PRINCIPIUM

The Newsletter of the Initiative for Interstellar Studies
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Scientia ad sidera
Knowledge to the stars

Editorial

Welcome to Principium, the quarterly newsletter from i4is, the Initiative for Interstellar Studies - and our US-based Institute for Interstellar Studies. We aim to report on and support all things interstellar. And a special welcome if you are a new reader . Please tell us if we have your details incorrect (info@i4is.org).

Our Introduction feature for Principium 21 is *"Slow down!": How to park an interstellar rocket* by regular contributor Tishtrya Mehta. It's based on work by a good friend of i4is, Prof Dr Claudius Gros.

Our front cover this time is an image created by the TU Delft, Evolving Asteroid Starships project. More about it in the Interstellar News.

Our rear cover is an impression of the Gaia astrometry observatory currently bringing us unprecedented detail on thousands of our nearest stellar neighbours from its orbit around Lagrange point 2.

The astronautical world gets together each year in the International Astronautical Congress (IAC). We present abstracts of nine papers by i4is team members accepted for the 69th IAC in Bremen, Germany, in October 2018.

We have the second and concluding part of Sander Elvik's analysis in *The Orbits of Seveneves - Part 2 - the orbits explained*. Here he gives some simple orbital dynamics from the novel, *Seveneves*. Neal Stephenson writes both outer space and 'inner space' but for this one his time at Blue Origin may have helped.

Two book reviews this time - *Going Interstellar - Build Starships Now!* an anthology of fiction and non-fiction edited by Les Johnson and Jack McDevitt, and *Rendezvous with Rama*, by Arthur C Clarke, a retrospective review in the light of that rather Rama-shaped interstellar asteroid the i4is Lyra team have been studying.

One of our newer visual art contributors, Efflam Mercier, has a picture feature *Imagining Interstellar* showing more of Andreas Hein's AI starship and a wider work from Efflam's brilliant imagination.

• Our Interstellar News this time includes a Project Lyra Update and includes news of ESA interest in DSTART - TU Delft Starship Team and their Evolving Asteroid Starships and of i4is team presentations at the 44th annual Asilomar Microcomputer Workshop, *Catching A Little Bit of Heaven.* News also of the BBC Sky at Night programme on 'Oumuamua and the NASA online learning resource -Asteroid Ace for Schools. We also report on Darryl Seligman's published work *In Situ Exploration of `Oumuamua-like objects*. Future events include the 16th Reinventing Space conference in London in November and the 69th IAC in Bremen, Germany, in October - with several of our team presenting. And our own upcoming events including

- the second *Interstellar Challenge for Schools* at the University of Warwick, in September
- an i4is summer school at the Royal Institution, London, *Skateboards to Starships*, in August
- an imminent presentation, *The Stellar Challenger-A Concept Study* by Mark Hempsell, President of the BIS at our HQ, the Mill, Friday 1 June.

And we announce our first Starship Engineer Summer School, also at the Mill, in August.

And we have three News Features - a report of the i4is contribution on novel propulsion technologies to the 2018 Breakthrough Discuss conference, news of a NASA-funded project *PROCSIMA - Diffractionless Beamed Propulsion for Breakthrough Interstellar Missions* and of a BIS study group report on options for launching nanosats from the UK.

Our major feature introducing Z-pinch fusion propulsion based on the Project Icarus Firefly concept is postponed to our August issue, P22. We will also have a piece, *Nomadic Planets and Interstellar Exploration* by Marshall Eubanks of Asteroid Initiatives and other contributions to the interstellar endeavour plus news of all the upcoming events mentioned in our News this time and more about the October IAC conference, especially the i4is presence at this biggest astronautical event of the year.

Comments on i4is and all matters interstellar are always welcome,

John I Davies, Editor, john.davies@i4is.org

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Follow us on Twitter at @I4Interstellar and seek out our followers too!
Contact us on email via info@i4is.org.
All issues of Principium are at www.i4is.org/Principium.

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

"Slow down!": How to park an interstellar rocket

Tishtrya Mehta

INTRODUCTION FEATURE

Solar physicist Tishtrya Mehta is a regular Principium contributor. Here she brings us an introduction to momentum braking, based on work by Professor Dr Claudius Gros, Johann Wolfgang Goethe-Universität, Institut für Theoretische Physik, Frankfurt/Main Germany.

So goes the old saying 'What goes up, must come down'. Since the dawn of human flight we've come to learn that this phrase no longer rings true and we have since launched probes, rockets and platforms deep into space without the intention of them ever returning to Earth. One of the most celebrated is the New Horizons probe which recently enjoyed a flyby of everyone's favourite dwarf planet Pluto, sending back breath-taking images of the small rock in incredible detail, and has continued to hurtle through space with no intention of slowing down. This is a problem facing aerospace engineers as so far we have developed successful technologies capable of accelerating fast enough to reach interstellar distances, but now we must face the challenge of slowing the craft down sufficiently so it may fall into orbit around its target or at least attempt a flyby with a significant enough duration to collect and transmit valuable data.

Currently the most appealing and realistic target for interstellar travel is the Proxima Centauri system, headed by a low-mass red dwarf star, a mere 4.25 light-years from us. Thus, using a probe that can accelerate to around a tenth of the speed of light, a journey seems feasible within the duration of a human lifetime. A difficulty lies in decelerating a probe travelling at 3×10^4 km/s to a near stationary state, as our usual methods of braking involve copious friction between the moving object and a stationary medium; think of the wheels of a slowing car against the surface of a road, or an Apollo capsule crashing to a halt upon contact with the Earth. In space there is no 'road' as such, just a sparsely populated 'interstellar medium' (ISM) which is of a very low density and so offers little friction in ordinary circumstances. This is why we can accelerate probes to such high speeds in space and expect little resistance and allow the probe to continue at a largely unchanged velocity many years after the initial acceleration.

Critically, the ISM is not a complete vacuum and the material within it, even if low density, contains a significant amount of ionised molecules which can be harnessed to serve as means to slow down a probe, which is the key mechanism behind the idea of momentum braking.

So how does it work? Momentum braking relies on transferring the kinetic energy of the probe to its surroundings, in this case the ISM, which can be effectively carried out via the use of a magnetic sail. Prof Gros puts forward a candidate of a Biot-Savart magnetic sail in his 2017 paper [1] which consists of a superconducting loop tethered to a payload, the mass of which doesn't exceed 1.5 tonnes. A Biot-Savart loop carries a current in a closed circle, which in turn creates a magnetic field. This magnetic field changes the trajectory of nearby ionized particles, (usually H+, ionised hydrogen; the simplest and most abundant element found in the universe) and causes them to be reflected, which slows the craft using conservation of momentum.

[1] C Gros, *Universal scaling relation for magnetic sails: momentum braking in the limit of dilute interstellar media*, 2017, J.Phys. Commun, I, 045007, arxiv.org/abs/1707.02801

The laws of Physics dictate that in any closed system (where nothing enters or leaves the 'frame' during the interaction) momentum cannot be lost, only transferred between different bodies. So the momentum lost by the craft must be equal to the momentum gained by the particle.

We can look at this further by considering the equation $p = mv$ where p is momentum, m is mass and v is velocity. So

$$mass_{total}\, v_{craft} = mass_{total\ particles\ encountered}\, v$$

The mass of the particles encountered by the craft in a given unit of time, say T_{unit}, can be given by the density of H^+ ions per m^3 (n_p) swept out by the area of the sail multiplied by the velocity of the craft and the mass per proton (m_p)

ie $$mass_{\text{total particles encountered during}T_{unit}} = Area of sail \times n_p \times m_p \times v \times T_{unit}$$

The particles are assumed to perfectly reflect (which gives the greatest change in momentum, and so the most efficient braking), and velocity is a vector quantity so that we define 'positive' velocity in the direction of travel for the craft. Therefore the change in velocity can be found by subtracting the 'new' velocity from the 'old' velocity, i.e. *(-v)-(+v) = -2v*

Therefore the momentum change in a unit of time may be given by:

$$mass_{total}\, v = -2v(Area_{sail} \times n_p \times m_p \times v \times T_{unit})$$

Or by employing basic differentiation, we can see that the rate of decrease in momentum (or analogously the rate of deceleration) is given by

$$\frac{d}{dt}(mass_{total}\, v) = -2v(Area_{sail} \times n_p \times m_p \times v)$$

Therefore it can be seen that the area of the sail has a great effect on how quickly and effectively we can begin braking the craft, which intuitively makes sense.

The craft is able to reflect particles via the principle that charged particles in a magnetic field travel in circular orbits. This phenomenon can be seen in cloud chambers which trace out the path taken of incoming particles as seen in Figure 1. The spiral orbits correspond to low mass charged particles, likely electrons and positrons, which have been guided into circular trajectories via a magnetic field but due to losses of energy due to friction etc fall into smaller orbits with each turn, which presents itself as a spiral path. The sail functions by the same principle.

When a particle approaches the craft from a region of negligible magnetic field it can be treated as having a velocity perpendicular to the craft's reference frame since the velocity of the craft is very high by comparison with that of the particle (see below).

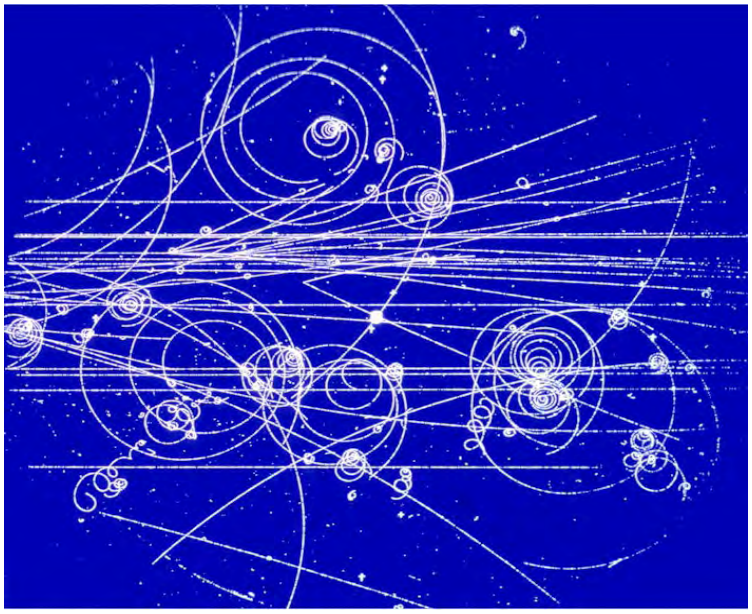


Figure 1: Tracks from particles in a cloud chamber. Source: CERN 2 cerncourier.com/cws/article/cern/28742 "A classic bubble chamber photograph. Millions of such interactions were studied during the 1960s and 1970s."

