not practical to propel such large vessels to the stars using only a 50-100 GW based ground beamer.

We could increase the ground beamer footprint size of course, to increase beam powers, but at some point you reach a limit of diminishing returns where the performance, lead time and cost becomes comparable to a space based approach. A space based architecture is simply more scalable in terms of mission utilisation.

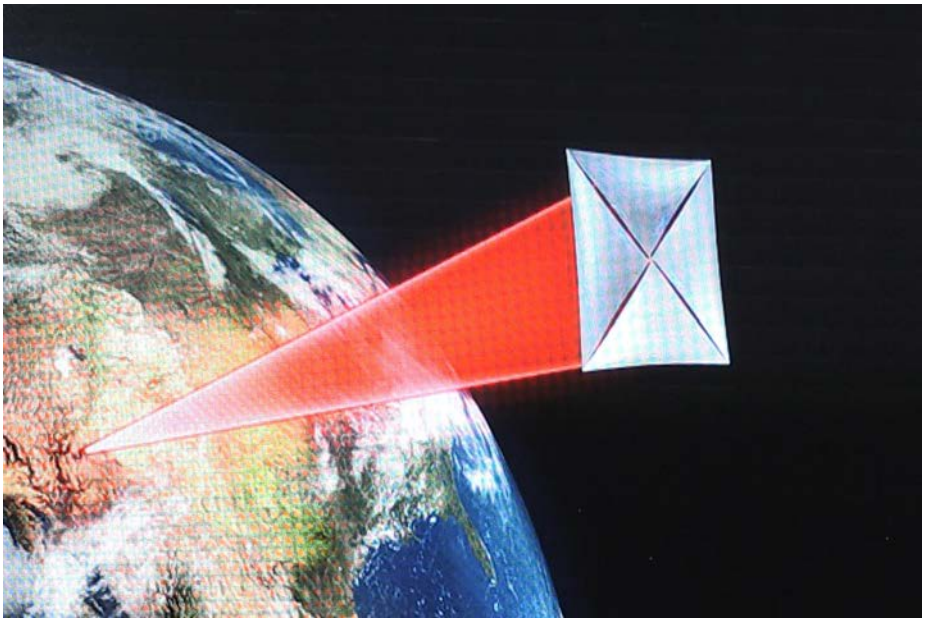
However, the architecture adopted for Project Starshot does get us

to a potential mission in theory much sooner and it will also demonstrate that it is possible and open up a new era in how space travel is conducted. The architecture could also be used for interplanetary propulsion, such as sending vital kg-like payloads to the planets (perhaps medicines for the future Elon Musk Mars colony).

Lots of good will come from Project Starshot. This includes public engagement and inspiration, educational opportunities, fundamental research and development, new scientific breakthroughs, technological advancement and innovations, and perhaps even new discoveries about our universe which have profound implications for world views. When Starshot succeeds it will be the furthest object human beings have ever placed into space, and so represent direct in-situ reconnaissance of those interstellar worlds to complement the superb achievements of the long distance observatory platforms. It will also assist in calibrating our measurements (ie astrometry) and theories of physics (eg the nature of dark matter and dark energy).

Once the capability is in place, we don't have to just send one of these probes, we can send many, and to many different destinations. In astronomical terms, the entire local interstellar neighbourhood will become accessible to our direct measurements and so, therefore, will our understanding of the Universe.

The thing that excites me most however, is that Starshot



forces us to look outwards as part of a transformation in our understanding of our position. To see a universe bigger than ourselves, to see the human journey in the context of the whole, and to reduce our imagined self-importance on a grander stage, and perhaps in awe at what we may discover. Just like Carl Sagan's "Pale Blue Dot" taken by the Voyager 1 spacecraft, the Starshot spacecraft will bring us the perspective of a "bright yellow dot" as it looks back on our Solar System many light years away. As long as we are looking upwards and onwards, our species has hope, that tomorrow will be better than yesterday, and our courageous efforts towards the stars are worth this effort. When Project Starshot was announced on 12th April 2016, it was serendipitous that it was at the One World Observatory in New York. Right now, the Breakthrough Initiative Project Starshot represents the leading candidate for a beacon of hope for humankind, to work on a project as one world, and with good will in our hearts, as we move towards a new epoch in the exploration of outer space.

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Images

All images are credit Breakthrough Starshot.

About the Author

Kelvin F Long, BSc, MSc, FBIS CPhys, is Executive Director and co-founder of the Initiative for Interstellar Studies. He is a world authority on the problems - and some of the possible solutions - to the challenge of interstellar travel and a passionate advocate of both the necessity and possibility of interstellar travel. He also co-founded Icarus Interstellar and was until 2016 the Chief Editor of the Journal of the British Interplanetary Society (JBIS).

Interstellar News

John Davies with the latest interstellar-related news

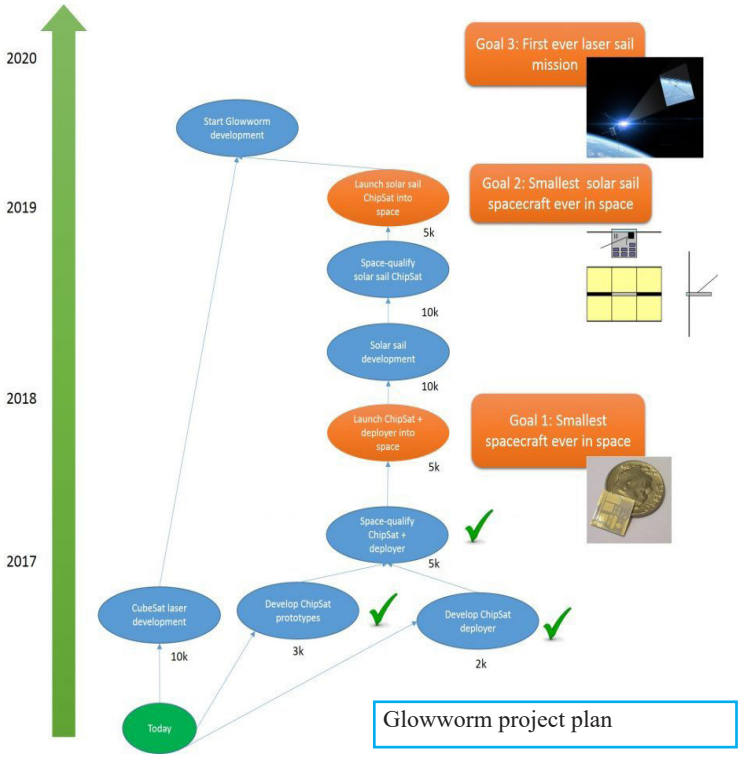
i4is Project Glowworm

Project Glowworm (i4is.org/what-we-do/technical/project-glowworm) is a new i4is project which came just a fraction too late for our last issue in November. The project team has been working for some months but launched to the wider world on 8 December 2016 (as projectglowworm.com). The project is lead by Andreas Hein, i4is Technical Committee, and Stefan Zeidler, i4is Enterprise Committee.

The plan is for a CubeSat spacecraft to demonstrate the first laser-sail in space. We aim to demonstrate key technologies for a laser-propelled future interstellar mission by pushing a gram-sized "ChipSat" with a laser beam in space for the first time.

We are funding this through donations and we already have individual donations of hundreds and a few thousands of Euros towards our EUR 50,000 target.

Our goal in 2017 is to develop and test a femtosatellite prototype in a simulated space environment. This would mature the technology to a technology readiness level of 5, which would be a considerable step towards developing actual space hardware.



Glowworm project plan

i4is Executive Director at NASA, Houston, Texas

Kelvin F Long, Executive Director of i4is, was at NASA's Johnson Space Center (JSC), Houston, this month. He gave two presentations -

Interstellar Travel, The Next Frontier of Exploration, Starshot Initiative - a public lecture to NASA staff- live streamed via NASA TV. (www.ustream.tv/recorded/99541952, starts at about 10 minutes, about 50 minutes total.)

A Preliminary Analysis of Particle

Kelvin addressing JSC. Credit: NASA

Kelvin with staff and students a Seabrook Intermediate School

Bombardment for Interstellar Flight, Starshot Initiative - presented to the NASA JSC Thermal Design - based on simulation software Kelvin has created.

He was also invited to present to 6-8th Graders (11-14 year olds) from Seabrook Intermediate School on *Interstellar Travel, The Next Generations Space Objectives.*

Kelvin had several meetings at JSC including one with Dr Harold "Sonny" White and his team at the Eagleworks laboratory to discuss breakthrough propulsion technologies - working on vacuum thrusters and warp field interferometry.

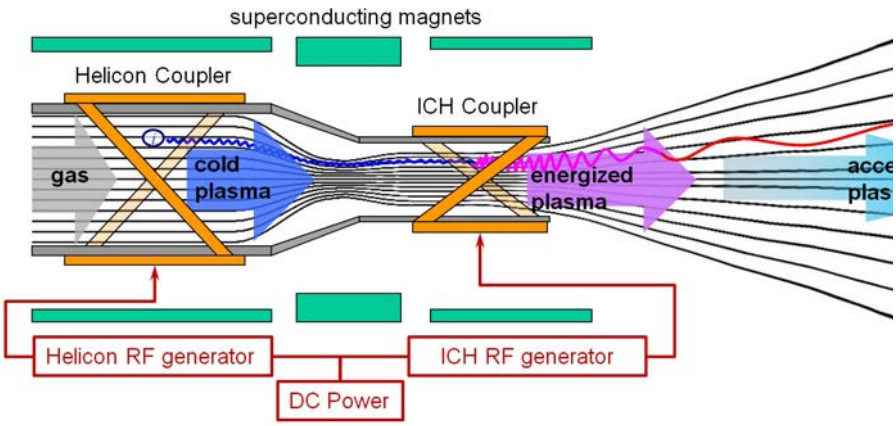
He also visited the Ad Astra Rocket Company - working on VASIMR, the Variable Specific Impulse Magnetoplasma Rocket.


Kelvin chatting to 6-8th Graders (11-14 year olds) at Seabrook Intermediate School

The new i4is website

If you have visited i4is.org then you will have noticed that it has a new layout and some new content. The new site was created by Jason King (www.kingjason.co.uk), a specialist in websites for non-profit organisations, working with Dave Miller, our Membership and Marketing Manager. Reactions have been very favourable so far but please tell us what you think yourself.

One of our main purposes of the new site is to support our membership scheme. We'll be



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Recording the podcast in the BIS Library.
Credit The Interplanetary Podcast

announcing this soon to Principium subscribers and the wider world.

Glowworm at Reigate Grammar

We report on our latest work, Project Glowworm, elsewhere in this issue. But it has already reached the rising generation. Kieran Twaites is the youngest member in the Glowworm team. He is a student at Reigate Grammar School, near London. He has written for Principium (Issue 13, *Warp drive is possible*). Kieran recently presented Glowworm to over 400 students at his school, extolling Glowworm and i4is. As a result, the Design & Technology department at his school has decided to donate £200 towards Glowworm! This money has been raised by students designing and selling Christmas decorations and baubles, an exemplary achievement by Kieran and the students. Fantastic work, Kieran!

i4is on the Interplanetary Podcast

John Davies, Senior Researcher, i4is, was interviewed by Matthew Russell and Jamie Franklin of the Interplanetary Podcast (www.interplanetary.org.uk) at the BIS, London, in December. They discussed i4is activities past and future. A relaxed and fun interview! It is accessible at: http://interplanetarypodcast.tumblr.com/post/155210140144/the-interplanetary-podcast-follow

ISU, Interstellar Elective 2017

The Initiative for Interstellar Studies has again been invited to deliver the Interstellar Elective at the International Space University in Strasbourg. This will happen in the first two weeks of May. Principium will of course be reporting on this.

Kelvin Long at the Royal Astronomical Society, July 2017

Kelvin will be at the Royal Astronomical Society, 20 July 2017, talking about *Interstellar Flight: The Benefit to Astrophysics* - making the case to the astronomical community for direct in situ reconnaissance missions in addition to remote observation.

The Interstellar Challenge 2016 and 2017

The Interstellar Challenge 2016 was delivered to London schools in December 2016. This is reported elsewhere in this issue. In 2017 i4is and STEM Learning will issue a new challenge to London schools we could not include in December and will be aiming to take the Challenge nationwide.

UK Space Conference, May-June

We'll be at the ESERO Teachers Conference alongside the UK Space Conference 2017 in Manchester 31 May - 1 June to talk to teachers, ESERO and STEM Ambassadors about how interstellar can inspire school students not just into Science, Technology, Engineering and Maths but also into wider subjects and creative activity in all its forms.

Interstellar flight workshop in New York, June 2017

On 13-15 June 2017, i4is will be co-organising a new style of interstellar flight workshop in New York with City University New York (CUNY) Theoretical Physics Department. This will be a "nuts and bolts" meeting with no top level presentations and the rule “no solution, no presentation”. More at Foundations of Interstellar Studies Workshop at City Tech, CUNY.

Institute for Interstellar Studies, USA

i4is does not yet have Institute status in the UK because of very tight corporate registration rules. Our US-based organisation is already registered as the Institute for Interstellar Studies and Robert Kennedy III, co-founder of the Tennessee Valley Interstellar Workshops, will be the President of i4is USA. Expect to see more US-based activity in the near future!