As stronger magnetic fields (given by 'B') produce smaller orbits, we can examine how B affects the efficiency of reflecting particles (where $B_1 < B_2 < B_3$).

In B_1 the magnetic field is extremely weak, and so this produces a large radius of orbit for the particle, which it cannot complete within the width of the magnetic field, and so the particle exits the region at an angle, but certainly not reflected. This is therefore inefficient.

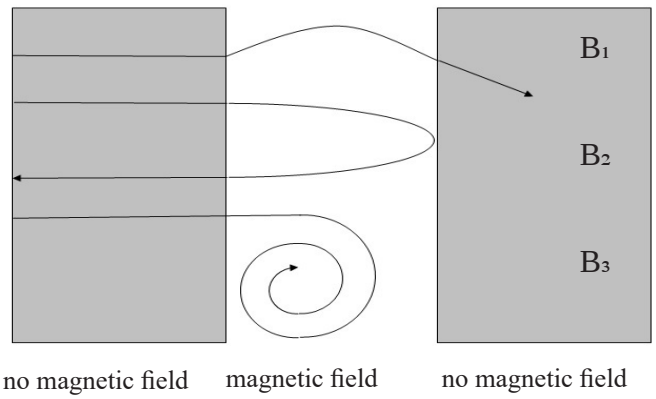


Figure 2: A sketch demonstrating how the strength of the magnetic field affects the trajectory for a charged particle encountering the craft. Source: Author's own.

In B_2 we have a magnetic field tuned so an oncoming particle may complete exactly half an orbit before exiting the region parallel to its direction of entry. This gives perfect reflection.

For any magnetic field strength greater than B_3, a particle will be drawn into a tight spiralling orbit upstream of the craft. This is less efficient than total reflection but still contributes to slowing the craft. Therefore the ideal magnetic field is in the vicinity of B_2 which in the case for a 1.5 tonne craft travelling at 0.1 c to Proxima Centauri as Prof Gros has put forward, requires a current of around 105 Amps, the feasibility of which is discussed further in his paper. Each particle is usually a single positive Hydrogen ion which therefore has the mass of one proton and a positive charge equivalent to the magnitude of one electron, since its 'normal paired' electron is missing.

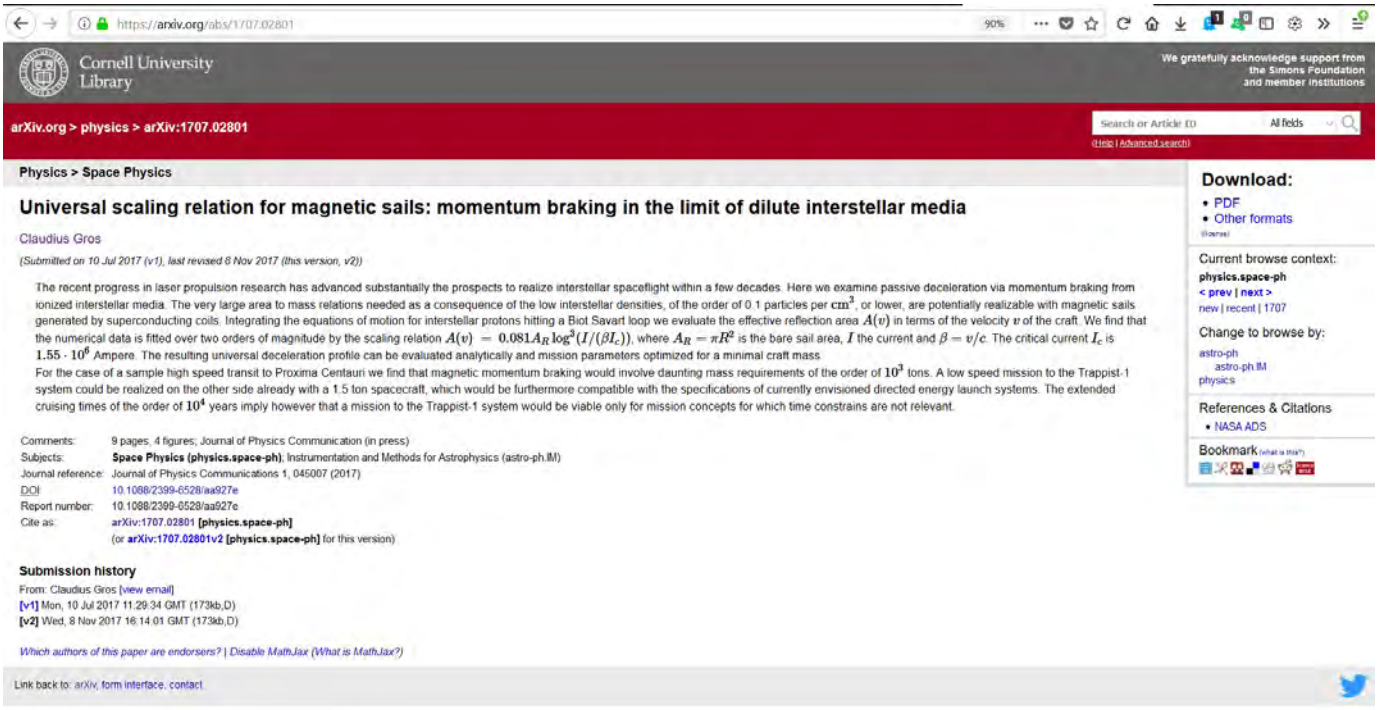
Hence it is plausible to consider the technology of momentum braking to be implemented on an interstellar craft in order to decelerate them as the materials, energies and mechanics underlying the principles are all within reasonable budgets and certainly within the timescales envisaged by even the most optimistic developers of interstellar craft! This technology represents an ingenious and exciting answer to a well-rehearsed problem and is one of several candidates put forward in recent years. Other issues to continue addressing and revising include the mechanisms of accelerating a craft to 0.1 c, developing a craft with all necessary capabilities to collect and send back data which has a mass of less than 1.5 tonnes, and ensuring the craft can 'survive' for several decades. There are of course many more barriers to overcome but this new insight in braking technology may place us one step closer to realising the goal of sending a probe to another star system within a human lifetime.

Acknowledgement

Special thanks to Prof Claudius Gros for his kind assistance in the writing of this article, errors and omissions are, of course, attributable to the author and not to Professor Gros.

Prof Gros heads a research group and lectures at the Institute for Theoretical Physics at Goethe University, Frankfurt, and recently wrote a textbook on CADS (Complex and Adaptive Dynamical Systems) [2]. He regularly gives talks on topics ranging from the philosophical "Can we personally influence the future with our present resources?" to the highly specialised "Interaction induced Fermi-surface renormalization".

[2] www.springer.com/gb/book/9783319162645
Complex and Adaptive Dynamical Systems
A Primer, Claudius Gros, Springer International Publishing (2015).
ISBN 978-3-319-16264-5,
DOI 10.1007/978-3-319-16265-2



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Universal scaling relation for magnetic sails: momentum braking in the limit of dilute interstellar media

Claudius Gros

(Submitted on 10 Jul 2017 (v1), last revised 8 Nov 2017 (this version, v2))

The recent progress in laser propulsion research has advanced substantially the prospects to realize interstellar spaceflight within a few decades. Here we examine passive deceleration via momentum braking from ionized interstellar media. The very large area to mass relations needed as a consequence of the low interstellar densities, of the order of 0.1 particles per cm^3, or lower, are potentially realizable with magnetic sails generated by superconducting coils. Integrating the equations of motion for interstellar protons hitting a Biot Savart loop we evaluate the effective reflection area $A(v)$ in terms of the velocity v of the craft. We find that the numerical data is fitted over two orders of magnitude by the scaling relation $A(v) = 0.081 A_R \log^3(I/(\beta I_c))$, where $A_R = \pi R^2$ is the bare sail area, I the current and $\beta = v/c$. The critical current I_c is $1.55 \cdot 10^6$ Ampere. The resulting universal deceleration profile can be evaluated analytically and mission parameters optimized for a minimal craft mass.
For the case of a sample high speed transit to Proxima Centauri we find that magnetic momentum braking would involve daunting mass requirements of the order of 10^3 tons. A low speed mission to the Trappist-1 system could be realized on the other side already with a 1.5 ton spacecraft, which would be furthermore compatible with the specifications of currently envisioned directed energy launch systems. The extended cruising times of the order of 10^4 years imply however that a mission to the Trappist-1 system would be viable only for mission concepts for which time constrains are not relevant.

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Subjects: **Space Physics (physics.space-ph)**; Instrumentation and Methods for Astrophysics (astro-ph.IM)
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Report number: 10.1088/2399-6528/aa927e
Cite as: arXiv:1707.02801 **[physics.space-ph]**
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About the author
Tishtrya Mehta is a postgraduate researcher at the University of Warwick, specialising in data analysis of quasi-periodic pulsations in solar and stellar flares. Tishtrya is Deputy Chair of the Education Committee of the Initiative for Interstellar Studies.

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This is the world's first dedicated five-day residential education course that focuses on deep space for interplanetary and interstellar exploration. Students will be introduced to the fundamental concepts of spacecraft design which involve all systems and include advanced propulsion methods and other relevant topics.

The course will be hosted at the i4is HQ in our brand new conference room and design centre, surrounded by inspirational art work, spacecraft models and flown in space artefacts to complement the lectures and learning. It will be presented as a series of lectures during the day and a workshop in the afternoon to get you into the deep end of how to design a spacecraft.

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The course will be run by the lead lecturers and supported by other lecturers for specialist topics. Kelvin F Long is the President of the i4is, with degrees in aerospace engineering and astrophysics. He is also the author of "Deep Space Propulsion: A Roadmap to interstellar flight". Rob Swinney is the Deputy Director of the i4is, with degrees in Astronomy and Astrophysics and also Radio Astronomy.

Price: **£450** or **£337** for registered students, unemployed or senior citizens. Price is excluding hotel accommodation. Price includes daily lunches and a workshop dinner.

The i4is HQ is 10 minutes by road from M5 junction 14, just north of the M4 interchange. It is 25 minutes by taxi from Bristol Parkway station on the Wales & Cornwall line from London Paddington station. For international travellers Bristol Airport has services from most major European cities and has a designated bus/train connection to Bristol Parkway station. We will follow up all reservations for this course with recommendations and contacts for accommodation in due course. Transport to and from i4is HQ will also be identified and group arrangements will be made.

For more information or to book your place, e-mail* course@i4is.org *and specify 'Starship engineer' in the subject line.

www.i4is.org

NEWS FEATURE

PROCSIMA - Diffractionless Beamed Propulsion for Breakthrough Interstellar Missions

NASA funds early stage research into a novel approach to beamed propulsion

Patrick Mahon

On 30 March, NASA's Innovative Advanced Concepts (NIAC) office announced funding for 25 early stage technology proposals. One of them may provide a solution to a problem that has bedevilled interstellar propulsion researchers for some time.

If you're trying to get to the stars, carrying your own fuel with you can be a real bind. The distances are so great that, if you want to get there within a human lifetime, you need to go quickly. More quickly than is reasonably achievable using chemical rockets.

One alternative to traditional rockets, which carry their fuel and oxidiser with them, is beamed propulsion, where the energy source which powers the spacecraft's acceleration to cruising speed is not carried on board but is generated remotely and beamed through space to the vehicle.

An example is the laser sail, close relation to the solar sail, where the vehicle is accelerated by light - provided by a large, powerful laser - bouncing off the spacecraft's reflective sail.

A major problem with beamed propulsion technologies comes from the spreading out of the power beam as it travels through space from its source to the spacecraft. Even a highly collimated laser beam suffers from some dispersion, the width of the beam increasing as it travels through space.

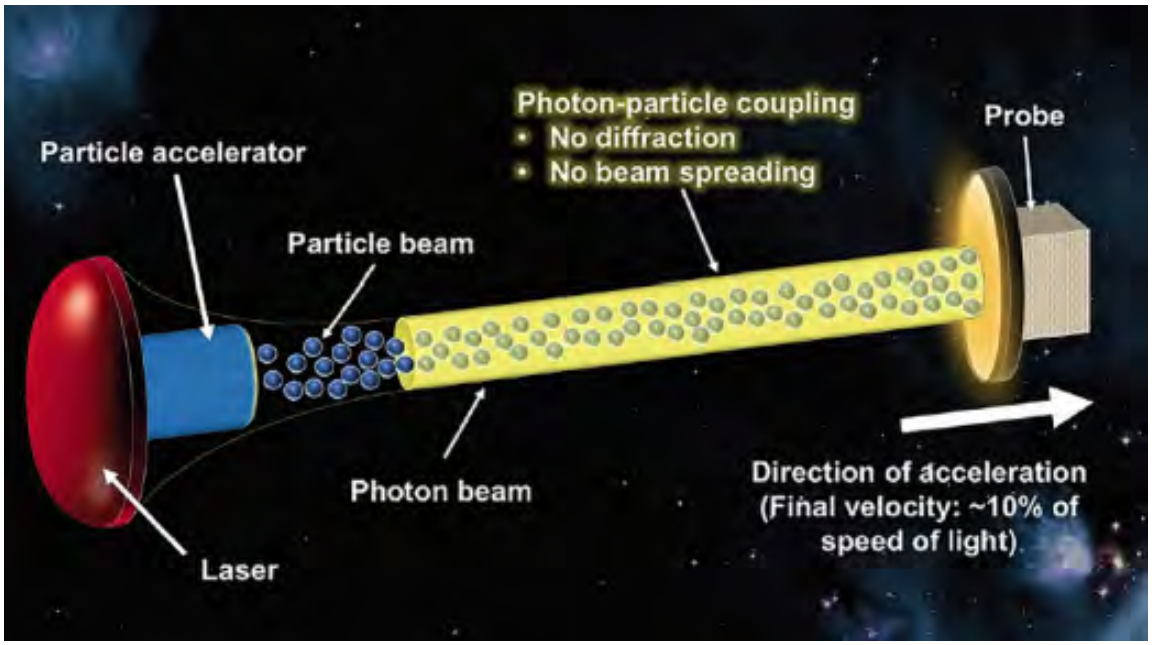
The NASA Innovative Advanced Concepts (NIAC) program nurtures visionary ideas that could transform future NASA missions
More at www.nasa.gov/directorates/spacetech/niac

As an example, the laser beams used to measure the distance from the Earth to the Moon precisely, by bouncing them off the retro-reflectors left on the surface of the Moon by the Apollo astronauts, spread from a few metres wide when emitted on Earth (the laser light is sent through a telescope aimed at the Moon, so the beam is the same size as the telescope's mirror) to being around 6.5 km wide, roughly two thousand times the original width, when they hit the Moon, some 385,000 km away.

Returning to a laser sail, once the diameter of the laser beam has spread out enough that it is wider than the spacecraft's sail, you start to lose performance, since some of the beam's energy misses the spacecraft and is therefore wasted. Beyond this point, you're in a losing battle with geometry, and soon enough the beam will effectively cease to accelerate the spacecraft any more.

The new project which has just been funded by NIAC

Graphic depiction of PROCSIMA: Diffractionless Beamed Propulsion for Breakthrough Interstellar Missions
Credits: C Limbach, Texas A&M Engineering Experiment Station and NASA



proposes a novel mechanism for sidestepping these problems, using a beam that combines a laser with particles, each of which keeps the other under control.

The project, as described by Chris Limbach of Texas A&M Engineering Experiment Station, who wrote the proposal, combines a beam of neutral particles (such as hydrogen atoms) with a beam of laser light, in such a way that the two interact to retain their overall focus.

As Limbach explains in NASA's press release [1], 'The elimination of both diffraction and thermal spreading is achieved by tailoring the mutual interaction of the laser and particle beams so that -

(1) refractive index variations produced by the particle beam generate a waveguide effect (thereby eliminating laser diffraction); and

(2) the particle beam is trapped in regions of high electric field strength near the centre of the laser beam. By exploiting these phenomena simultaneously, we can produce a combined beam that propagates with a constant spatial profile.'

Limbach goes on to say that this approach should increase the distance through which the beam can continue to accelerate the spacecraft by a factor of ten thousand, enabling the sending of a 1kg payload to Alpha Centauri at 10% of the speed of light, so that it arrives in just 42 years.

A discussion of how the proposed photon-particle interactions might work can be found in two successive posts on the Centauri Dreams blog [2], [3].

Chris Limbach will receive phase 1 funding of $125,000 over nine months from NIAC, in return for which he must produce an initial definition and analysis of the proposed system. If this is well-received by NASA, he may then be able to apply for phase 2 funding of up to $500,000 over two years, so that he can develop his ideas further.

References

[1] 'PROCSIMA: Diffractionless Beamed Propulsion for Breakthrough Interstellar Missions', NASA press release, 30 March 2018. www.nasa.gov/directorates/spacetech/niac/2018_Phase_I_Phase_II/PROCSIMA

[2] 'PROCSIMA: Wedding Two Beam Concepts', Paul Gilster, 4 April 2018. www.centauri-dreams.org/2018/04/04/procsima-wedding-two-beam-concepts .

[3] 'Tightening the Beam: Correspondence on PROCSIMA', Paul Gilster, 5 April 2018. www.centauri-dreams.org/2018/04/05/tightening-the-beam-correspondence-on-procsima .

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

Interstellar News

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

DSTART - TU Delft Starship Team

Angelo Vermeulen, founder of the TU Delft Starship Team (DSTART), says "In light of our insatiable appetite for exploration, it is inevitable that the human species will ultimately travel outside of the known solar system. It is the next step in human evolution." (www.tudelft.nl/en/tpm/research/projects/from-creative-chaos-to-interstellar-spaceship/). The team have ESA interest in their Evolving Asteroid Starships and will be presenting at the first joint AgroSpace-MELiSSA workshop (www.esa.int/Our_Activities/Space_Engineering_Technology/Melissa/Register_for_AgroSpace-MELiSSA_workshop_16-18_May_2018) as we go to press.

BBC Sky at Night - 'Oumuamua

The veteran BBC astronomy programme recently broadcast *The Mystery of 'Oumuamua*. Sadly the BBC have removed this episode from their i-Player service but there is a YouTube copy at www.youtube.com/watch?v=PMbf71VHh5I. We will naturally keep Principium readers up to date on developments concerning our first known interstellar visitor. See elsewhere in this News for an update on our Project Lyra, a study of a possible intercept mission to Oumuamua.

Catching A Little Bit of Heaven

President of i4is-US, Robert G Kennedy III, is a founder of the Asilomar Microcomputer Workshop (www.amw.org). The 44th annual workshop last month (April 2018) included an interstellar segment, *Catching A Little Bit of Heaven*, led by T Marshall Eubanks (Asteroid Initiatives LLC, www.asteroidinitiatives.com), who Principium readers will remember from his piece in the last issue, *Preparing for the next Interstellar Object*. Robert Kennedy gave a backgrounder, *Interstellar Interlopers: Getting Ready for the Next Surprise*. Marshall Eubanks discussed the exploration of passing interstellar asteroids in *Such a Long Time To Be Gone, Only a Few Milliseconds To Be There*. Dan Fries (Georgia Tech) explained *Interstellar Capabilities: Why the Biggest Laser is Not Big Enough*. All these presenters were part of our Project Lyra (i4is.org/what-we-do/technical/project-lyra) team, which analysed how we might reach Oumuamua, the first known interstellar asteroid (see our Project Lyra Update in this issue and much more in our previous issue, P20).

Interstellar Challenge - Warwick

The second Interstellar Challenge for Schools will take place at the University of Warwick on 11 September 2018. Readers may recall the first challenge at Imperial College London in December 2016 (see Principium 19, November 2017).

Tishtrya Mehta, a researcher at the university is also our Deputy Chair of Education, and will be leading this year's challenge with

Impression of 'Oumuamua from *The Mystery of 'Oumuamua*
Credit: BBC Sky at Night

John Davies. We are currently contacting nearby schools to participate but please contact John (John.Davies@i4is.org) if you are a school staff member near Warwick and have not yet heard from us or about this team event for space enthusiasts in schools.

16th Reinventing Space Conference

RIspace 2018 will be from Tuesday 30 October until Thursday 1 November 2018 at 4 Hamilton Place, London, UK (rispace.org).

IAC Bremen 2018

The 69th International Astronautical Congress is this year in Bremen, Germany, 1-5 October 2018. Members of the i4is team will be there and you can find us by Tweeting to @i4interstellar or at the BIS stand. Several of the team are presenting at the Congress and we publish their abstracts, *Papers by the i4is Team*, elsewhere in this issue. More about IAC 2018 in our next issue in August.

i4is at the Royal Institution

i4is will be presenting a summer school event at that oldest of UK scientific organisations, the Royal Institution, on Monday 20 August. John Davies and Satinder Shergill will take school students from *Skateboards to Starships* via the story of three heroes of maths science and engineering - Al-Karismi for algebra, Isaac Newton for his equations of motion and Konstantin Tsiolkovsky for the tyrannical rocket equation. More information and how to attend on the RI website (www.rigb.org/whats-on/events-2018/august/summer-schools-skateboards-to-starships-age-1315).