New Scientist: Tiny spacecraft could brake at exoplanet using alien starlight

In a "Short Sharp Science" item in New Scientist, Michael Brooks introduces ideas from Rene Heller of the Max Planck Institute for Solar System Research, Göttingen, and independent space researcher Michael Hippke; using a combination of the target star's gravity and radiation pressure which might slow down a Starshot-like craft (Deceleration of high-velocity interstellar photon sails into bound orbits at αCentauri, Heller & Hippke, ui.adsabs.harvard.edu/#abs/2017arXiv170108803H/abstract and arxiv.org/abs/1701.08803). Professor Avi Loeb, Harvard, chair of the Advisory Committee for the Breakthrough Starshot Initiative, points out some difficulties including the extremely thin sail material assumed. And Paul Gilster, our old friend at Centauri Dreams, also has some reservations ('Photogravitational Assists' to Proxima b, www.centauri-dreams.org/?p=37053). Nevertheless, this looks like a possible route to solving the deceleration problem. Starshot envisages an encounter velocity of 20% c, or 40 minutes per AU, which would mean the probe would cross Earth's orbit in less than one and a half hours! More about Starshot in our Introduction in this issue.

Institution of Mechanical Engineers at Anglia Ruskin University

On 25th January John Davies was at the monthly meeting of South Essex Area Institution of Mechanical Engineers, to talk about Starship Engineering. The meeting also included people from the North Essex Astronomy Society and the Institute of Physics. Peter Wotherspoon, chair of the branch, was a fine host and the questions from the floor were interesting, and in several cases, penetrating.

Starship Engineer 2016

The second i4is Starship Engineer course was at the BIS in London, 12-13 November. Again a highly enthusiastic group were led by Kelvin Long and Rob Swinney through both the physics and engineering required to reach the stars and the imagination of SF writers and film makers who have inspired us with both practical and fantastic visions.

Sam Harrison enthuses from IAC

The 67th International Astronautical Congress was a fantastic conference run in Guadalajara, one of Mexico's leading tech capitals after Mexico City, in September 2016. The event was largely dominated by the unveiling by Elon Musk of SpaceX's new launch vehicle. He was greeted with a rock star-like entrance with crowds of people running to get the best seats. The questions from the audience were well-supplemented by the Reddit Q+A.

SpaceX's work has helped many to view interplanetary travel and settlement as no longer confined to science fiction. Not since the Apollo era has a spark like this been lit - and few with such positive long term implications for interstellar flight.

Starship Engineer 2016, first day

LETTER TO THE EDITOR: Propulsion strategy and laser-sail spacecraft

From: Stephen Ashworth

To the Editor of Principium

Dear Sir,

With the renewed interest in laser-sail propulsion for early interstellar probes recently stimulated by Yuri Milner's Breakthrough Starshot programme, I think it is necessary to take a hard look at the drawbacks as well as the advantages of this approach to interstellar flight.

The advantage is clear enough: laser-sail seems to be the only proposed propulsion method that can launch any kind of spacecraft with a relativistic (>1% of c) speed within the next 50 years or so. It is therefore the only option for reaching any nearby star with a spacecraft within the natural human lifetime of people now living. This is assuming that the technical problems of generating a sufficiently powerful beam, of control and heating of a sail craft while it is accelerated in the beam, and long-range communications from the destination, can be solved.

But I should like to ask whether it is more efficient in the long run to focus on flying an interstellar probe (or a swarm of them) as early as possible, or to focus more on building up the infrastructure to enable a later, but more economically sustainable, series of more capable flights.

I ask this as a so-called "orphan of Apollo": one whose viewpoint has been shaped by disappointment that the potential of the Apollo programme to lead on to a moonbase and to astronaut flights to Mars was not realised. This experience led me to the view that a giant leap forward is of little value unless the infrastructure is in place to capitalise on that leap. What counts in the longer term is building up a sustainable economic and technological system that can make the necessary step-by-step progress towards a society whose spaceflight capabilities are an integral part of the economy. Starting from this position, two specific questions about laser-sail propulsion disturb me.

Firstly: it is difficult to see how to decelerate a laser-sail spacecraft at its destination . Clearly, the overwhelming advantage of sending spacecraft to explore a star, rather than using large telescopes based in the Solar System (including the possibility of using the Sun's gravitational focus), is to get instruments in orbit around the planets of the destination star, and where possible on **and under** the surfaces of terrestrial planets. The most engaging scientific questions are whether there is native life, and of what nature, and these can only be answered by a combination of orbiters and landers (with Curiosity/ExoMars-style rovers which can pick up a rock to see what is under it, and drill down to the water table).

At this point, Breakthrough Starshot seems to be contemplating an undecelerated flyby of the Alpha Centauri system at relativistic speed. But will this return more science than an equivalent expenditure on telescopes? The limitations of the flyby method were very clear, for example, in the misleading results obtained from Mariners 4, 6 and 7. Mars only really began to come into focus with Mariner 9 and Vikings 1 and 2, and the key question about life on Mars has still not yet been answered, 40 years later.

The question of whether small terrestrial (ie those with a solid surface) solar system worlds have subterranean or submarine life (Europa, Enceladus and Pluto have been raised as possible Solar System examples) is of major significance, and intrinsically impossible to resolve through remote sensing (let alone the question of sequencing the DNA of any organisms found! – crucial in order to establish its relationship or lack of relationship with terrestrial life).

The Forward–Norem scheme for deceleration using the Lorentz force from the galactic magnetic field, and the Forward scheme for deceleration using a multi-stage sail, strike me as Heath-Robinson ideas which are

Stephen Ashworth is a prolific writer on matters interstellar. His previous piece for Principium was *The Thousand-Year Starship* in Issue 13. His blog is at www.astronist.co.uk

unlikely to be practical [1]. The first is not even testable on a smaller scale.

Electric and magnetic sail braking seems only to work when the speed is above a few per cent of c, so even if they are used for an initial phase of deceleration, a powerful engine is still required for terminal deceleration (on the order of 1000 km/s) down to orbital speeds for capture in the target system.

A second concern is the low energy efficiency intrinsic to any laser-sail system. I investigated this in detail in an appendix to a paper published a few years ago [2]. Low efficiency may of course be acceptable for a very small robotic probe such as a chipsat, whose total energy budget is small, but has the disadvantage that it will not realistically scale up to the size of vehicle advocated by Ian Crawford for effective robotic exploration of the target system [3], let alone to manned worldships.

This has a knock-on effect, which is that laser-sail propulsion is unlikely to be competitive within the Solar System, where velocities are relatively small, energy efficiency is correspondingly small, and other systems will therefore be more competitive. This does not affect solar sailing, by the way, because raw solar radiation comes free of charge. But the laser beams have to be generated by very large-scale infrastructure, and therefore the cost of the beam comes into play and has to be compared with the cost of other options.

Going to the stars is such a massive undertaking that I am convinced it will not be done using a theoretically ideal propulsion system, whatever that may be. Rather it will be done by scaling up some system which is already in widespread use in the Solar System economy, and can piggy-back on centuries of development that give it the manufacturing infrastructure and the reliability it must have. Remember how the Apollo moonflights piggy-backed on the existing ballistic missile industry, or global maritime exploration on the existing short-range shipping capability.

If laser-sail propulsion is not competitive for use within the Solar System, a push to develop it results in a product with only one customer: interstellar exploration. Apollo demonstrated that a product with only one customer is not a product that is likely to be on the market for long.

On the other hand, a case could be made for the usefulness within the Solar System of magnetoplasma engines (such as Chang-Diaz's Vasimr) which draw power from a microwave beam generated at a station on a moon or in orbit. Parallel development of solar sails might mean that the two elements of a laser sail system would be independently useful within the Solar System, and could be brought together for an interstellar probe. This possibility should be considered as part of any interstellar study, if it wishes to avoid focusing so exclusively on a dash to the stars that Solar System applications of the technology are forgotten.

Although they are looking further into the future, the Daedalus/Icarus studies appear to offer greater ultimate value in that nuclear fusion propulsion is more likely to be of widespread application within the Solar System as well as beyond it. The possible synergies between fusion technology for propulsion and for electrical power generation, both on Earth and off it, could well make fusion propulsion economically viable and sustainable for interstellar applications.

To conclude, my recommendations to current laser-sail development projects would be:

(1) Compare the cost of the science that could be done by flyby probes with the cost of the same science done by telescopes within the Solar System over the same period of time in order to establish the most efficient use of resources.

(2) Consider new technology development not only for the single purpose of interstellar flight, but also for its possible applications on Earth and elsewhere within the Solar System, applications which could lead to the development of that technology in practice, and thus make its use for interstellar missions economically viable.

I think these points are obvious enough, and I expect that others will already have raised them, but I trust that Principium will consider them important enough to be worth repeating now.

Yours sincerely,

Stephen Ashworth

References

[1] Mallove and Matloff, The Starflight Handbook (Wiley, 1989), ch.5.

[2] "Appendix 2: Energy Efficiency of a Beam-Propelled Light Sail", in my paper "The Emergence of the Worldship (II): A Development Scenario", JBIS, April/May 2012, p.173-174.

[3] I. A. Crawford, "Project Icarus: Preliminary Thoughts on the Selection of Probes and Instruments for an Icarus-Style Interstellar Mission", JBIS, January 2016, p.4-10.

ISU Masters Degree Projects
The i4is contribution

John Davies

One of the Initiative for Interstellar Studies' most important areas of work is our Education Programme, which aims to build greater knowledge of, and interest in, the challenges of interstellar flight amongst students at all levels. This extends from primary schools to postgraduate work, notably with the International Space University.

As part of this programme, the Initiative for Interstellar Studies (i4is) has been working with the International Space University (ISU) in Strasbourg since the academic year 2012/2013 (A Learning Experience, Chris Welch, Principium 3, Feb 2013, i4is.org/wp-content/uploads/2016/10/Principium_3_Feb_2013.pdf).

The ISU exists to develop the future leaders of the world space community (www.isunet.edu/blog), and thus is an ideal partner for our educational work. One of our major collaborations with ISU has been providing External Advisers to students studying for the Masters Degree in Space Studies. i4is experts have worked with individual students and their research supervisors on a number of projects since 2012. This work is carried out under the general supervision of Professor Chris Welch of ISU and Rob Swinney, Education Director of i4is.

This collaboration enables i4is to work with promising students. They also gain through access to the wide-ranging and up-to-date technical expertise of our External Advisors.

For example, here are the latest completed i4is-supported projects. They were with 4 Masters students in the year 2015/2016:

Marta Oliveira, "Financing Options for a Precursor Interstellar Mission", ISU/i4is Individual Thesis project, April 2016, **External Advisor Stefan Zeidler.**

Which led to "Strategies to Implement a Precursor Interstellar Mission: from Mission Concepts to Financing Options", presented at the 67th International Astronautical Congress, Mexico, September 2016. See iafastro.directory/iac/archive/browse/IAC-16/D4/1/32005.

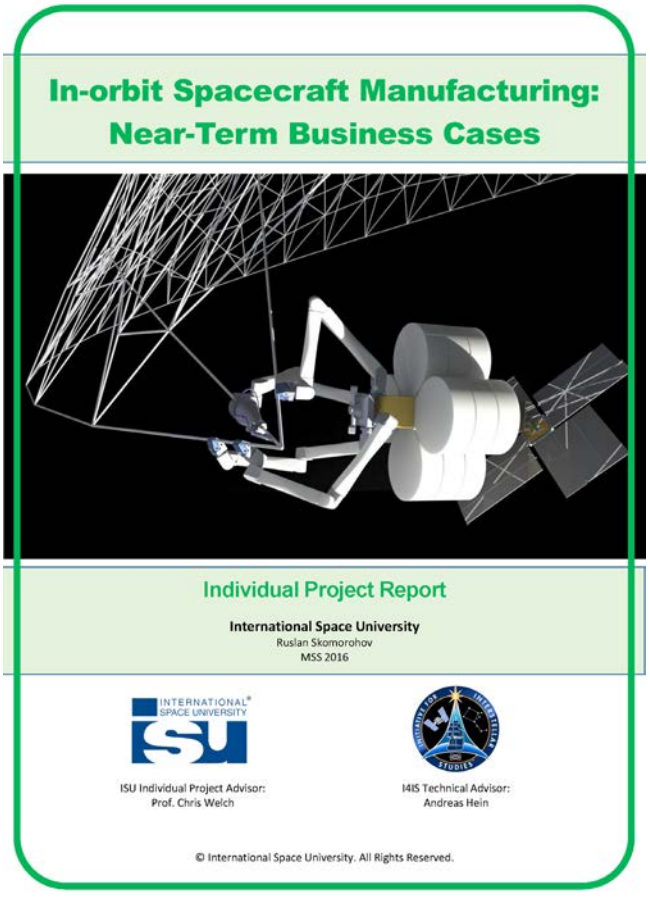
Marta is a graduate of the Instituto Superior Técnico, Lisbon.