Mark Hempsell at the Mill

Mark Hempsell, President of the BIS, has kindly agreed to replace David Baker at our HQ lecture- 1 June 2018 5pm. *The Stellar Challenger- A Concept Study* - proposes a nuclear rocket engine combining thermodynamic and electrical heating yielding exhaust velocities above 12 km/sec - about twice the maximum for a chemical rocket. Contact us at info@i4is.org to attend.

In Situ Exploration of `Oumuamua-like objects

As we mentioned last time, Darryl Seligman of Yale University has also been looking into missions to interstellar visitors. His paper, *The Feasibility and Benefits of In Situ Exploration of `Oumuamua-like objects*, by Darryl Seligman and Gregory Laughlin is now available (arxiv.org/abs/1803.07022). You may find Paul Gilster's summary at Centauri Dreams a little more accessible - *Mission to an Interstellar Asteroid* (www.centauri-dreams.org/2018/03/21/mission-to-an-interstellar-asteroid).

NASA -Asteroid Ace for Schools

NASA have produced, for their 5th *Pi in the Sky* feature, *Asteroid Ace* www.jpl.nasa.gov/edu/teach/activity/pi-in-the-sky-5/ challenging school students to derive the angular rotation rate of asteroid 'Oumuamua in radians per second from the observed rotation period.

Starship Engineer Summer School

And finally, don't miss the poster on page 6 in this issue for the first Starship Engineer Summer School at our HQ, The Bone Mill, 15-19 August. This is an opportunity to attend the world's first five day course on deep space and interstellar exploration. Our Early Bird offer gives you 20% discount if you book before 1st July.

The Royal Institution of Great Britain
Credit: Gryffindor+Wikipedia

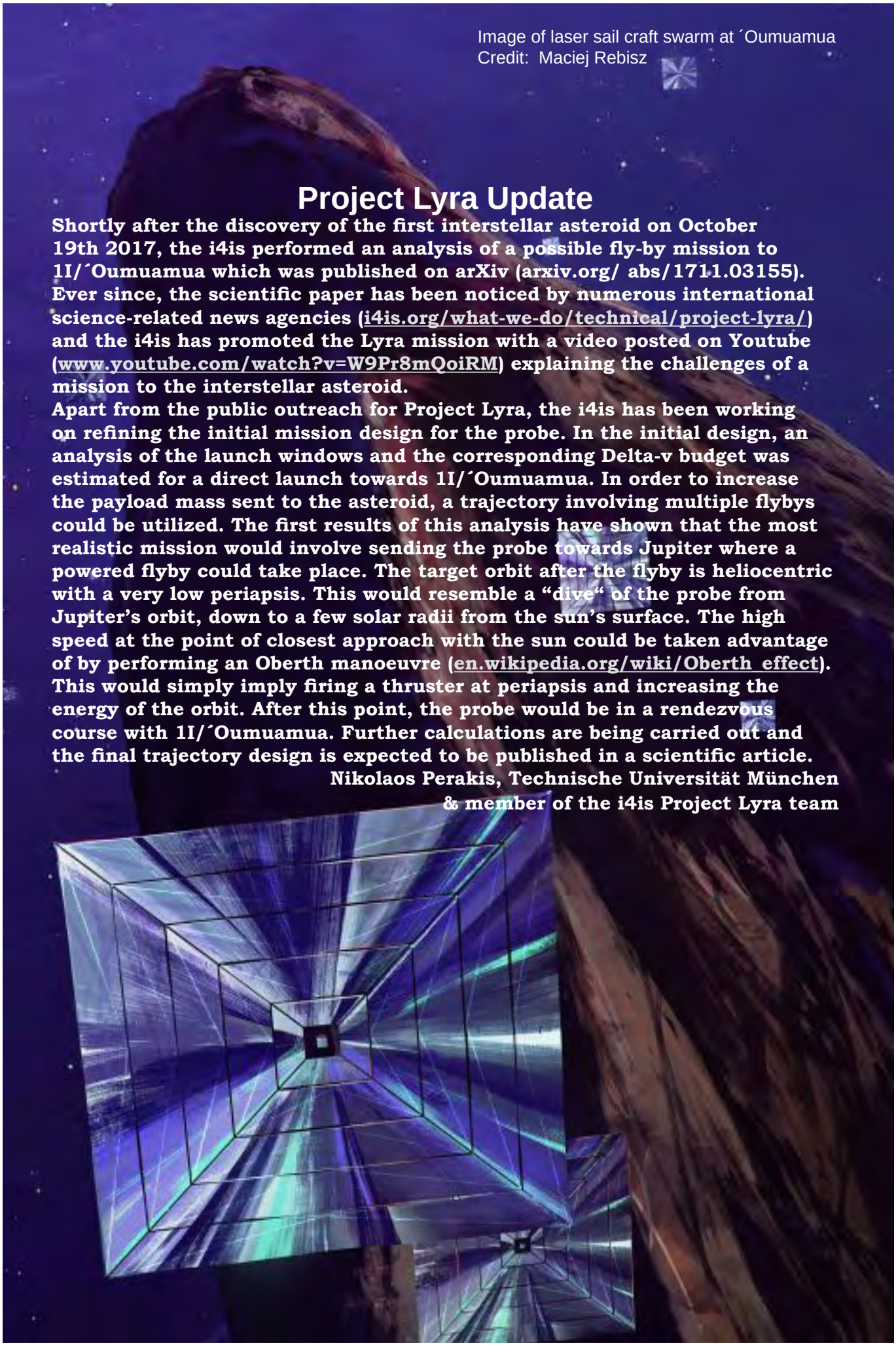


Image of laser sail craft swarm at ´Oumuamua
Credit: Maciej Rebisz

Project Lyra Update

Shortly after the discovery of the first interstellar asteroid on October 19th 2017, the i4is performed an analysis of a possible fly-by mission to 1I/´Oumuamua which was published on arXiv (arxiv.org/ abs/1711.03155). Ever since, the scientific paper has been noticed by numerous international science-related news agencies (i4is.org/what-we-do/technical/project-lyra/) and the i4is has promoted the Lyra mission with a video posted on Youtube (www.youtube.com/watch?v=W9Pr8mQoiRM) explaining the challenges of a mission to the interstellar asteroid.

Apart from the public outreach for Project Lyra, the i4is has been working on refining the initial mission design for the probe. In the initial design, an analysis of the launch windows and the corresponding Delta-v budget was estimated for a direct launch towards 1I/´Oumuamua. In order to increase the payload mass sent to the asteroid, a trajectory involving multiple flybys could be utilized. The first results of this analysis have shown that the most realistic mission would involve sending the probe towards Jupiter where a powered flyby could take place. The target orbit after the flyby is heliocentric with a very low periapsis. This would resemble a "dive" of the probe from Jupiter's orbit, down to a few solar radii from the sun's surface. The high speed at the point of closest approach with the sun could be taken advantage of by performing an Oberth manoeuvre (en.wikipedia.org/wiki/Oberth_effect). This would simply imply firing a thruster at periapsis and increasing the energy of the orbit. After this point, the probe would be in a rendezvous course with 1I/´Oumuamua. Further calculations are being carried out and the final trajectory design is expected to be published in a scientific article.

Nikolaos Perakis, Technische Universität München
& member of the i4is Project Lyra team

NEWS FEATURE

BIS study group publish report on options for launching nanosats from the UK

The UK is not normally considered a venue for space launches but our older sibling, the British Interplanetary Society (BIS), proposed UK launches in the 1930s and 1940s and there has been renewed interest in both spaceplane launches and polar launches using conventional rockets. Here Patrick Mahon reports recent BIS work on nanosat launches.

In mid-April, the British Interplanetary Society's Nanosat Launch Vehicle (NLV) feasibility study group published their phase 1 report [1], concluding that orbital access to space from the UK is feasible, and could be investor funded. Given i4is's interest in launching technology demonstrators such as Project Glowworm [2] into space, this report looks highly relevant.

The feasibility study started in March 2016 and was produced by a group of volunteers headed up by the Chair of the BIS Technical Committee, Robin Brand FBIS [3]. What makes their report stand out is the approach they have taken, focusing primarily on the economic, rather than the engineering, issues. In particular, they have investigated the question of whether a viable business case can be made for the development of a UK-based launch capability for payloads up to 100 kilogrammes. (Technically, this weight bracket includes microsatellites as well as nanosatellites, but the study's original name stuck.)

The study modelled a number of launch vehicle designs and found that a ground-launched, three stage, pump-fed launch vehicle was the lowest cost, technically feasible option. This would be launched from one of two sites in Northern Scotland into a sun-synchronous or polar orbit. At a proposed schedule of six missions per year, each launch would generate an estimated $4.1-4.9 million in revenues, providing a sufficiently high return to interest investors whilst offering an affordable cost to orbit of around $57,000 per kilogramme of payload.

The report was formally launched at an event at BIS HQ in London on 17 May [4]. The study group will now continue their work into a second phase, which will delve deeper into the practicalities of the approach proposed in the phase 1 report. Anyone interested in getting a copy of the phase 1 report, or of volunteering to join the study group for phase 2, is invited to contact Robin Brand via BIS HQ.

Robin Brand, chair of the BIS Technical Committee announces the nanoSat Launch Vehicle study at UKspace 2017. Credit BIS

References:

[1] 'Investor funded access to space from the UK? The BIS Nanosat Launch Vehicle feasibility study - phase 1 final report', BIS NLV feasibility study group, 13 April 2018.

[2] 'Project Glowworm', i4is project summary, www.i4is.org/what-we-do/technical/project-glowworm/ .

[3] 'BIS Nanosat Launch Vehicle Feasibility Study', BIS Projects webpage, www.bis-space.com/what-we-do/projects/project-nlv.

[4] 'Orbital access to space from the UK?', BIS event calling notice, 1 March 2018, www.bis-space.com/2018/03/01/20283/orbital-access-to-space-from-the-uk. (note that BIS provides members with access to lecture videos).

NEWS FEATURE

i4is debate novel propulsion technologies at Breakthrough Discuss 2018

i4is President Kelvin F Long and i4is team member Elena Ancona both took part in a panel on novel approaches to space propulsion at this year's Breakthrough Discuss Conference last month.

Patrick Mahon

Breakthrough Discuss is an annual scientific conference which forms one of the projects run under the envelope of the Breakthrough Initiatives, a $100 million programme founded by Yuri Milner and others in 2015. The 2018 Breakthrough Discuss Conference was held at Stanford University on 12-13 April. The theme of the conference was 'Alien Life - Diversity in the Universe' [1].