Ms K Shanthini, "TAU Laser Sail Mission", ISU/i4is Individual Thesis project, April 2016, **External Advisor Angelo Genovese.** (TAU = Thousand Astronomical Units.) See iafastro.directory/iac/archive/browse/IAC-16/C4/8/34508/ .

Ms Shanthini is a graduate of the KCG College of Technology, Chennai, Tamil Nadu, India.

Ruslan Skomorohov, "In-orbit Spacecraft Manufacturing: Near-Term Business Cases", ISU/i4is Individual Thesis project, April 2016, **External Advisor Andreas Hein.** See www.researchgate.net/publication/307607599_In-orbit_Spacecraft_Manufacturing_Near-Term_Business_Cases. Presented at the 67th International Astronautical Congress, Mexico, September 2016.

Ruslan is a Space and Telecommunications Specialist. A graduate of Brown University, Providence, Rhode Island, USA, he is also a business consultant and analyst. Ruslan was awarded



the i4is Alpha Centauri Protégé Award (i4is.org/what-we-do/alpha-centauri-prize/) for 2016 for this project.

Anushree Soni, "Minimum Interstellar Precursor Mission", ISU/i4is Individual Thesis project, April 2016, **External Advisor Martin Langer**. See www.researchgate.net/publication/310444920_MINIMUM_INTERSTELLAR_PRECURSOR_MISSION. Presented at the 67th International Astronautical Congress, Mexico, September 2016.

Anushree is a graduate of Ryerson University, Toronto, and is now an Engineering consultant in the Office of the Chief Scientist, NASA Ames Research Center.

This was a year which included much crossover with i4is Project Dragonfly - see i4is.org/what-we-do/technical/project-dragonfly/ and Principium issue 12 (and earlier issues 6, 9 & 10).

A little about each of the i4is External Advisors:

Stefan Zeidler is founder of Robotcloud (www.robotcloud.eu), a pioneer in the application of Robotic Learning to Industrial Services and has also worked for Deutsche Pfandbriefbank AG and Accenture. Stefan has a Masters in Business Studies from the University of St. Gallen, Switzerland, and has studied at the University of British Columbia and the London School of Economics. Stefan has been active for several years in the Technical Committee of i4is, notably in Projects Dragonfly (see above), Andromeda (Principium issue 15) and Glowworm (see News in this issue and i4is.org/what-we-do/technical/project-glowworm/). He is a co-author of Marta Oliveira's paper *Strategies to Implement a Precursor Interstellar Mission: from Mission Concepts to Financing Options*, presented at the 67th International Astronautical Congress, 2016.

Angelo Genovese is Senior Electric Propulsion Engineer at Thales Deutschland and was previously with the Austrian Institute of Technology. Angelo has a Masters in Aerospace Engineering (specialising in Space Propulsion) from Università di Pisa. Angelo is a key member of the i4is Technical Committee working on Projects Dragonfly and Andromeda (see above). He presented *Advanced Electric Propulsion for Interstellar Precursor Exploration* at the Tennessee Valley Interstellar Workshop, 2016 and has published many widely-cited papers on spacecraft electrical propulsion.

Andreas Hein is a Researcher at Université Paris-Saclay and is i4is Director of Technical Programmes. Andreas has a PhD and first degree from the Technische Universität München (TUM). He has also studied at Stanford University Graduate School of Business and MIT. Andreas has worked on and coordinated all i4is technical projects since its foundation. Andreas has published many papers on interstellar studies and technology, ranging from *Project Icarus: stakeholder scenarios for an interstellar exploration program* (Journal of the British Interplanetary Society, vol. 64, 2011) to *Transcendence Going Interstellar: How the Singularity Might Revolutionize Interstellar Travel* " on Centauri Dreams (13 June 2014 – see www.centauri-dreams.org/?p=30837) and *Artificial Intelligence Probes for Interstellar Exploration and Colonization*. The latter is a paper in preparation for formal publication and is the subject of a picture feature elsewhere in this issue of Principium.

Martin Langer is a PhD Student at Technische Universität München (TUM) where he gained a Masters in Aeronautical Engineering. He has been active in the Technical Committee of i4is for several years and has contributed to Projects Dragonfly, Andromeda and Glowworm. Martin is a specialist in spacecraft reliability and was a co-author of *Minimum Interstellar Precursor Mission,* presented at the 67th International Astronautical Congress, Mexico, 2016.

i4is is currently working with 3 more students in the 2016/2017 Masters degree programme at ISU. Their dissertations will be submitted in 2017. Summaries of all this work are at i4is.org/what-we-do/education/isu-projects/

By working with tomorrow's leaders of the global space community, i4is will help to promote knowledge of, and interest in, the challenges of interstellar flight amongst those most likely to be able to turn it from theory into practice. We are extremely grateful to ISU for the opportunity to work with so many promising young people and we look forward to working with many more in the years to come.

FILM REVIEW: Arrival

Reviewed by Patrick Mahon

Director: Denis Villeneuve. Script: Eric Heisserer, adapted from ‘Story of Your Life’, by Ted Chiang.
Cast: Amy Adams (Dr Louise Banks), Jeremy Renner (Ian Donnelly), Forest Whitaker (Colonel Weber), Michael Stuhlbarg (Agent Halpern), Tzi Ma (General Shang). Running time: 116 minutes.

Official poster, Credit Paramount Pictures

Over recent years, we’ve been blessed with several Hollywood blockbusters that have tried to present science fiction in general, and space travel in particular, in a more realistic way than has historically been the case. I’m thinking, in particular, of Gravity (2013), Interstellar (2014) and The Martian (2015). As 2016 drew to a close, not one but two more such films were released: Passengers, which John Davies covers elsewhere in this issue, and Arrival, which I’ll review here. Does the latter deliver the goods?

The storyline

The script for this film, written by Eric Heisserer, is adapted from Ted Chiang’s award-winning 1998 SF novella ‘Story of Your Life’. Having read the novella there are some significant differences between book and film, but the underlying plot is essentially the same: how will humanity respond to First Contact if we can’t work out how to communicate with the aliens?

When twelve huge ellipsoidal spacecraft appear in the skies above random points on the Earth, the most powerful governments of the world immediately try to make contact with the aliens that are presumably on board, to find out what their intentions are.

Not meeting with immediate success, the US military recruit Dr Louise Banks (Amy Adams), a linguistics professor, and team her up with physicist Ian Donnelly (Jeremy Renner). They are tasked with entering the nearest spacecraft and finding out how to communicate with the inhabitants. This is easier said than done, but Banks’s and Donnelly’s patience is eventually rewarded when the aliens reveal themselves, although they always remain in a separate part of the ship from the humans, visible through a glass wall, presumably because the atmosphere they breathe would be toxic to humans (and vice versa). Then the hard work really begins. The Heptapods as they are dubbed, due to the seven-fold symmetry of their ‘hands’, communicate via both written and oral language. However, after many false starts, Banks realises that the two forms of alien language are not analogues in the

same way that written English is an alternate representation of spoken English.
While all this is going on, Donnelly and Banks slowly become friends and, through that friendship, we start to find out about a tragedy that sits at the heart of Banks's life and provides the film with a deep emotional resonance.
Whereas Donnelly and Banks are making slow but steady progress, none of the teams attempting the same task inside the other eleven spacecraft around the world has any luck. And as time moves on, some governments become ever more concerned that the aliens mean humanity harm. Can Louise and Ian decode the aliens' languages before another nation decides that the best form of defence is attack?

Hit or miss?

Arrival is most definitely a hit. The science fictional elements of the storyline are extremely well presented, given that the subject matter – xenolinguistics – is complex and very far from most people's everyday experience. The visuals are spectacular, whether you're looking at the gorgeous spacecraft, the alien creatures themselves or their strange circular writing. And the pictures are accompanied by a haunting soundtrack that adds enormously to the emotional power of the film.

The fact that Heisserer's script and Villeneuve's direction have managed to translate the intricacies of Chiang's novella into a story suitable for a mainstream audience is hugely impressive. To my mind, though, what lifts the film above its recent SF competitors is Amy Adams' beautifully understated performance as the emotionally vulnerable Louise, trying to make sense of her life, just as much as of the aliens, in the aftermath of great loss.

If I had to point to one weakness, which the film shares with Chiang's original novella, it is that the character of Ian Donnelly is remarkably one-dimensional. This is not because Jeremy Renner is a bad actor but simply that we never really find out anything interesting about the physicist. To a large extent, he exists in the story solely as the foil to Amy Adams' Louise, and for me that's a shame.

What about the science?

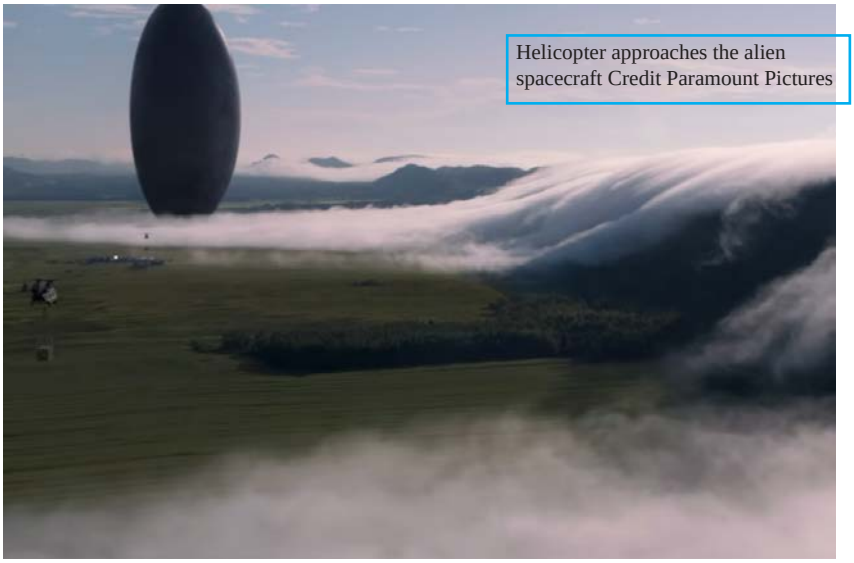
It's difficult to say much about the heptapods' highly advanced technologies, other than by referencing Arthur C Clarke's famous dictum, that 'any sufficiently advanced technology is indistinguishable from magic.'

In this case, the aliens' spacecraft can hover silently just a few metres above ground level, they have no obvious means of propulsion nor fuel tanks with which to power the same, and when Banks, Donnelly and others go inside the spacecraft to communicate with the aliens, it quickly becomes clear that they are able to control both the strength and direction of the local gravitational field without using anything so obvious as a rotating frame of reference to provide artificial gravity.

Under these circumstances, it seems a little presumptuous to try to make any comment on the technological realism of the film, other than to say that, in context, it all seems to make perfect sense.

Conclusion

Arrival is an intelligent, thoughtful and engaging science fiction film which marries a fascinating premise to an emotionally complex central character. Amy Adams delivers a stellar performance, ably supported by the rest of the cast and crew. I can't wait for the film to come out on DVD so that I can watch it again.



Helicopter approaches the alien spacecraft Credit Paramount Pictures

About the reviewer
Patrick Mahon is an i4is member who works in the waste and resources sector. He was encouraged to study mathematics and physics at university after falling in love with astronomy and spaceflight when Sir Patrick Moore gave a talk to his school's astronomy club in 1981, the same year as the first Space Shuttle flight. He now writes science fiction in his spare time.

Passengers: Magnificent but Flawed

Is it the first true interstellar film?

Reviewed by John I Davies

Director: Morten Tyldum, Writer: Jon Spaihts, Starring: Jennifer Lawrence (Aurora Lane, magazine journalist), Chris Pratt (Jim Preston, practical engineer), Michael Sheen (Arthur, android barman), Laurence Fishburne (Gus Mancuso, chief deck officer), Production designer: Guy Hendrix Dyas, VFX Supervisors: Erik Nordby, Pete Dionne, Composer: Thomas Newman, Running time: 116 minutes.

I assume everyone who wants to see *Passengers* will have seen it by the time this issue of Principium "hits the streets". However for small screen viewers I have tried to minimise the spoilers in the first part of this review.

I have called this piece "Magnificent but Flawed" because it sums up my feelings as we left the cinema just before Christmas 2016. The film takes us on a small part of a very long journey in the company of just a handful of characters; its story unfolding on the giant starship *Avalon*, destined to reach a colony outpost in 120 years.

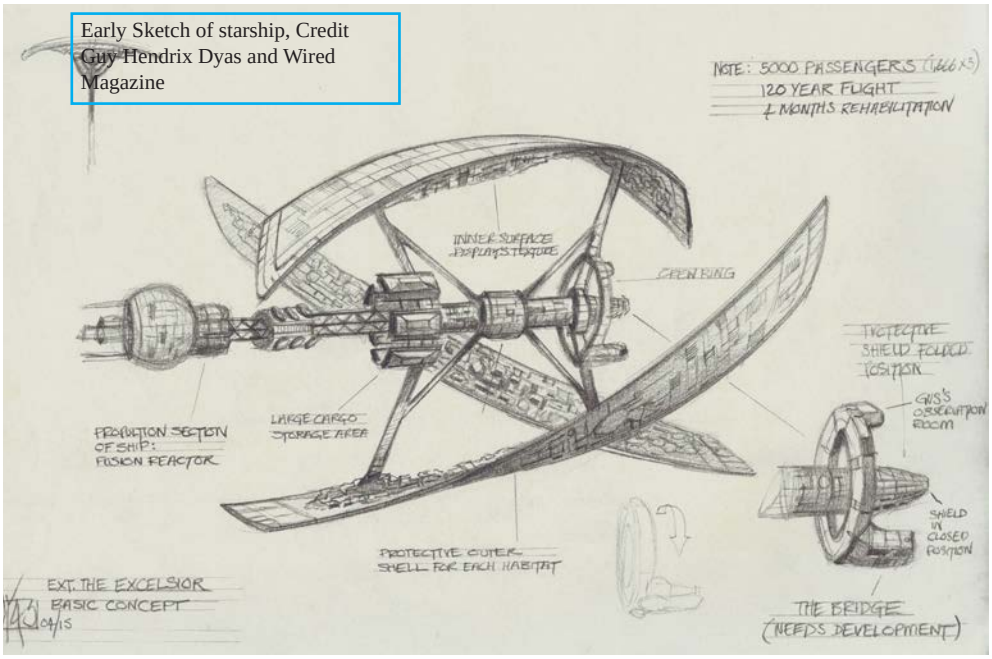
The story in one sentence: a beautifully designed starship begins to develop faults - as a result of which two passengers are revived from hibernation far too early to live long enough to make it to the final destination. A brief coda shows us how it all turns out in the end. The story is one of early interstellar colonisation rather than exploration and it's built on ideas from history so perhaps this is the first really plausible interstellar film. I asked my i4is colleagues to give me their impressions and I have incorporated some of them into what follows. Credits to them are at the end.

Magnificent

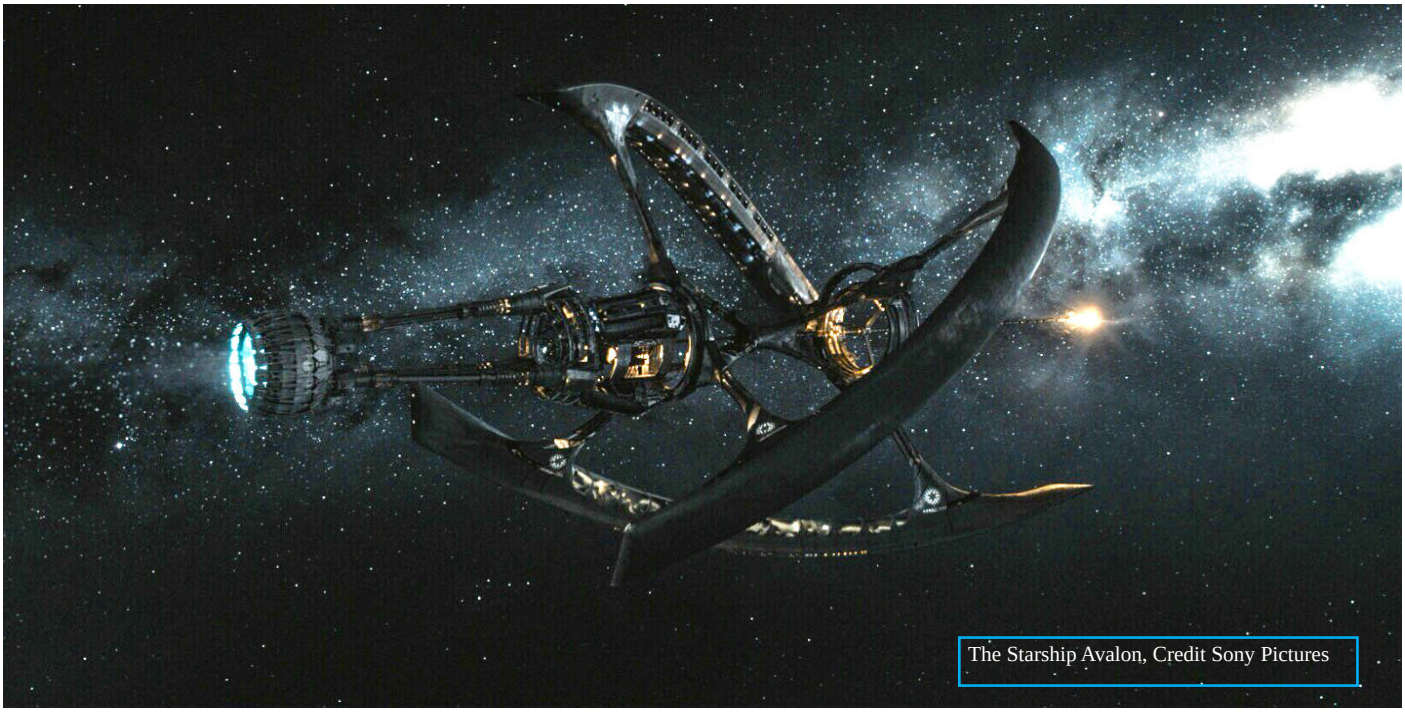
Let's start with the magnificent. The ship is the most visually convincing starship I have yet seen, corkscrewing through space like an interstellar tunnel boring machine. The effects teams have done a brilliant job, though they had to cheat a bit with the lighting[1].

The underlying plot idea, that of migration using a sleeper ship, has been much discussed in interstellar studies[2] and much used in written SF but this seems to be the first film to represent it. In fact, it seems to be the first attempt to represent a starship using something close to what we believe may be achievable. The Avalon may also be the most beautiful starship yet conceived on film - sorry Mr Roddenberry!

But is it a good story? Do our heroes look plausible? Looking at the film as entertainment, the two main leads engineer Jim (Chris Pratt), and rich journalist



Early Sketch of starship, Credit Guy Hendrix Dyas and Wired Magazine



The Starship Avalon, Credit Sony Pictures

Aurora (Jennifer Lawrence), deliver competent performances, falling for each other (of course) while trying to live with the bad news that they themselves won't actually get anywhere until after they're dead. The only other constant presence is Arthur, a humanoid AI robot barman. Michael Sheen gives a creepily charming performance as an archetypal empathic bartender, almost the soul of discretion, dishing out cocktails and sympathy to his only two customers. Things could be worse!

Apart from the bar there are large and sumptuously designed Art Deco hotel and recreational areas - fortunate, of course, for our couple to make use of in their limbo existence together. Facilities include (surely the definitive?) infinity pool - which presents a nice swimmer's nightmare when things go wrong - and skydiving experiences to blow your mind. Despite the huge scale of the starship, the action all takes place in two or three areas of the ship, which, given the minimal cast, sometimes gives the film a rather play-like feel. The great external scenes give the lie to this of course, and are well done. The film achieves a feeling of claustrophobia, set in massive interiors and the infinity of space. The hotel in Kubrick's The Shining has been suggested as a source and the interiors of the prototype hotel in Yosemite certainly bring it to mind[5].

Damned for moral ambiguity in a Hollywood film?

Well, the first thing to say is that the plot revolves around what the Guardian's critic called it "a single act of staggering selfishness"[3]. She expresses most clearly a feeling which was widespread amongst critics. And if you have seen the film I suspect you may be inclined to agree. The problem for this writer is that the decision which Jim takes is set in a context of well-represented despair building up over a whole year and the film deals quite seriously with this and the consequences when Aurora discovers his "staggering selfishness". There was a subtly different ending in writer Spaihts' original script[4], though the same moral issue arises.

Spaihts is very deliberate about the moral issue at the centre of the plot. And we can debate it via the views of Kant, Bentham and J S Mill but many critics have simply dismissed Jim as a moral weakling without seriously considering the context. My suspicion is that the judgement of mainstream critics is distorted when confronted with a mass market SF film. If this was an indie film, SF or non-genre, with a minimal budget or even a big SF film made by a respected veteran like Ridley Scott then moral judgement might have been more subtle. The consequence is that the film may have been doomed to poor box office. And regrettably this may discourage the making of relatively realistic films on interstellar themes. At the time of writing (29 January 2017) it had made $270m versus a budget of $110m[6]. This is a crude Return on Investment (ROI) of about 145%. Compare with the latest Star Wars offshoot on $1016m versus a budget of $200m[7], a crude ROI of 408%. The business judgement is clear - stick to lightweight adventures "A long time ago in a galaxy far, far away...."! Perhaps because mainstream critics think the "proles" require simple moral messages and moral ambiguity

should only be presented to we, the culturally sophisticated.

Luke Chilton, writing in London free sheet, Metro, before release, (*Jennifer Lawrence and Chris Pratt get up close and personal in new Passengers trailer*, 20 Sep 2016) tells us that the idea appeared in 1950's EC comic book, 50 Girls 50. It's in the anthology, *50 Girls 50: And Other Stories, By Al Williamson* (in Google Books). The title story is a cruder version of the big moral issue in Passengers but it also includes a sleeper ship story *The Quick Trip*. In this story two astronauts awake to discover their destination star had "blown to smithereens" just before they set off.

But what about those flaws?

Technological flaws

A quick summary of what really looks iffy, even Star Wars-ish, in this brave attempt to show how interstellar migration might really work -

Loss of artificial gravity. The ship spins to create artificial gravity[8] (see sidebar) but at one point, while Aurora is in the swimming pool, the gravity suddenly disappears and the contents of the pool, including Aurora, float "upwards". In a matter of a second or two a spacecraft half a kilometre in diameter goes from rotating at about 1.8 RPM to virtually zero RPM. That's a lot of angular momentum to dump! And quite soon after, the ship starts rotating again. Well, if we believe one implausible thing (gravity removed in less than a second) we have to believe the other (gravity restored in less than a second).

Only one automated medical machine (Autodoc) for 5000 people? Only one anything

Artificial Gravity for the Avalon

The outer part of the ship rotates at 1.8 RPM, says VFX Supervisor Pete Dionne (PASSENGERS: Pete Dionne – VFX Supervisor – MPC www.artofvfx.com/passengers-pete-dionne-vfx-supervisor-mpc/) and Aurora and Jim seem to have a nice 1g to walk around in. So we can work out the diameter of the ship. Here's the standard formula:

g = {Radius*[(pi*RPM)/30]^2} / 9.81 (Lots of references, for example - ffden-2.phys.uaf.edu/212_spring2007.web.dir/kevin_galloway/gravity.html)

So if g=1 then Radius = 9.81/[(pi*RPM)/30]^2

And RPM=1.8 so -

Radius = 9.81/[(pi*1.8)/30]^2 = 9.81/[5.66/30]^2 = 9.81/[0.19]^2 = 9.81/0.036 = 272 metres. So the Avalon is about 545 metres in diameter, just over half a kilometre.

You can cheat using - www.artificial-gravity.com/sw/SpinCalc/

Which also, handily, gives you the tangential velocity. In this case 52 metres per second - which corresponds to the visual impression in the film.

The inner hub of the ship rotates at 3.6 rpm (Mr Dionne again) and our heroes seem to be living in a 1g environment when they are here too - so let's plug that into SpinCalc to get a radius of 69 metres and diameter of 138 metres. Provided, of course that Aurora and Jim stick to the outer bits of the hub. And let's assume they are tall, say 2 metres, then their heads would be about 3% lighter. I don't think they would notice! Plug the numbers into SpinCalc with a radius of 69-2=67 metres.

There are also some weird effects of rotation-based artificial gravity. If you drop something it doesn't fall in a straight line, Coriolis forces will push you sideways if you move in any direction except parallel to the spin axis and you feel heavier if you run with spin direction and lighter if you run against it (see *Artificial gravity as a countermeasure for mitigating physiological deconditioning during long-duration space missions*, Gilles R. Clément et al, June 2015 www.ncbi.nlm.nih.gov/pmc/articles/PMC4470275/). A couple of earlier examples on film: the artificial gravity wheel in the film 2001, and the spacecraft Hermes in The Martian. The Martian gym has a running machine so you are "running on the spot" and would not feel heavier or lighter dependent on which way you were facing. But the astronaut on the Discovery mission to Jupiter in *2001: A Space Odyssey* actually runs around the wheel. He will feel heaver or lighter depending on whether he is running with or against the spin.

What about that sudden loss of gravity? Isaac Newton is our guide here. Things keep moving unless something pushes them (Law number one). Acceleration, and deceleration, is equal to force divided by mass (Law number two). The ship has two counter-rotating components, the outer "sycamore seeds" where most of the action happens and the inner command and drive system core, says Pete Dionne, VFX Supervisor (see citation above). So how do we de-spin one or both of these whirligigs? If we do both at the same time and the angular momentum of each is the same then all you need is brakes - and dumping the resultant heat is probably trivial compared with the inevitable inefficiencies of those fusion reactors. If it's just the sycamore seeds, or the angular momentum is unequal, then you need thrusters. I'll leave the reaction mass and exhaust velocity calculations required to do it with thrusters to the more mathematically inclined readers.

which is small and light on a big starship. If there were just two then Jim and Aurora could have gone back to sleep for the rest of the journey!

Restarting the engine: Let's bump-start a fusion reactor by having a man in a space suit let the plasma out, protected only by a door he tore off the ship.