The conference was divided into three sessions, tackling 'The search for life in our solar system', 'Possibilities for non-Terran life in the universe' and 'Progress in Novel Space Propulsion'. There were two keynote speeches: one from Carolyn Porco, Leader of the Cassini spacecraft's imaging team, on the possibility of life in the subsurface oceans on Saturn's moon Enceladus, and another from the Astronomer Royal, Emeritus Professor Martin Rees, asking the question 'Will SETI Detect Organic or Electronic Intelligence?'

Kelvin and Elena both took part in a panel debate at the end of the third session, following talks on six different propulsion approaches from such luminaries

Kelvin (centre) in discussion

as Bob Zubrin, Geoffrey Landis and Les Johnson. The panel discussed such diverse topics as:

- the importance of materials science advances to the development of laser sails;
- the value of adopting hybrid approaches to propulsion engineering by using different technologies in tandem;
- the extent to which exotic propulsion approaches would actually solve all our problems; and
- the importance of not just getting young students interested in the interstellar question, but also enabling them to undertake projects in this area.

All the sessions from Breakthrough Discuss were recorded and are available to watch on You Tube (see the weblinks in the conference agenda), while contemporary commentary on the event can be found on Twitter, using the tag #Discuss2018 .

References:

[1] Breakthrough Discuss 2018 conference agenda, breakthroughinitiatives.org/events/discussconference2018,

Image Credits

Our thanks to Andrew Higgins for these images. Andrew is a Visiting Scholar at UCSB Department of Physics - from McGill University, Canada,where he is an Associate Professor in Mechanical Engineering.

Kelvin (centre) sketching beamed light sail architectures

The Initiative for Interstellar Studies

image: ©ALEX STORER

Working towards the real Final Frontier

Help us to realise our mission to reach the stars - we need your help - physics to software engineering, graphic design to project management - and rocket science of course! ...and much more....

We have a great team. But we need more talent in all departments. Come and join us!

Here are just some of our team -

- **Dr Andreas Hein: i4is Executive Director, System architect & Engineer**
- **Kelvin Long: i4is President, Advisory Council of Project Starshot, author *Deep Space Propulsion, A Roadmap to Interstellar Flight* (Springer)**
- **Paul Campbell: Software Engineer**
- **Richard Osborne: Rocket Scientist**
- **Rob Swinney: Director Education, Project Leader - Project Icarus**
- **Terry Regan: creator of BIS Daedalus model & i4is 2001 Monolith, Truck technician**
- **Tishtrya Mehta: i4is Deputy Director Education, Solar physics researcher**
- **Conor MacBride: Website Editor, Maths / physics student**
- **Patrick Mahon: Programme Manager & Principium deputy editor, Policy analyst**
- **John Davies: Principium editor & schools organiser, Telecoms consultant**

Contact: info@i4is.org
- and let's talk!

Web: i4is.org
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Facebook: InterstellarInstitute
Principium:
tinyurl.com/principium

69th International Astronautical Congress 2018

Papers by the i4is Team

John I Davies

The Initiative for Interstellar Studies brings together an all-volunteer team committed to the achievement of interstellar travel and communication. Several of us have submitted, and had accepted, papers to be presented at the 69th International Astronautical Congress to be held in Bremen, Germany, 1 - 5 October, 2018. We present here abstracts of papers by -

Adam Crowl - Client Service Officer, Queensland Health, Brisbane, Australia

Dr Andreas Hein - Executive Director of the Initiative for Interstellar Studies and Researcher / System Architect at CentraleSupelec, Paris

Kelvin F Long - President of the Initiative for Interstellar Studies, Managing Director of Stellar Engines Ltd, UK, and member of the Advisory Committee of the Breakthrough Initiative Project Starshot

Satinder Shergill - PhD student, Cranfield University, UK and teacher of Physics and Robotics at Space Studio West London

The Principium editors, John Davies and Patrick Mahon, will be reporting from the Congress. Find us via twitter.com/I4Interstellar and at the British Interplanetary Society stand.

Paper ID: 42235
oral
student

IAF SPACE EXPLORATION SYMPOSIUM (A3)
Interactive Presentations (IP)

Author: Mr. Satinder Shergill
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ADAPTIVE IN-SITU RESOURCE UTILISATION (ISRU) FOR LONG TERM SPACE EXPLORATION.

Abstract

This paper aims to present initial results from a pilot study assessing the feasibility of designing an 'Adaptive ISRU system', defined here as an ISRU resource extraction system adaptable to different rocky planetary bodies, and adaptive in its ability to extract resources. Preliminary guiding questions for this study related to whether several ISRU processes could be combined within one enclosed system to enhance functionality and allow smoother transition between different levels of processing, and also whether a system that combines such processes can adapt to the different terrains present on planetary bodies within the inner solar system. The main motivation behind this research is the incorporation of ISRU into long term interplanetary infrastructure. Through attempting to understand how and where ISRU can best be incorporated into long term interplanetary infrastructure, the direction of this research led to considering the need of ISRU systems to be adaptable. While upcoming precursor missions will inevitably help constrain mineralogical distribution and general environmental conditions at certain locations, there is still uncertainty inherent with constraining mineral content and distributions at surface and subsurface boundaries as well as regolith compaction at ISRU destinations of interest. Hence it is believed by the author that functional ISRU systems will need to be adaptive by nature, particularly if they are required to operate autonomously. This paper addresses criteria that would be applicable to a range of different extraction scenarios suitable for the conditions expected on rocky bodies such as the Moon, Mars and Asteroids, as a means of ascertaining the feasibility of an adaptive ISRU system. Although the main focus is on excavation and processing, aspects such as storage and transit are also discussed. Alongside the significance of differing regolith retention and compaction rates, the obtainable and required particle sizes for ISRU processing, and how this should influence the ordering of combined processes is also considered. The proposal of an adaptive ISRU system is based on a desire to focus on the commonalities found in extra-terrestrial environments to then be in a stronger position to deal with the differences.

Paper ID: 43104
oral

SPACE PROPULSION SYMPOSIUM (C4)
New Missions Enabled by New Propulsion Technology and Systems (6)

Author: Mr. Kelvin Long
Initiative for Interstellar Studies, United Kingdom, kelvin.long@i4is.org

THE INTERPLANETARY CROSSBOW: TECHNOLOGY AND ARCHITECTURE DESCRIPTION FOR AN INTERPLANETARY LASER-SAIL SYSTEM FOR THE USE OF SMALL PAYLOADS.

Abstract

Laser sail propulsion offers one of near term access to deep space exploration that may even go beyond the planets. The Breakthrough Initiatives Project Starshot (50 GW, 20%c, 1 gram) and also the I4IS Andromeda Probe (1 GW, 10%c, 10s grams) have been studying such concepts for interstellar application for possible launch later this century. However, nearer term there is the prospects of a human colony on the Moon or Mars, and technological roadmaps are already under way by companies such as Space Exploration Technologies Corp. To meet what is perceived as a near-future need, we would like to explore the concept for a MW-GW power beaming system that positions a single converging lens in Earth orbit and an identical one in orbit around another planet, such as in Mars orbit. Both would then be used for the sending of small mass (grams to kg) payloads at high speeds (100s to 1,000s km/s) with sure transit times (hours to days) between planets. Such a system would provide for fast delivery of urgently needed supplies for the Earth to Mars route (such as medicines, microelectronic components, plant seeds) or for return of materials for the Mars to Earth route (such as surface sample returns, microorganism samples for further analysis). The project would build on the studies already performed but apply them to the construction of this interplanetary Crossbow delivery architecture.

Paper ID: 43106
oral

SYMPOSIUM ON FUTURE SPACE ASTRONOMY AND SOLAR-SYSTEM SCIENCE MISSIONS (A7)
Space Agency Strategies and Plans (1)

Author: Mr. Kelvin Long
Initiative for Interstellar Studies, United Kingdom, kelvin.long@i4is.org

INTERSTELLAR PROBES: THE BENEFITS TO ASTRONOMY AND ASTROPHYSICS.

Abstract

Long range observations by the field of astronomy has opened up our understanding of the Solar System, the Galaxy and the wider Universe. In this talk we discuss the idea of direct in-situ reconnaissance of nearby stellar systems, using robotic probes. In particular, we consider what additional knowledge can be learned that can only be obtained by such close encounters. This may include calibration of existing measurements, detailed observations of stellar winds, astrometry measurements of stellar parallax, refinement of our understanding of physics through the use of long baseline interferometers. In addition, getting close to an exoplanet will enable detailed knowledge of planetary interiors, surface processes, geological evolution, atmospheric composition and climate, internal seismology, detailed surface morphology and even the speculative possibility of detecting the presence of microbial life, detailed palaeontology or even indigenous life-forms. We argue that astronomical remote sensing should be pursued in parallel with in-situ reconnaissance missions by robotic probes, so that both can enhance the discoveries and performance of the other. This work is in support of Project Starshot, an effort to send a Gram-scale probe towards another star at 0.2c within the next two decades, and return images and other data to the Earth.

Paper ID: 43122
oral

47th IAA SYMPOSIUM ON THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI) - The Next Steps (A4)
SETI 1: SETI Science and Technology (1)

Author: Mr. Kelvin Long
Initiative for Interstellar Studies, United Kingdom, kelvin.long@i4is.org

A CRITICAL REVIEW ON THE ASSUMPTIONS OF SETI

Abstract

The Search for Extraterrestrial Intelligence (SETI) makes certain assumptions which guide all current search programs. To illustrate some, this includes (1) that interstellar flight is not possible (2) that the motivations of interstellar cultures are based largely on anthropomorphic understandings of homo sapiens (3) that the Fermi Paradox and the Drake equation are the starting point (axioms) of all reasoning (4) that definitions of 'life' are based largely on our understanding of homeostasis (5) that radio waves are the most likely method of interstellar communications (6) that unknown single event source signatures detected in space are not amenable to scrutiny due to the demands of the scientific method to be reproducible (7) that such anomalous signatures are either astronomical or communications based in type, with no consideration for emissions from advanced industrialisation or propulsion and power technology. These assumptions, and others, have guided the SETI community towards a constrained level of thinking that is equivalent to philosophical dogma. In this paper, we unpack these assumptions, and others, and argue that the potential for life and intelligent life in the Cosmos, is much greater than the SETI community currently appears to conclude. It is also argued, that more progress in our understanding of our place in the Cosmos, can be made, if the separate disciplines of astronomy, interstellar spacecraft design, SETI, biology and philosophy can work together in a complimentary way.

Paper ID: 43127

SPACE POWER SYMPOSIUM (C3)
Space Power System for Ambitious Missions (4)

Author: Mr. Kelvin Long
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PROJECT ICARUS: CONCEPT DESIGN FOR AN INERTIAL CONFINEMENT FUSION DRIVE INTERSTELLAR PROBE.

Abstract

In the 1970s members of the British Interplanetary Society designed a deuterium-helium-3 fusion powered 450 tons two-stage interstellar flyby probe to reach the stars in half a century travelling at 0.12c, in a study known as Project Daedalus. Such a design would require jet powers of 40 TW and 3 TW, and specific powers of 42.4 MW/kg and 9.6 MW/kg for the first and second engine stages respectively. In 2009 Project Icarus set out to re-design the Daedalus with a reduced system architecture mass, carrying a 150 tons payload on an orbital insertion mission to the nearest stars at around 0.05c completing the journey in around a century. One of the concepts to come out of this study was a shock ignition based inertial confinement fusion powered system utilising a single engine stage (Resolution) and multiple engine stages (Endeavour). This results in reduced jet powers and specific powers and an overall more plausible design solution, compared to Daedalus, but also demonstrates that interstellar probe missions are hard to achieve. We summarise the study by comparison to the alternative propulsion system of GW and TW powered laser beamers that utilise parallels in space to improve beam collimation, and show that although interstellar flight does appear to be possible from a physics, it is never going to be easy from an engineering and economic perspective

Paper ID: 43474
oral

SPACE EDUCATION AND OUTREACH SYMPOSIUM (E1)
Lift Off - Secondary Space Education (2)

Author: Mr. Satinder Shergill
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SPACE STUDIO WEST LONDON - A PROJECT BASED LEARNING MODEL FOR SPACE EDUCATION

Abstract

Space Studio West London (SSWL) is a new 'Studio' School aimed at 14-19-year olds that is based in West London, and delivers a mix of high quality scientific education and industry-related activity, equipping young people with the skills and qualifications needed to become skilled technicians, operators, engineers, scientists, inventors and entrepreneurs in aerospace and space related industries. This paper examines many aspects of the school's unique vision of developing independent and engaged learners through project-based learning (PBL) and by following guiding principles of Self-Worth, Engagement, and Purpose. SSWL's incorporation of PBL has included teaching through enterprise projects and real work, encouraging students to understand concepts such as finding solutions by working to the problem. This approach ensures that student learning is rooted in the real world and helps them to develop the skills they need to flourish in life and, also contribute to the space industry. Past Core Projects at Space Studio have included themes such as 'Colonisation of Mars', 'Is there life out there?', 'Theory of flight', 'Payload Design' and 'Why do we go to space?'. Students have worked in teams, both collaborating and working individually to support their team, while receiving support and master classes from staff and subject specialists. PBL learning has also been utilised successfully in the more formal aspects of classroom-based teaching with mini projects connecting curriculum subject content to the real world and the space industry. Learning outcomes of core and mini projects have been subject to continual iterations of evaluation and critical assessment (including feedback from staff and students) to aid in the development of effective project templates and lesson plans. Space themed outreach work to primary schools by SSWL students, has also built their sense of self-worth and has allowed them to take on roles of leadership and responsibility. SSWL students have attended workshops at various NASA centres, the British Interplanetary Society, the UK National Space Centre, Kingston University, St Mary's University and have worked with Surrey Satellite Technology Limited, the Institute for Interstellar Studies and the National Space Academy with a view to continue building much needed links between schools, industry and university academia. As such, this paper also documents some of the major achievements and challenges of this pioneering school in it's opening three years.

Paper ID: 47396
oral

16th IAA SYMPOSIUM ON VISIONS AND STRATEGIES FOR THE FUTURE (D4)
Space Mineral Resources, Asteroid Mining and Lunar/Mars insitu (5)

Author: Dr Andreas Makoto Hein
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EXPLORING POTENTIAL ENVIRONMENTAL BENEFITS OF ASTEROID MINING.

Abstract

Asteroid mining has been proposed as an approach to complement Earth-based supplies of rare earth metals and supplying resources in space, such as water. Existing research on asteroid mining has mainly looked into its economic viability, technological feasibility, cartography of asteroids, and legal aspects. More recently Hennig (2016) and MacWhorter (2015) have introduced environmental arguments for asteroid mining, in particular with regards to platinum group metals. However, these arguments are not quantified. Hence, the question whether or not asteroid mining could have significant environmental benefits, both for supplementing Earth and providing resources in space has not been answered satisfactorily. This paper attempts to determine if and under which conditions asteroid mining would have environmental benefits compared to either Earth-based mining or launching equipment and resources into space. First, a state-of-the-art of current life cycle assessment results of terrestrial rare Earth metal mining and space launchers is provided. Second, a first order environmental life cycle assessment of an asteroid mining mission is presented, including an inventory of systems and its environmental impact. Finally, a comparison of the environmental impact of terrestrial rare Earth metal mining and in-space rare Earth metal mining and a comparison of launching water to dedicated places in the cis-lunar space is compared to providing water from an asteroid.

Paper ID: 47407

16th IAA SYMPOSIUM ON VISIONS AND STRATEGIES FOR THE FUTURE (D4)
Space Mineral Resources, Asteroid Mining and Lunar/Mars insitu (5)

Author: Dr Andreas Makoto Hein
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A TECHNO-ECONOMIC ANALYSIS OF ASTEROID MINING.

Abstract

Asteroid mining has been proposed as an approach to complement Earth-based supplies of rare earth metals and supplying resources in space, such as water. However, existing studies on the economic viability of asteroid mining have remained rather simplistic and do not provide much guidance on which technologies would need to be improved in order to increase its economic viability. This paper provides a first techno-economic analysis of asteroid mining with the objective of providing recommendations for future technology development and performance improvements. Both, in-space resource provision such as for water and return of rare earth metals to Earth are considered. Starting with first principles of techno-economic analysis, gradually additional economic and technological factors are added to the analysis model. Using reference architectures from the literature and new mining architectures, such as using small spacecraft, their economic viability is assessed, taking cost and price sensitivities into account. Finally, conclusions on key technological factors are provided, where performance improvements would bring asteroid mining closer to its economic viability.

Paper ID: 47690
oral

47th IAA SYMPOSIUM ON THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI) - The Next Steps (A4)
SETI 1: SETI Science and Technology (1)

Author: Mr. Adam Crowl
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STRATEGIES FOR COMPLETE GALACTIC SURVEYS.

Abstract

An often repeated concept in SETI discussions, particularly the Fermi Paradox, is that civilizations will completely survey their home Galaxies. The timescale is typically estimated to be millions of years, but the exact strategy for surveying 100 billion stars isn't often explored. In this work several options are discussed, possible limits on maximum distances per hop and a possible energy saving strategy - close stellar flybys - examined. The maximum speed for using stellar flybys to circumnavigate the Galaxy is computed and is surprisingly high. An often discussed option is Self-Replicating Probes. The assumption that Self-Replicating Probes will be obvious and abundant, and thus Fermi's Paradox can be invoked, is challenged and their impact on available mass in star-systems is critically examined using the work of Boyce [1979].

The Orbits of Seveneves

A book review with a touch of orbital dynamics

Part 2 - the orbits explained

Sander Elvik

In our last issue Sander reviewed Seveneves by Neil Stephenson, concentrating on the story. In this second he explains the orbits and trajectories in the near future part of the book. We hope to persuade him to write again about the even more spectacular dynamics in Stephenson's vision of a far future later in the novel.

Introduction

Stephenson's orbital work is accurate, but at times brief or tightly interwoven into the story such that some pre-knowledge of orbital dynamics is convenient to grasp the finesse of what is being described. This part of the review aims to provide the reader with an introduction to the specifics of circular orbits, elliptical orbits and the so-called L1 gateway in the Earth-Moon system. By no means is this intended to be a class book explanation, but a high level visual exploration of the concepts with the aim of providing a reader new to orbital dynamics a better understanding of them.

Circular orbits

Let's start with the basic circular orbit by going back to Doc's experiment: [page 217]*

"I can't drift far, confined as I am to the pressure hull. But you can imagine that if I hadn't been able to stop - if I'd been out on a space walk - I might have drifted a long way. And what the science of orbital mechanics tells is that no two objects in orbit can have the same six numbers, except in the special case I just showed you, where I was inside the hollow arklet so that both of our centers of gravity could coincide."

The six numbers Doc is referring to in the above are the position (x, y and z) of the object in space, and its velocity along these three axes (ẋ, ẏ and ż in Cartesian form). But let's first try to better understand the concept of the circular orbit.

A circular orbit around the Earth, or any centre of mass, can be visualized by a disk cutting through the centre of mass at an angle with respect to the equator (called the inclination, which we will discuss further below). The spacecraft orbits the disk along its edge. For the purpose of this review: in relation to the centre of mass, the disk is fixed in space while the Earth revolves within the disk. Hence, after making a full round, when a spacecraft returns to the initial position in its

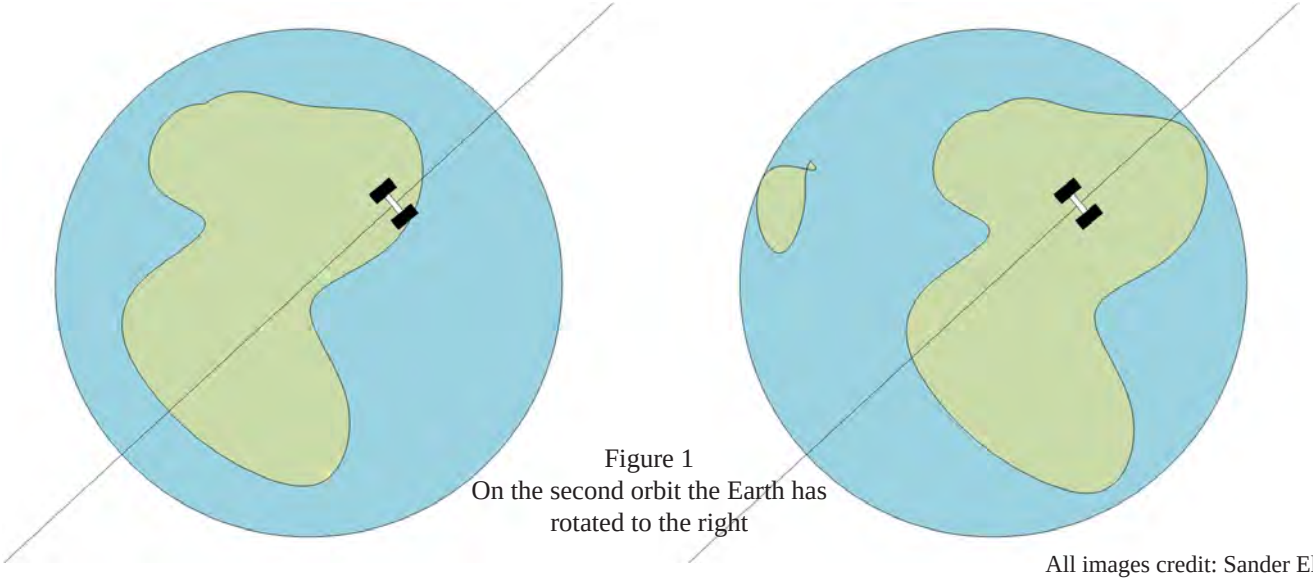


Figure 1
On the second orbit the Earth has rotated to the right

All images credit: Sander Elvik unless otherwise specified

*page references correspond to the 2015 UK paperback edition.

orbit, the Earth will have rotated beneath it. The spacecraft now looks down at a different location on the surface than before (see Figure 1).