And some attractive but questionable bits I think we should forgive them for -

The engine is running the whole time. Perhaps if people had seen the engine was off, they'd have been thinking already that something was wrong because we can't avoid friction down here on Earth. So the audience expects the engine to be always on, because that's what you have on an aircraft or ship. It's a bit sad that Dave Scott's (Apollo 15) hammer and feather demonstration on the moon has been forgotten.

The split of the outer inhabited parts of the ship, the "sycamore seeds", by function, as explained by screenwriter Jon Spaihts[9], is risky. This looks like bad systems design to me! Redundancy is a good idea on long voyages - so each "seed" should have a degree of autonomy. "No single point of failure" is fundamental in systems reliability.

Economics of propulsion. Passenger Aurora is a journalist planning to stay only one year on Homestead II, and then to catch the next starship back to Earth. An optimistic view of the future cost of energy is always nice to have, even if most viewers will probably not appreciate just how much "gas" a ship like the Avalon would really need to guzzle. (One million tonnes at 50% of c represents a kinetic energy of 22.5 x 10^24 J, equivalent to the annihilation energy of 125,000 tonnes of matter with the same mass of antimatter at 100% efficiency. Perhaps the speed figure was put into the script more for its "Wow!" value than for technical accuracy (see sidebar - 50% of Light Speed?).

Too cute in those pods? Maybe hibernation can be done without floating people in something like amniotic fluid but Spaihts admits[10] that "we needed people to be cute in those pods". And a Forbes correspondent interviewed Dr John Bradford, SpaceWorks, funded by NASA to research hibernation for deep space travel[11]. So maybe it's coming?

A Bussard ramjet? Writer Jon Spaihts suggests this is how the engine can keep going without fuel[12]. In recent years Bussard's idea has been less favoured by researchers. The interstellar medium (ISM) is probably not dense enough to provide sufficient fuel. And gathering it is likely to produce a lot of drag (i4is.org/the-starship-log/interstellar-ramjets). It's mostly plain old hydrogen so it's difficult to turn into fusion fuel and only about 20% is ionised[13] and thus easily gatherable. Pity it's not Helium 3, nicely ionised, à la Daedalus! The engine is still firing at the end but Spaihts tells us the ship had dropped its fuel tanks before Jim woke up so deceleration into the target system needs Spaihts' Bussard ramjet to work in reverse thrust, like a jet aircraft. No reason why not?

No engine is 100% efficient and fusion produces rather a lot of energy. In a vacuum the only way to dump this is by radiation. So all recent starship designs have had what look like wings, but are, in fact, radiators. Clarke wanted them for the Jupiter ship in 2001: A Space Odyssey but Kubrick seems to have thought that "wings" would have looked wrong. Passengers suffers from the same "double bind". Put wings on it and every ten-year-old scientist will say "You don't need wings"; spend time explaining what they are for and you turn the film into a science lesson.

Dodgy deflection mechanism. The beam pointing ahead seems to be part of a deflection mechanism for what you don't want and a gathering mechanism for a Bussard ramjet (more below about propulsion). The initial asteroid collision which leads to all the drama, starting by waking Jeff up, doesn't seem to be stopped by this interstellar insect-zapper and the self-healing systems evident elsewhere don't fix the fault. Further, those systems don't try to wake up the crew. More bad systems design!

Plot flaws

Only one bar on a starship for 5000 people. Maybe it's only for first class? But then how did steerage class passenger Jeff get in there and why would Arthur (Michael Sheen), the smooth android barman, serve him? One thing is for sure, he's going to be pretty busy when hundreds of thirsty customers wake up. Unless there are lots more of him waiting in nearby cupboards?

But why the sumptuous facilities in a ship designed to house its revived passengers for only a short time? It's hard to understand the rationale for carrying such luxury living spaces on a long starship voyage when everyone is "out for the count" for most of the duration.

A crew member wakes up, Gus (Laurence Fishburne), gives our heroes his access permission but tells them he's deck crew, not command, so he can't fix the fault. Then all three of them try to fix the ship themselves

instead of waking up one of the command crew, preferably the chief engineer. Gus then dies and there's now no time to wake up anyone else so our heroes have to fix it themselves.

Propulsion implausibilities and mysteries

The biggest flaw from the interstellar technology point of view is in the propulsion. The drive is shown operating whenever the exterior of the ship is visible. So it's accelerating. Presumably the inhabited areas can be oriented to compensate for this so that "down" feels like "down". If the acceleration is small (see the discussion of propulsion above) then the gravity vector will be mostly determined by the rotation and it wouldn't feel too weird if the vessel structure looked slightly skewed when you looked through the giant windows. But Jeff goes on a spacewalk and later takes Aurora out with him. Admitted they are on tethers, but there's no sense of them being dragged behind - like tin cans on a newly wed's car! Again, maybe the acceleration is now small.

Production designer Guy Hendrix Dyas told Space.com that the ship is powered by eight nuclear fusion reactors and is about 1 kilometre long[8]. This looks about right for 1.8 RPM and a diameter of about 545 metres (see sidebar - Artificial Gravity for the Avalon).

Writer John Spaihts says it is propelled by a constant thrust ion drive and "probably gets up to high speed with the aid of some booster or launcher" and "after that, it's a fractional G constant thrust ion drive. He also tells us "It has a kind of meteor screen at the front which is probably electromagnetic, but I imagine it has some aspects of a Bussard ramjet ... [by]harvesting mass … it solves the propellant problem. He tells us he "was the diehard science nerd in the production saying, 'We're going to need more counter-rotating mass to stop the spin of the ship. Can I get some attitude jets in this?'" But "You win some arguments and you lose some arguments" He claims "..we kept a pretty nice high bar for the basics of space travel. Everyone really leaned into that enterprise, trying to make it inspiring and realistic at the same time."[8]

This is fairly vague and Spaihts does not quote any scientific

50% of Light Speed?

If a Bussard ramjet can be made to work then you can get arbitrarily close to c (see its extreme conclusion in Poul Anderson's 1970 novel, Tau Zero,) but can we achieve 0.5c with a fuelled vehicle? I raised this with our Executive Director, Kelvin Long. He has a little more background in this (see Further Reading below)! He was sceptical but went on to say:

"However, I like to play, so let's apply some of that 'Starship Engineer' methodology we have been pushing for those of you that have attended the course (November 2015 and 2016, see Principium 12 and this issue). Okay, let's allow it to break the known laws of physics and accept that speed. With some moderate assumptions we can come up with some numbers for the concept. Let's assume it has a Daedalus-like exhaust velocity of 10,000 km/s and a cruise velocity of 0.5c or 1.5E5 km/s. Then the mass ratio dV/Vex = 15, and Exp(15)=326,9017 = Mo/Mf.

Let's also assume an average person mass of around 60 kg (these are low weight people) and a supporting hibernation mass of per person of 40 kg, so that's 100 kg/person at 5,000 people = 500 (metric) tons. Then there is an additional 200 crew. Are they in hibernation? I guess so, so that's an additional 200×100 kg = 20 tons, so a total people mass of 520 tons.

Now the various Closed cycle habit studies have a lower end (Russian studies) mass for human crews of around 15 tons/person (air, water, supplies….) (FYI Gerard O'Neill studies suggested 65 tons/person) but okay these people are mostly in hibernation so let's be kind and lower it to 10 tons/person. So that's an additional 5,200 × 10 tons/person = 52,000 tons. So now our total mass is at 52,520 tons. Looking at the graphics for Avalon, those engines are quite big, so let's assume something around the size of the Daedalus first stage engines (though using a fusion reactor to power an ion drive) and say around 1,000 tons engine mass.

Let's also assume an additional 20% mass on top for ancillary structure mass, power, radiators...., which is around 10,500 tons. So now the total vehicle mass (payload + structure) is at around 64,000 tons.

Then: For flyby only mission:

Ro = 15, Propellant mass = (15×64,000) –

64,000 tons = 896,000 tons fusion propellant required.

Total wet mass = 960,000 tons.

For Deceleration mission:

R = sqrt(Ro) = 3.873 = the mass ratio to decelerate 64,000 tons into target system.

Additional Propellant mass : (3.873×64,000 tons) – 64,000 tons = 183,872 tons. So, this is a very large starship.

But a fusion rocket cannot achieve 0.5 so they need a realistic looking Bussard! Avalon is clearly a meant to be a ISM-fuelled fusion reactor powering an ion drive engine, which still won't give you 0.5c"

or technical adviser. His inner "science nerd" seems to have lost the argument a lot of the time.

Summing Up

All in all an entertaining film, and if you can ignore some of the more incredible skin-of-the-teeth moments, delivers a good tale with some nice humorous touches amid the drama, an unsentimental ending, and some very lovely spaceship externals along the way. So let's forgive the technical implausibilities and live with a plot delivering something like a morally-inverted Titanic rather than any new equivalent of Star Trek. In the end a magnificent though flawed representation of our interstellar dream!

Credits

Several i4is people contributed to this review - Kelvin Long, Robert Kennedy III, Patrick Mahon, Stephen Ashworth and Lindsay Wakeman. The final version is my responsibility alone - brickbats to john.davies@i4is.org.

Afterword

There hasn't been space to discuss the possible destinations and the film does not go into this issue except to say it's an Earth II and you need 120 years at 0.5c to get there. With the rate of exoplanet discovery likely to accelerate we will probably find somewhere to fit the bill quite soon!

The film stands for itself as a starship story but a search for more detail has not revealed any obvious technical advisers on the physics, engineering and systems design. And this clearly shows in the technical flaws we found.

References

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[10] 'Passengers': 8 Things to Know About the Science Behind the Space Drama collider.com/passengers-movie-things-to-know-jon-spaihts/

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[12] see 10 above

[13] *Physics of the interstellar and intergalactic medium*, Bruce T. Draine, Princeton University Press 2011, p.4

Further reading

Interview with VFX supervisor Erik Nordby and MPC VFX supervisor Pete Dionne www.postmagazine.com/Publications/Post-Magazine/2016/December-1-2016/VFX-i-Passengers-i-.aspx - both Nordby and Dionne worked on *Elysium*, remember that great Von Braun wheel space station? Discussing the visual effects challenges including their own work and that of director Morten Tyldum, Cinematographer Rodrigo Prieto, editor Maryann Brandon (several Star Wars and Star Trek movies), writer Jon Spaihts (*Prometheus*, the Alien prequel) and production designer Guy Hendrix Dyas.

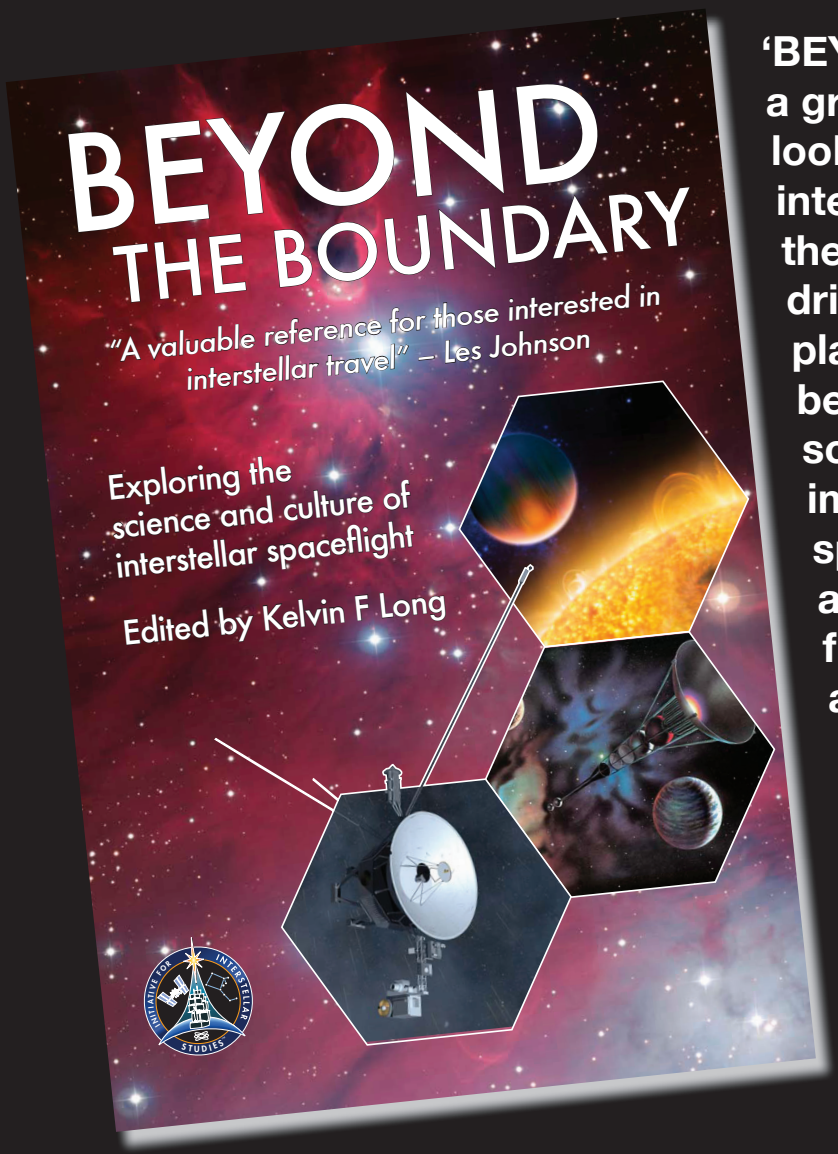
Interview with Production Designer Guy Hendrix Dyas including more magnificent art work www.wired.com/2016/12/seeds-inspired-swooping-starship-passengers

Starship Engineering: The Starflight Handbook: A Pioneer's Guide to Interstellar Travel, Eugene F Mallove; Gregory L Matloff, Wiley, 1989. The first serious and comprehensive textbook on the subject.

Deep Space Propulsion: A Roadmap to Interstellar Flight, Kelvin F Long, Springer, 2011. The current definitive text on the subject.

The Initiative for Interstellar Studies

PRESENTS



'BEYOND THE BOUNDARY' is a ground-breaking new book looking at the possibilities of interstellar flight, including the technology that will drive our starships, the planets and stars that will be our destinations, the sociological basis and impact of becoming a space-faring civilisation and how our interstellar future is depicted in art and culture.

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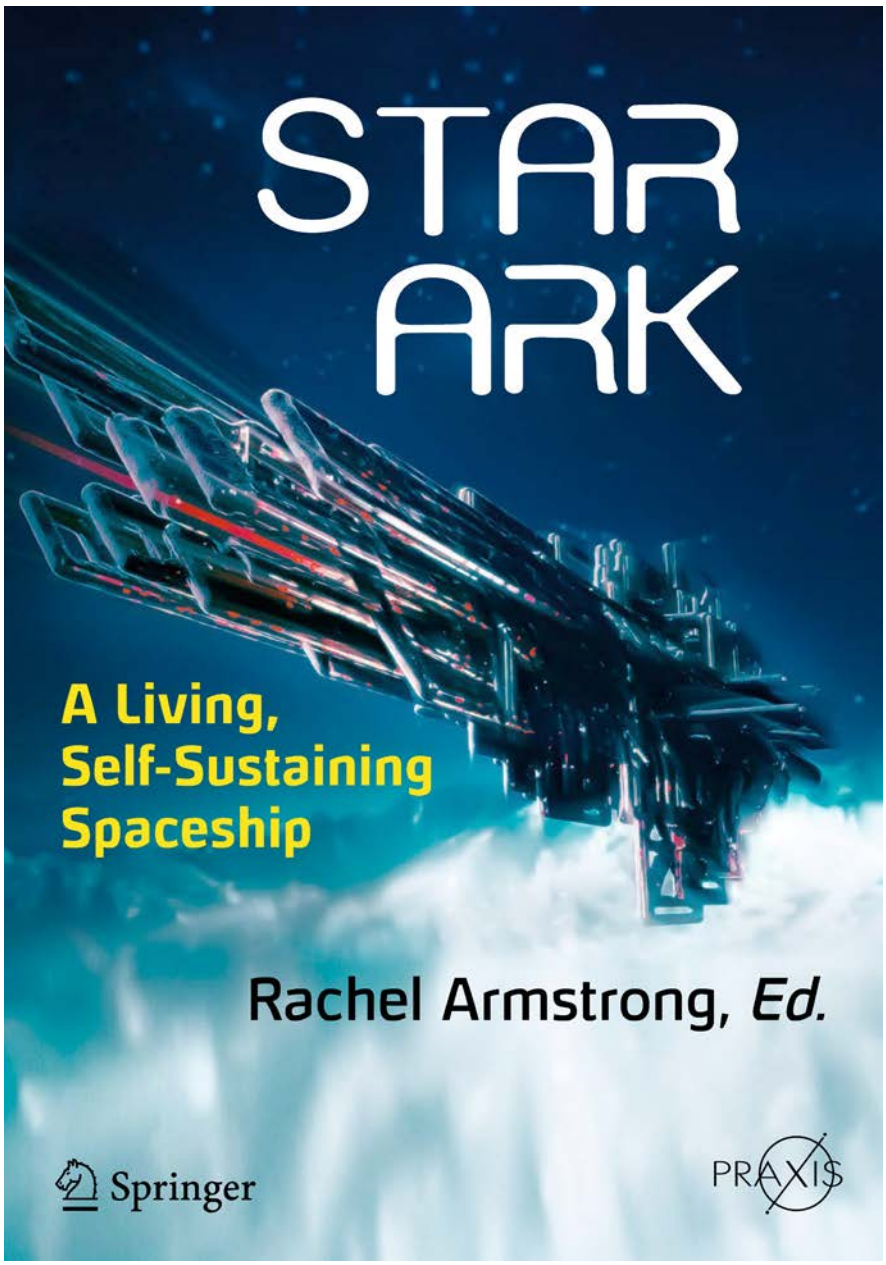
Book Review - STAR ARK: A LIVING SELF-SUSTAINING SPACESHIP

Edited by Rachel Armstrong, Published by Springer-Praxis, 2016.
Paperback ISBN: 978-3319310404

Reviewed by Kelvin F Long



Richard Buckminster Fuller was an American architect, author and inventor. He popularised the term 'Spaceship Earth' in his many writings, such as: *"We are not going to be able to operate our spaceship Earth successfully nor for much longer unless we see it as a whole spaceship and our fate as common. It has to be everybody or nobody"*. Rachel Carson was an American marine biologist and conservationist whose book 'Silent Spring' is credited with an influence on the global environmental movement. She said: "*But man is a part of nature, and his war against nature is inevitably a war against himself*". James Lovelock is a scientist, environmentalist and futurist who postulated that the Earth functions as a self-regulating system. He said: "*Life does more than adapt to the Earth. It changes the Earth to its own purposes*". These are people that stood out, took a position, and gave us good insights into how to live better and in co-operation with this world.


Professor Rachel Armstrong

Enter the next generation of thought leaders, and this includes Rachel Armstrong, Professor of Experimental Architecture at Newcastle University, the lead author and editor of the recent Springer book "Star Ark: A Living Self-Sustaining Spaceship". This is a comprehensive and rigorous book and it is impossible to do it justice in any review when limited to just a short essay. Instead, I will attempt to give the reader a snapshot of the direction the author is coming from in her approach to finding new ways of designing for both the cities and the stars. One of Armstrong's key starting points of reasoning is that we need to move away from an industrial era in our thinking

about space exploration and move towards an ecological perspective. She suggests a more dynamic relationship between science and design, and this is no surprise given she is not only an architect but also a medical doctor, a science fiction writer and someone who has explored the intersection between the sciences and arts over many projects. She leaves behind her own legacy of thoughtful quotations:

"We urgently need to challenge the global developmental conventions that are holding us in an environmental gridlock here on Earth, where, effectively, our industrial practices are reverse-terraforming our planet." Section 3.3 Apollo's orphans, page 52

"My world is an experiment, restlessly testing new possibilities – this way, and that. It tirelessly challenges the assumptions on which our architectural past and present have been produced – to propose, often surprising, new and enlivened relationships".

"The interstellar question – whether humankind will ever colonize the stars – is not about business as usual in a place that is just a very long way away." 1.2 Prototyping the Interstellar Question, page 5

"An ecological perspective no longer finds it acceptable to simplify the challenge into a dance of mutual survival between human and machine. Rather, the issues at stake must first be understood through a reading of the cosmos as an ecosystem and working through multiple, overlapping perspectives and includes science, technology, the arts, and humanities." 1.2 Prototyping the Interstellar Question, page 8

"A static world, occupied by unchanging, uncaring forms and hierarchies of order that decorate modern cities like tombstones, is merely a species of architectural death".

The term 'Experimental Architecture' was first coined by Peter Cook in 1970 in a book published with the same name[1], where he critiqued the avant-garde of modernism. The term was then developed further by architect and artist Lebbeus Woods to denote a visionary architectural practice that challenged architectural canons, mores of practice and even Nature. Professor Armstrong has become a thought leader in a group of experimental architects. She is a self-professed -

> 'living architect, a constructor of prototype ecologies, a *"vibrant materialist who acknowledges the voice of the non-human amidst the cacophony of human needs and desires".* They speak through architectural experiment, and it is the aim to co-design new environmental futures in which we can continue to flourish alongside the natural realm but in creative partnership, rather than in competitive opposition.'

In essence, she makes the case for 'vibrant architecture' and matter as a co-designer of living structures.

Her book details many of her own contributions to the field of experimental architecture which seeks to move the practice beyond the medium of drawing and into a laboratory space, where models, prototypes and installations can be realised.

Professor Armstrong also explores the technology of protocells. She argues that these are an example of a natural computing platform and are made from very simple ingredients. However, they do not need a central programming system, like DNA, to co-ordinate their actions since they possess their own energy and so spontaneously display some of the properties of living things such as sensitivity and movement. Her key insight was in realising the potential of protocells for design by applying natural computing techniques to generate a range of life-like effects in design and engineering, such as producing sculptural microstructures or being able to transform one substance like soluble carbon dioxide into an insoluble carbonate precipitate. This ability to transform one state of existing into another is what differentiates this technical platform from machines. The protocells are able to transform, as they exist, in populations that interact with each other in spontaneously forming, loose, reversible groupings that generate the life-like behaviours and account for the flexibility, robustness and environmental sensitivity of the system. Yet it is said that for the protocells to be useful agents for design, their operations need to be open to manipulation at the human scale.

For the 2010 Venice Architectural Biennale, she designed a series of life-like chemical systems for Philip Beesley's cybernetic installation, Hylozoic Ground[2]. These 'architectural organs' responded to their environment through a range of materials and natural computing strategies. This included Liesegang ring plates which marked the passage of chemical time. This included programmed oil droplets that produced mineral coats like pearls in the presence of dissolved carbon dioxide, whilst others gradually built up chemical gardens in centimetre scale

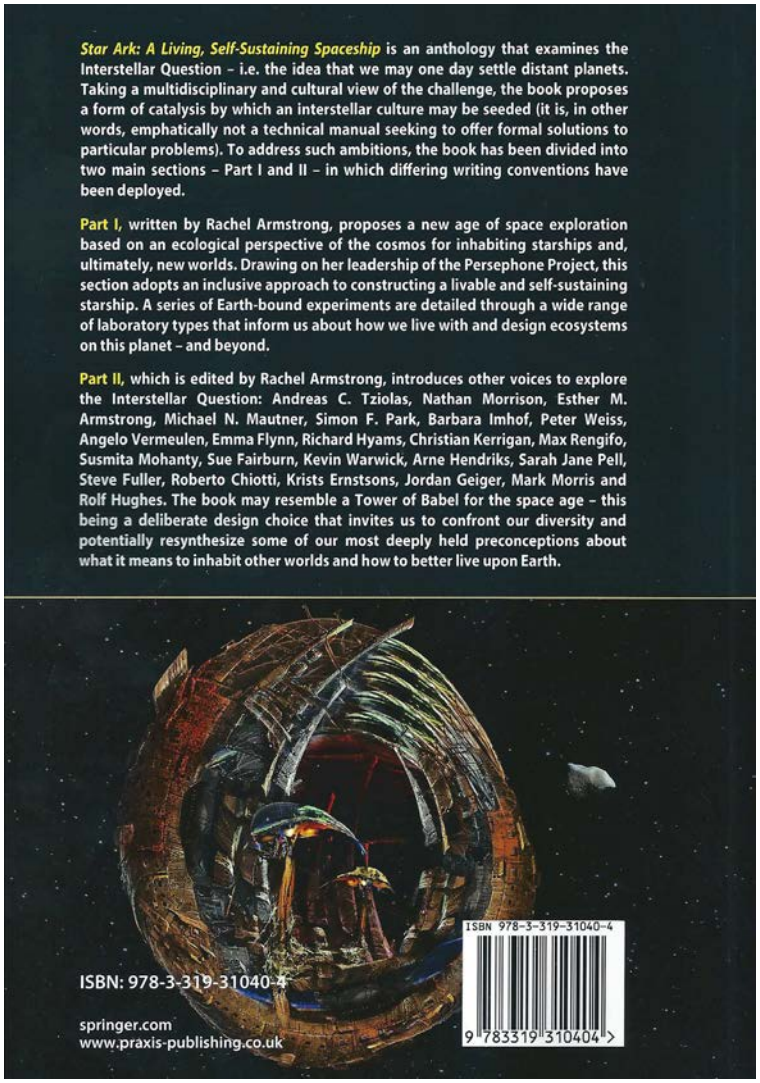
microbiomes by fixing carbon dioxide from the atmosphere into mineral form.

Another project Armstrong has been involved with is the Future Venice project. This explores on an urban scale how to secure the longevity of the city of Venice by empowering its very fabric to fight back against the natural elements in a struggle for survival. The project involves the experimental design of a series of protocells that could hold up a range of 'chemical conversations' with the lagoon environment. The aim is to use these living agents to build an artificial garden reef under the foundations of the city, which currently rests on woodpiles driven into soft mud, and thereby prevent the historic city from sinking so quickly. Droplets were given metabolisms that allowed them to perform a variety of tasks such as being able to move away from the light in the Venetian waterways and towards the city's darkened foundations.