Without going into the mathematics of it, the velocity of the spacecraft in a circular orbit is constant, and directly related to the radius, r, of the orbit:

$$V_c = \sqrt{\frac{\mu}{r}}$$

(μ is the gravity parameter, which is a different constant for each planet*). The velocity is also perpendicular to the radius. Hence, to get into a circular orbit, a spacecraft must not only match the specific speed of this orbit, but also have this speed in the direction perpendicular to the radius.

Relating the above equation back to Doc's explanation: the r is basically a vector defining the x,y,z numbers, while the vector Vc accounts for the last three numbers: ẋ, ẏ and ż (more about these Keplerian coordinates in en.wikipedia.org/wiki/Orbital_elements).

Now, as the radius of an orbit increases, its circular velocity decreases. At one point the velocity will coincide with the rotational speed of the Earth. When the disk of the orbit is aligned with the Earth's equator, you then have a geostationary orbit: the spacecraft appears to hang stationary above a point on the ground here on Earth. Similarly, if the radius decreases, the circular velocity increases. Or in other words, the inner lane goes faster. Hence, if you want to rendezvous with a spacecraft, get into the same orbital plane, and choose the inner lane to catch up!

Returning to Doc's experiment, we can now look further into the two issues following from it. First, imagine that at a given point in an orbit two spacecraft are flying next to each other, but separated perpendicularly to their direction of flight by 10m.

Now imagine looking at their orbital disks edge on, with the spacecraft on the top of the disk, flying directly away from you. Although the two spacecraft are flying next to each other right now, their orbital disks make a cross. Which means that in half an orbit's time the spacecraft flying on the left will be flying on the right side, and a quarter orbit before that the two will cross each other's path (see Figure 2).

In other words, the two spacecraft, although seemingly on the same orbit, do not have the same six numbers defining their orbit. Interestingly, certainly in the light of the book, this is also true for large space structures, introducing tension and strain that should be accounted for.

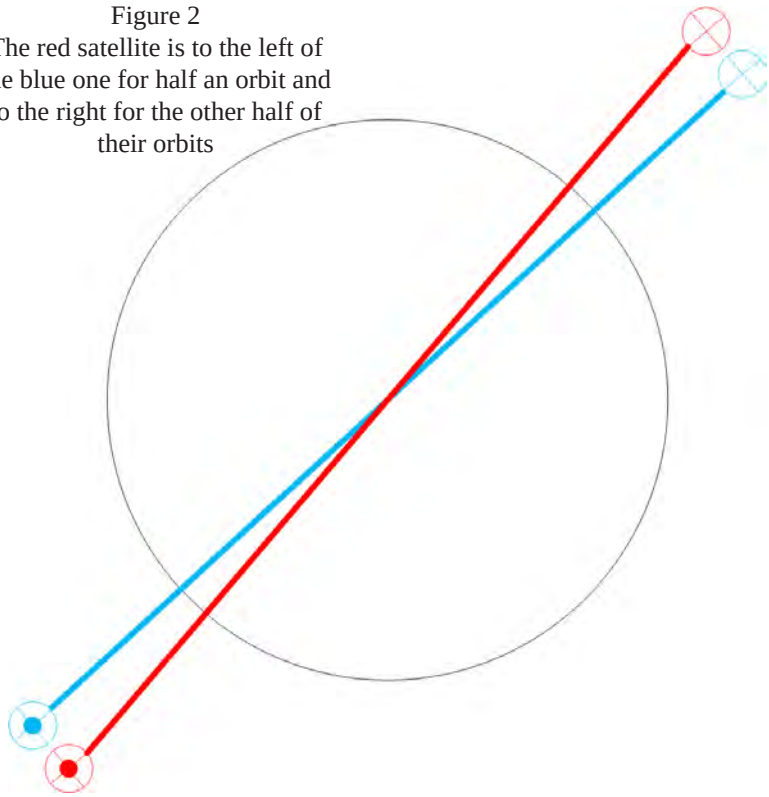
Editorial Aside

Neal Stephenson - Witty Geek

Neal Stephenson is one of that group of our species who grew up in, and was profoundly influenced by, the first wave of small computers. In his case this eventually turned him towards fiction and gaming. But, like the rest of us whose careers began in that area, he still finds what we can do with small, cheap, computers fascinating. If you have not read his novels than I hope this piece and its predecessor inspire you to do so. If you have, and like them, then may I draw your attention to a slim volume he wrote in 1999 - originally as an online plain text document *In the Beginning was the Command Line*. Its a bit out of date (have you heard of the BeOS operating system?) But its explanation of how the world bought Windows and how it would adopt open source and even buy Apple (long before they did) still rings true and - better still - will make you laugh!

JID

Figure 2
The red satellite is to the left of the blue one for half an orbit and to the right for the other half of their orbits



* The standard gravitational parameter μ of a celestial body is the product of the gravitational constant and the mass of the body en.wikipedia.org/wiki/Standard_gravitational_parameter

The other issue concerns changing the orbit. Above we briefly touched upon catching up on a spacecraft. However, without changing its orbit, the spacecraft catching up will pass underneath the target and fly away from it.
In 1925 W Hohmann found the optimal transfer orbit (i.e. the transfer trajectory requiring the least amount of fuel) to be an elliptical orbit which touches the initial and end orbits. That is, the velocity vectors (green arrows in illustration below, Figure 3) of the transfer orbit is tangential to the initial and end orbits:
In the optimal transfer the velocities are always in the extension of each other. Use is made of the velocity already available. The above concerns raising the height of an orbit.
Changing the plane, i.e. the inclination, of the orbit is a different matter, which Stephenson also touches upon in his book. From the physics involved, it turns out that making a plane change is quite expensive in terms of energy:
The amount of energy, or ΔV (change in velocity), required to perform an inclination change of 30º in a circular orbit costs as much ΔV as a Hohmann transfer raising the orbital altitude from 250 km to 44800 km. It can be shown though, that the amount of ΔV required for a plane-change manoeuvre decreases when it is executed at a higher altitude.
A practical result of the above is the inclination of the orbit of the International Space Station (ISS), which needs to be served by both US and Russian spacecraft. Russian spacecraft are launched from Baikonur with a high latitude of 46° N (and therefore has a default orbit inclination of 46º), while the more capable space shuttle is launched from Cape Canaveral at 28.5 ° N. The ISS orbit inclination of 51.6 degrees was chosen so that it could be reached by the respective shuttles/rockets of both countries (and it provides a large coverage of the Earth's surface as well).
The maximum payload a rocket can carry to space is to an orbit with an inclination equal to the latitude of its launch site (i.e. its offset in degrees North or South of the equator). Any other inclination will cost extra energy (as discussed in the plane change above), therefore decreasing the available payload capacity).
Why is the orbit's inclination equal to the launch site latitude? Look at the illustrations below and on the next page.
We are looking at a launch from a flat Earth perspective. The easiest way to orbit (i.e. costing the least amount of energy) is to go straight up, and then turn to the East to get into a circular orbit around the Earth at the desired altitude. No bending to the North or the South, just up and then due East. Since the Earth rotates eastward, the rocket gets an additional speed boost from the rotational speed of the Earth, reducing the required amount of energy to get to the circular velocity required for the orbit.
Now let's zoom out and look at the Earth head on.
Our rocket is at Cape Canaveral (28.5° N). The rockets first goes straight up and then turns to the East (away from us). As this illustrations shows, with this launch the orbit inclination is equal to the launch site latitude. [page 444]

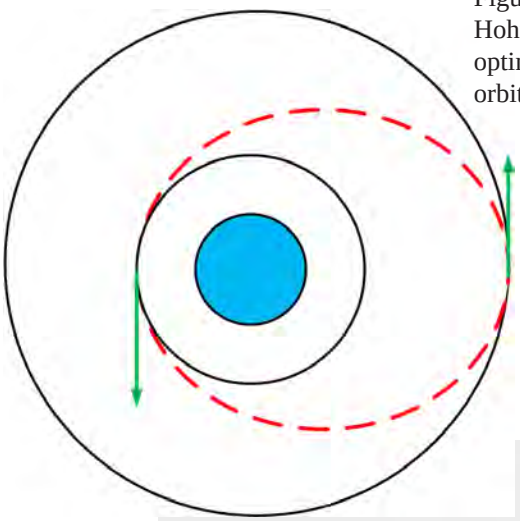


Figure 3
Hohmann's optimal transfer orbit

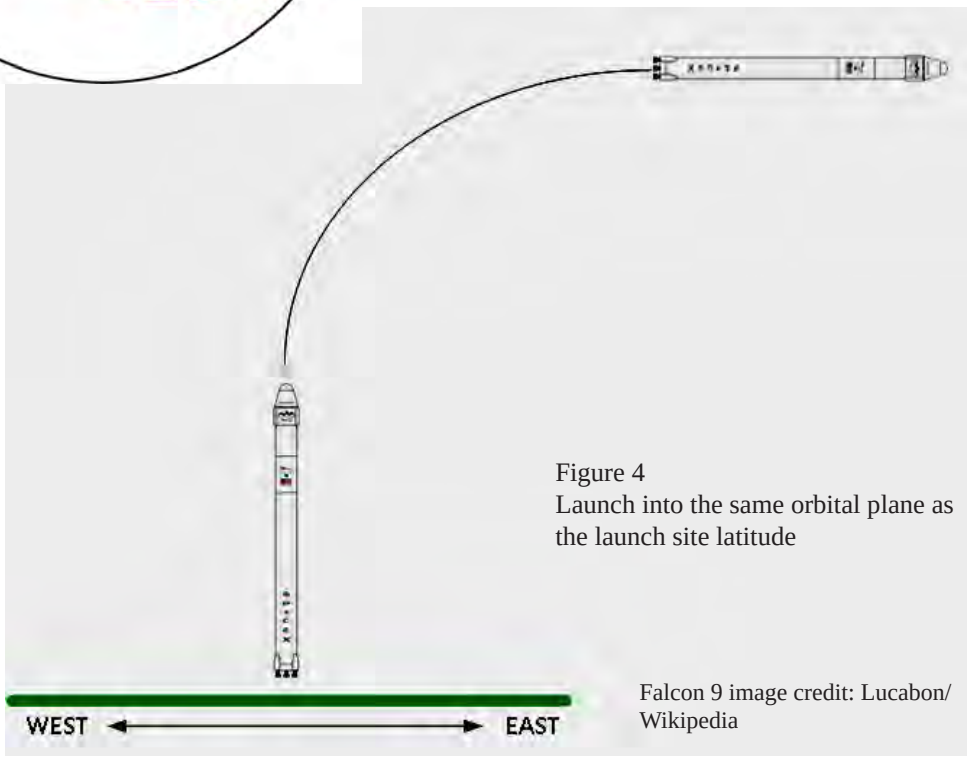


Figure 4
Launch into the same orbital plane as the launch site latitude

Falcon 9 image credit: Lucabon/ Wikipedia

In one sense, they had missed their target by a mile; the total delta vee she had achieved had been less than a third of what they'd hoped for. And yet this had