Armstrong's ambition is to scale up the architectural experiments in which she is involved and to push them to an extreme and consider the design and engineering of living materials at planetary dimensions. Ultimately, this could lead to the construction of a crewed interstellar craft, called Persephone, within a century or so. She proposes to design and engineer the entire living interior of the starship as a kind of 'space nature' from the bottom-up starting with the construction of its soils and asks questions regarding our cities and survival. This is apparently in contrast to modern notions of worldship design that propose non-terrestrial habitats will perform in very similar ways to terrestrial ones. This is a bold and inspirational ambition which is sure to contribute to the productive development of human society in Earth and in Space, and the efforts deserve both recognition and applause.

However, when Armstrong talks about modern notions of worldship design I have to ask, what designs? There is in the literature today only one attempt at a proper worldship design, which was published by Alan Bond and Tony Martin in the Journal of the British Interplanetary Society in 1984[3]. The authors, who were physicists and engineers, focussed mostly on the external configuration and the performance of the propulsion system, as an exercise in concept scoping. They did what they could using what they knew. Looking at their papers, although they do quote large quantities of atmosphere and soils and water, by no means did they attempt any internal design work or go into detail about how any closed cycle system would work. It could be argued, that there has been nobody qualified to do that until now, with the arrival of the experimental architecture movement. There are also the Gerard O'Neill design studies in the 1970s for space ecologies[4], and for this Armstrong's criticism is a valid one. Her principle and well-argued question: "Where does all the soil come from?" Yet, ideas have to start somewhere, and these people were largely building on from the science fiction literature with its romantic visions. They start from only that which they know.

Armstrong's criticisms of the modern notions of worldship design pertain to what she sees as a tradition of closed environmental system design established by the likes of Buckminster Fuller. The basic premise of a dynamic system is that it can self-regulate indefinitely without any need for external resources, and yet as our own attempts on Earth at the Biosphere projects have shown, we were unable to build an ecosystem in a sealed environment that would definitely support humans. Project Persephone aims to represent a new kind of built ecology, which is not directed towards efficiency but at life-promoting activities within a space that is not closed. Instead, she proposes to use advanced materials and technologies to entangle the performance of built and natural systems. Examples include hydrogel films into surfaces to support plant growth as an alternative to current living wall systems and creating bioreactors that can perform useful work by harnessing the synthetic power of algae and bacteria into the building fabric. Persephone aims to construct actual prototypes that generate a matrix in which life can thrive, like a design for an artificial soil, and in doing so, proposes to set the foundations for the next generation of 'sustainable' building designs. This will also inform the design of our future cities, in which the built and living environments are one, and mutually reinforce each other and constitute a new kind of ecological architecture that is integrated with the culture of an emerging ecological era. I agree we are moving towards this ecological era, but I question whether it would have been possible to arrive at that point without first going through an industrial era first. The future is a race between our ability to perfect our design practices which embrace a 'living architecture' and our destructive tendencies to



Front and back cover credits: Springer International

utilise whatever natural resources are available to us, no matter the consequence.

The book 'Star Ark: A Living Self-Sustaining Spaceship' is a tour de force publication exploring the ideas of sustainability and experimental architecture placed in the context of both the Starship Cities and the Starships in space. In addition to the first section of the book by Armstrong, the second half of the book contains chapter contributions from her many collaborators, demonstrating her enthusiasm for interdisciplinary collaboration. Her approach to seeing the world as "*an experiment, restlessly testing new possibilities*" also marks her out as a scientist of the highest order. Among the many voices out there in the world today talking about the future, Rachel Armstrong should be listened to. Her vision of an ecologically led design practice towards experimental architecture and the applications towards Earth and space based systems is inspirational, compelling, and difficult to argue against. I predict history will show this publication was revolutionary for its time if enough people can be encouraged to take on its intellectual, philosophical and sometimes poetic tone. 'Star Ark', is the book from 2016 that anyone who cares about the future should read. It's the manual for how to build a better planet Earth and ultimately, how to build a human carrying starship.

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1 Peter Cook, Experimental Architecture. Universe Books, 1970. ISBN 0-87663-130-8

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3 multiple papers in JBIS, Vol.37, No.6, June 1984

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The Initiative for Interstellar Studies is Hiring!

For the moment this is pro bono - though we have ambitions. We produced the flyer above for the BIS Charterhouse Conference, July 2016, but the message is, of course, universal. We have new team members already helping but we need more - from all the talents and from all parts of this planet. Get in touch with any of our team if you have a drive to help us go to the stars - or just email info@i4is.org

The 2016 Interstellar Challenge for Schools

Reported by John Davies

The Education Committee of i4is extended its schools outreach programme in 2016 to deliver the first Interstellar Challenge for Schools in December at Imperial College London (School students reach for the stars at Imperial). We devised the Challenge based on an exercise set for students of the Interstellar Studies elective at the International Space University, Strasbourg, in May 2016, reported in earlier issues of Principium. This first event was for London schools but we plan to reach further in future.

The schools Challenge envisaged three scenarios -

- Worldship - a whole community of humans averaging 1% of light speed.
- Colony Ship - humanity aiming to populate a new world with a much smaller ship.
- Robot Probe - a probe to another star at 10% of light speed.

And set questions for students, some examples -

- What stars could be reached at the speeds given in the Scenarios and how long would it take?
- What sort of propulsion could achieve the required average speed? What are the advantages and disadvantages of each?
- What genetic diversity would be needed for a healthy population at the destination? How could this be improved by sending sperm and eggs?
- How much would the ship cost either at current launch costs into low earth orbit or if most of the ship could be built from asteroid material? How might such a sum be found?
- Given all of the above, write two short stories for one or more of the ships you have chosen. One imagining a failure and one complete success.

Space Studio West London hard at work

So this was not just engineering and physics but included economics and creative writing. In all there were fifteen questions and teams were asked to tackle up to six of them in the time available.

We worked with our principal partners, STEM Learning (www.stem.org.uk) and with the support of the British Interplanetary Society (BIS), student volunteers from Imperial College SEDS (www.union.ic.ac.uk/guilds/icseds) and especially the Outreach Department of Imperial College, London.

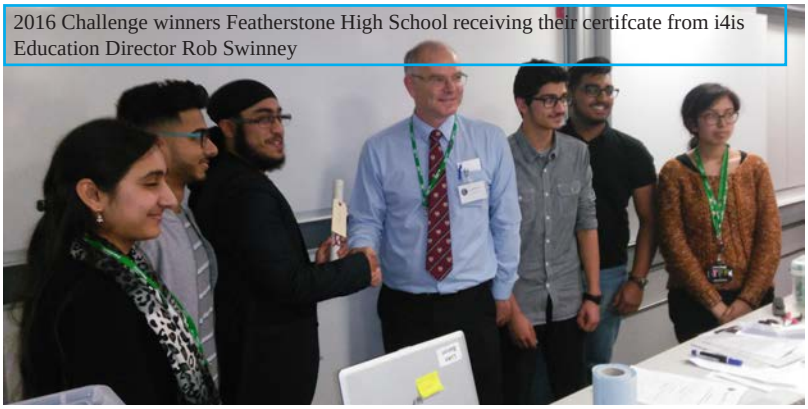
More than 20 schools responded to the invitation from STEM Learning and i4is but we had limited space and the first 8 to respond took part. They were -

Claremont High School
Coopers School
Featherstone High School
Greig City Academy, Hornsey
Harris Academy, Battersea
Space Studio West London
St Thomas the Apostle College, Peckham
West London College

The results were -

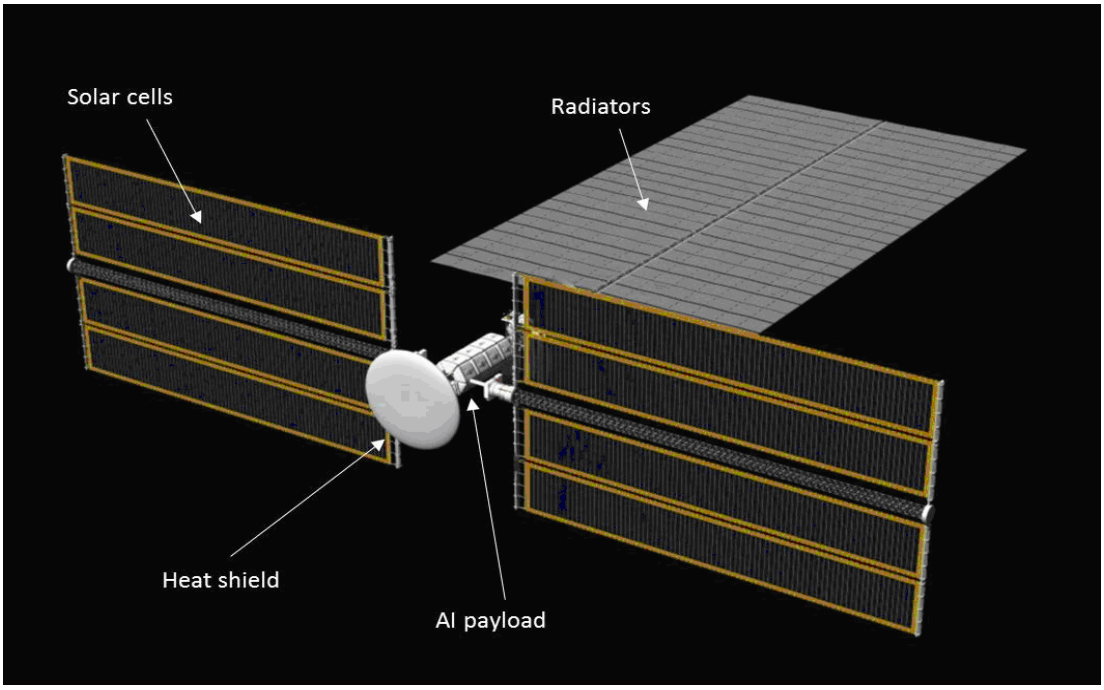
- Winner: ***Featherstone High School***
- Runner up: ***Space Studio West London***

We plan to run the Challenge again this year, giving some of the schools we had to disappoint a chance to participate. We also hope to roll out similar ideas to schools in the UK, Europe and the the rest of the world. In particular, we will be at the UK Space Conference 2017 in Manchester, 31 May - 1 June, to engage with the parallel ESERO-UK Teacher Conference to spread the Challenge and find other ways in which the interstellar vision can inspire school students.



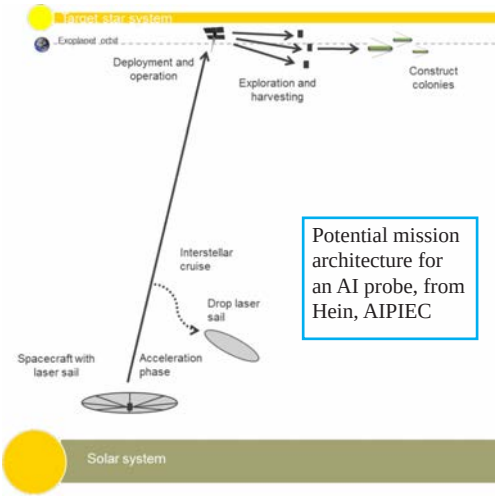
2016 Challenge winners Featherstone High School receiving their certifcate from i4is Education Director Rob Swinney

Artificial Intelligence Probes for Interstellar Exploration and Colonization : Images inspired by the vision of Andreas Hein



AI probe subsystems (Credit Adrian Mann) Hein, AIPIEC

Dr Andreas Hein, Technical Director of the Initiative for Interstellar Studies, is a busy man! He coordinates the technical work of the Initiative and has contributed to most of it including Projects Dragonfly (see sidebar), Andromeda (*How to Design a Starship in Three Days*, Principium 15) and Glowworm (World's first laser-sail in space, projectglowworm.com). But Andreas also has another major vision for our interstellar future via Artificial General Intelligence (AGI). He has written for our friends at Centauri Dreams (*Transcendence Going Interstellar: How the Singularity Might Revolutionize Interstellar Travel*, www.centauri-dreams.org/?p=30837) and inspired a two part feature in Principium (*Sending ourselves to the stars?*, P12 and P13). His most recent thinking is Artificial Intelligence Probes for Interstellar Exploration and Colonization (www.researchgate.net/publication/311872021_Artificial_Intelligence_Probes_for_Interstellar_Exploration_and_Colonization) - AIPIEC.



Potential mission architecture for an AI probe, from Hein, AIPIEC

Images of an AI Probe

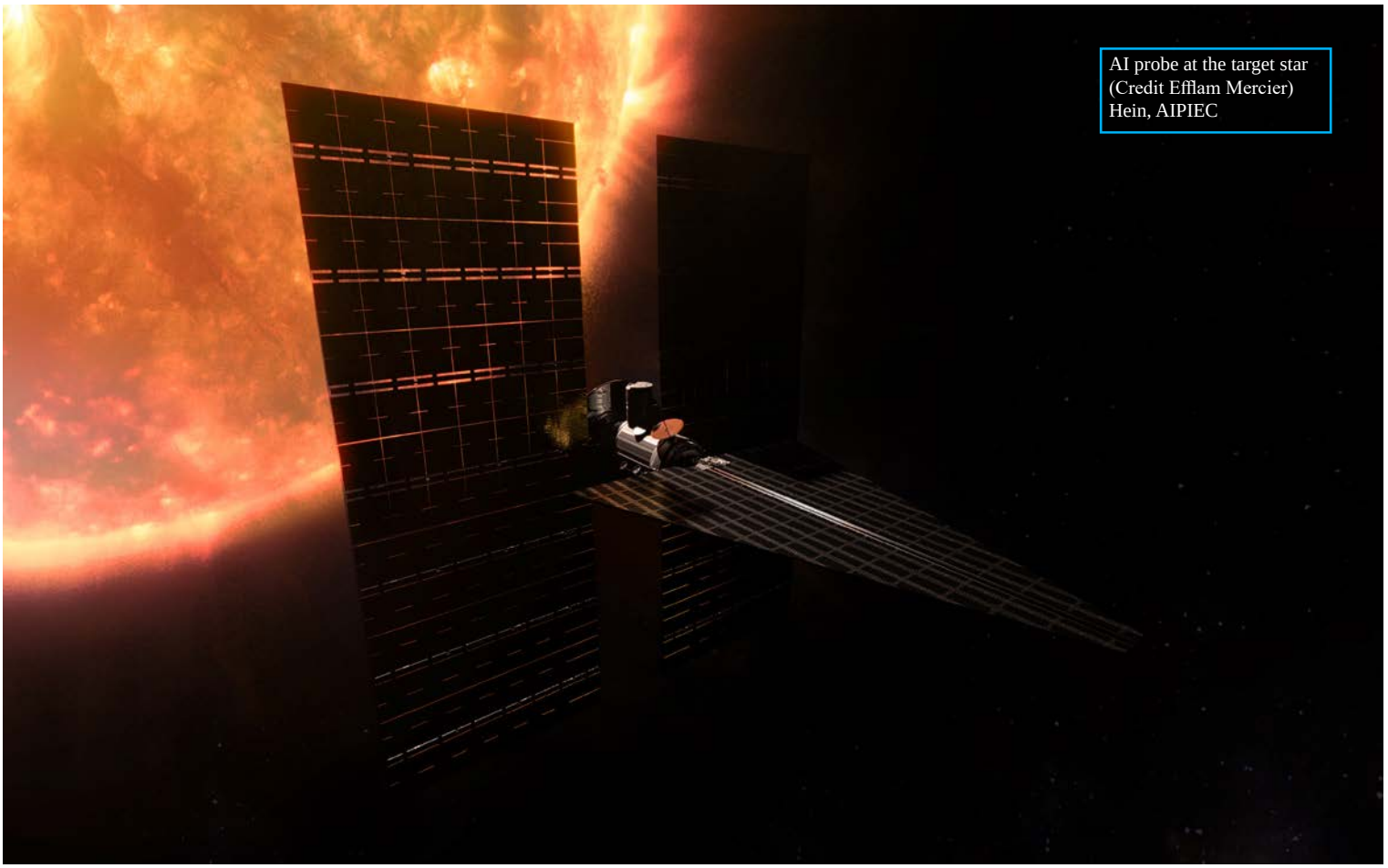
Once again we at i4is are immensely grateful for the interpretations of our thinking by visual artists. Andreas' recent paper has been enhanced by the work of Adrian Mann (www.bisbos.com) and you will find his visualisation of the probe subsystems above.

Andreas also called upon the vision of a new artist, Efflam Mercier, and it is his vision we especially celebrate here. You will find two of his images in Andreas' paper but he was inspired to create many more. And he has kindly allowed us access to them all so

Project Dragonfly in Principium

Dragonfly has featured in several editions of Principium. You can find them all at i4is.org/Publications/Principium/

- Principium 6 - Project launch
- Principium 9 - Competition funding
- Principium 10 - The competition result
- Principium 11 - Project Dragonfly - The Movie! and Sailing to unknown shores: The i4is Project Dragonfly Competition
- Principium 12 - Project Dragonfly - the way forward



AI probe at the target star (Credit Efflam Mercier) Hein, AIPIEC

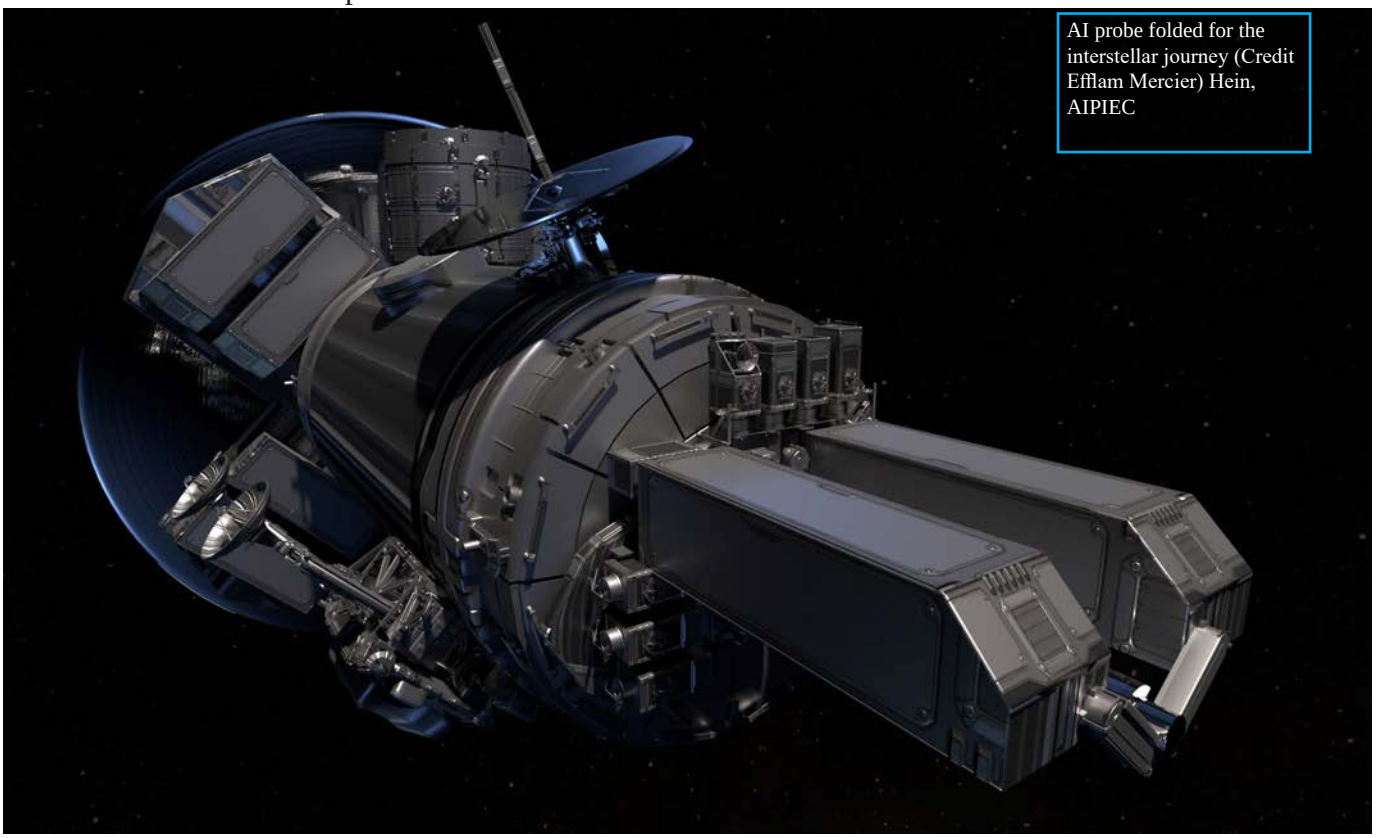
we present a selection here and on our cover. You can find his wider work at www.efflammercier.com.

The AI Probe in Action

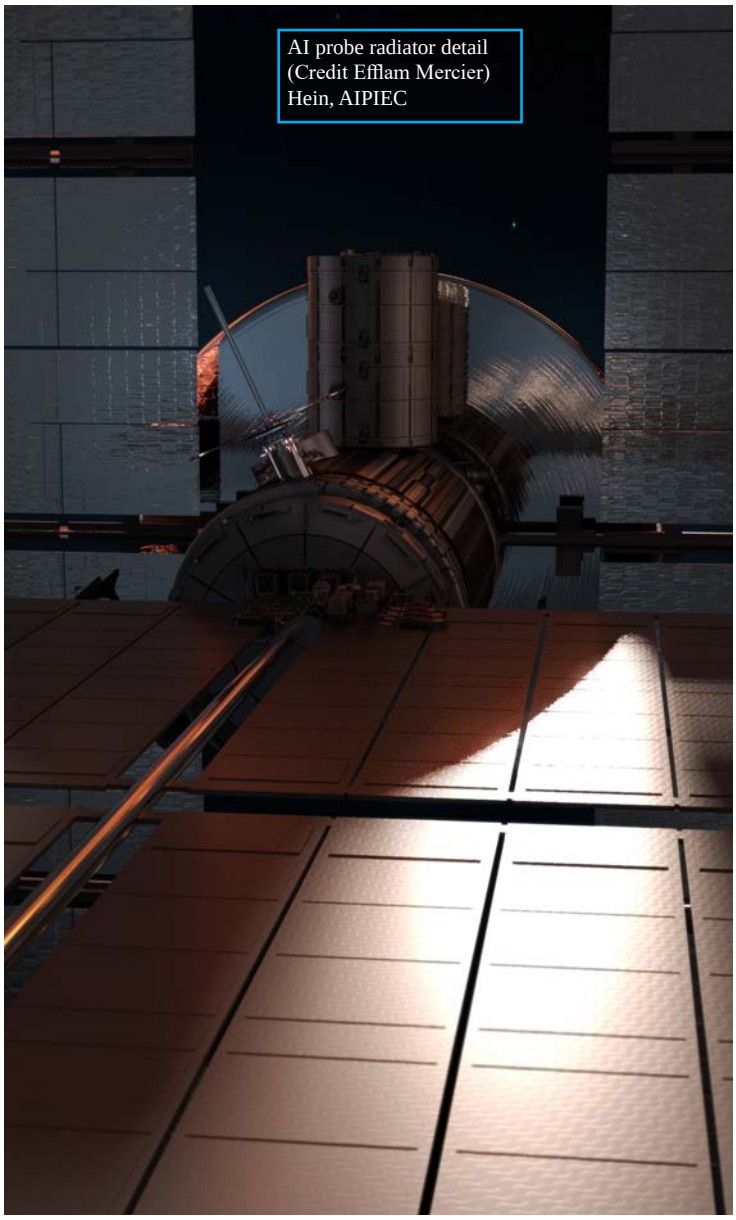
Andreas analyses the computing requirements which might be expected of a probe exhibiting full AGI and concludes that the power demands will be substantial. So his probe would operate close to its target star to draw power from it. Efflam shows this and includes another necessity, a radiator shielded by the solar array and facing "black" space at 4 degrees Kelvin.

The AI Probe in Transit

But first you have to get your probe there and you need to make it as compact as possible for the journey. Efflam has visualised the probe in its folded state.



AI probe folded for the interstellar journey (Credit Efflam Mercier) Hein, AIPIEC



AI probe radiator detail (Credit Efflam Mercier) Hein, AIPIEC

Solar panels and radiator (Credit Efflam Mercier) Hein, AIPIEC

Energy in and out

The energy input and dissipation naturally dominate the structure of the probe. And the energy source may be a hotter white star. Efflam visualises this magnificently here.

We hope to see more of his work in Principium and other i4is publications.

A whiter, hotter, star may be the target (Credit Efflam Mercier) Hein, AIPIEC

About our artists

Adrian Mann (www.bisbos.com) has an unsurpassed record as an astronautical illustrator and film maker. His images of the Reaction Engines Skylon single stage to orbit launcher (www.bisbos.com/space_rel_skylon.html) and the BIS Daedalus starship (www.bisbos.com/space_n_daedalus.html) have been especially celebrated in Principium.

Efflam Mercier is a more recent visionary working in space and fantasy art - from static images to gaming and films (www.efflammercier.com). Most recently he was a Concept Artist on *X-men Apocalypse* and he is currently working in the world building / IP team at Riot Games.

NEXT ISSUE

Guest Introduction: High specific impulse propulsion by prominent propulsion engineer, Angelo Genovese
Is the Alcubierre Drive the answer to Interstellar Travel, Tishtrya Mehta
Orbital Mechanics in SevenEves by Neil Stephenson, Richard Osborne

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.

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, Twitter (@I4Interstellar) or LinkedIn to join in the conversation.

Editor: John I Davies
Deputy Editors : Kelvin F Long, Patrick Mahon
Layout: John I Davies

The Initiative For Interstellar Studies is a pending institute, incorporated in the UK in 2014 as a not-for-profit company limited by guarantee.

Front cover: AI probe orbits star, Credit: Efflam Mercier
Back cover: ESO ALMA and the centre of the Milky Way, Credit: ESO

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Scientia ad sidera
Knowledge to the stars