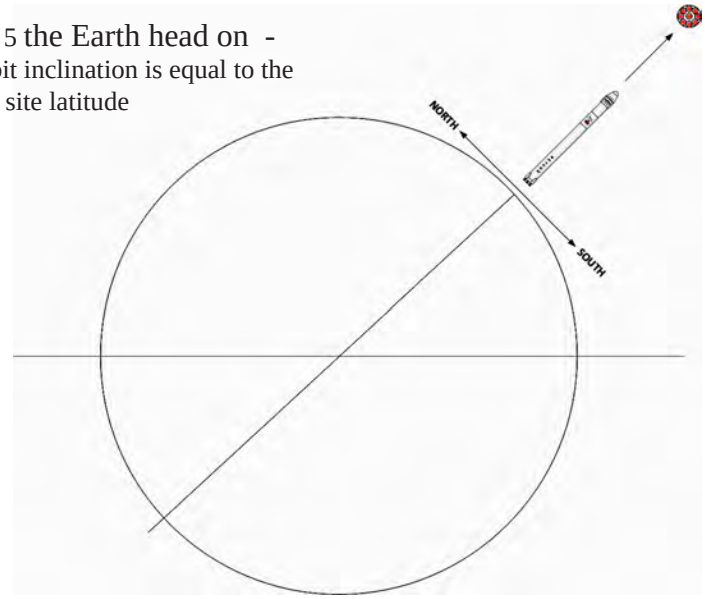


Figure 5 the Earth head on - the orbit inclination is equal to the launch site latitude

been enough to bring her apogee down from far beyond the moon's orbit to a figure only about thrice the altitude they needed. Likewise, the period --- the amount of time it took to complete an orbit --- had dropped from seventy-five days to a mere eight hours. The lesson being that huge alterations in those figures could be purchased for comparatively small amounts of delta vee. The apogee might have been radically altered, but her perigee altitude was unchanged --- meaning that it was still dangerously low.

The above excerpt is taken from a moment of reconciliation in the middle of a very action packed and exciting part of the book, where the team flying the spacecraft is faced with [page 413] *"so many imponderables, a well-managed aerospace engineering project would have called a halt to all further work and devoted several years to analyzing the problem down…"* Their challenge is to match their highly elliptical orbit to a circular low-Earth orbit. Before, we discussed the aspects of circular orbits, and at this point Stephenson broadens the subject to include elliptical orbits.

Elliptical orbits

The image [Figure 6] below shows the basic orbital parameters of an elliptical orbit of spacecraft m2 around a central mass, m1. The eccentricity of the orbit, e, determines how elongated the ellipse is, with e=0 resulting in a circular orbit. The eccentricity of the recently discovered interstellar comet 'Oumuamua is ~1.2, meaning it is on a hyperbolic trajectory and will not return again. For comparison, Halley's Comet has an eccentricity of 0.967.

At pericentre, the point in the orbit closest to the central mass which is orbited, the speed of the object is the largest, and at apocentre, the point furthest away, the speed is the lowest. It is therefore true, as Stephenson points out, that large alterations of orbital parameters can be achieved for relative low energy cost (delta vee, Δv), if executed at pericentre or apocentre. Also, due to the low speed near apocentre, the spacecraft spends most of its time there.

A great practical example of using highly elliptical orbits are the orbits of the Russian Molniya communication satellites, which were configured to have their apocentre, and hence most part of their orbital period, above Soviet territory. As much of Russian territory is located at high latitudes, providing satellite communication from geostationary orbits (at the equator) requires considerably more power than when using these highly elliptical orbits.

Saving the best for last, as described in the introduction to this review, Stephenson also throws in the very imaginative term "L1 gateway".

Lagrange gateways

In my opinion, these gateways are even cooler than they sound. They are solutions to the so-called three-body problem, which in astronautics is used to determine the motion of a spacecraft under

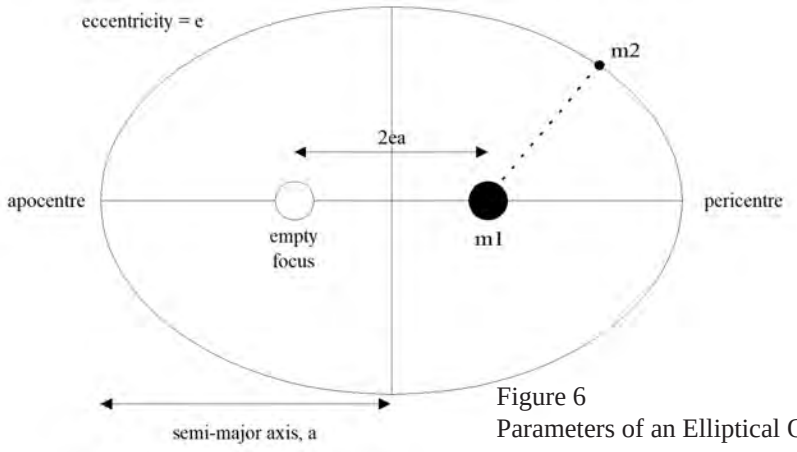


Figure 6
Parameters of an Elliptical Orbit

the gravitational influence of two celestial bodies, like the Sun and the Earth in Stephenson's example.

But the Earth-Moon system also has these gateways. Simplified, it can be described as follows:

A so-called 'rotating reference frame' is introduced, in which the Earth and the Moon do not move with respect to each other. Only the spacecraft is moving within this reference frame. As introduced by "Doc", the orbit of the spacecraft is described by its position and velocity, or in other words: 'energy level'.

For a given energy level of the spacecraft, using the equations of the solution to the three-body problem, the "Surfaces of Hill" can be determined. These are areas within the reference frame that the spacecraft cannot reach.

Starting at low energy, the reachable space is confined to two bubbles: one around the Earth and one around the Moon (Figure 7).

As the spacecraft gains energy (by firing its engine), the size of the bubbles increases, until a connection is made between them: the L1 gateway from the Earth to the Moon (Figure 8).

In the Sun-Earth rotating reference frame, the L1 gateway allows a spacecraft to escape the Earth's sphere of influence and enter interplanetary space between Venus and Earth. The spacecraft then enters a heliocentric orbit around the Sun as opposed to a geocentric orbit around the Earth. Returning to the Earth-Moon system. A further increase in energy will make a connection between the Moon bubble and surrounding outer space, making an escape of the Earth-Moon system possible: the L2 gateway (Figure 9).

These L-points are also known as "Libration points", a term conveniently coined by the great mathematician Lagrange, in 1772, and nowadays often referred to as Lagrange points*. Allegedly the first Apollo missions flew on energy levels that kept the L2 gateway closed, but later missions flew with higher energy levels. Therefore one of the first actions of the Apollo 13 crew after the famous mishap, was to conduct an engine burn to close the L2 gateway, ensuring the capsule would stay within the Earth-Moon system.

This piece was written for readers with limited knowledge of orbital dynamics. I hope you enjoyed this visual exploration of the classical orbital concepts that Stephenson used in his book, and that it will make reading his exciting novel a greater experience.

* en.wikipedia.org/wiki/Lagrangian_point

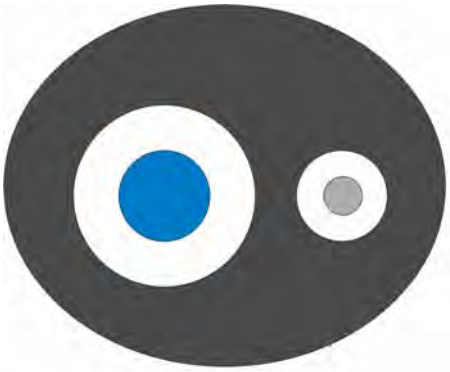


Figure 7 - two gravitational "bubbles" one around the earth and one around the moon

Figure 8 - spacecraft gains energy so size of bubbles increases until a connection is made : the L1 gateway from the Earth to the Moon.

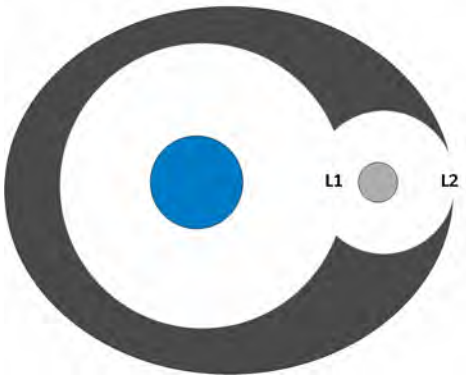


Figure 9 showing Lagrange points L1 and L2

Orbital Dynamics

Orbital Mechanics is a vast subject. A good starting place is Wikipedia - en.wikipedia.org/wiki/Orbital_mechanics.

For a simple video explanation of earth orbital mechanics see NASA's forum.kerbalspaceprogram.com/index.php?/topic/119449-nasa-school-of-orbital-mechanics-worth-watching/

Standard texts include -

Orbital Mechanics for Engineering Students. Howard D Curtis (3rd edition, 2013) Butterworth-Heinemann, www.elsevier.com/books/orbital-mechanics-for-engineering-students/curtis/978-0-08-097747-8 ISBN 978-0-08-097747-8

Orbital Motion. A E Roy, (4th Edition, 2004) CRC Press ISBN 978-0-75-0310154, www.crcpress.com/Orbital-Motion-Fourth-Edition/Roy/p/book/9780750310154.

About Sander Elvik

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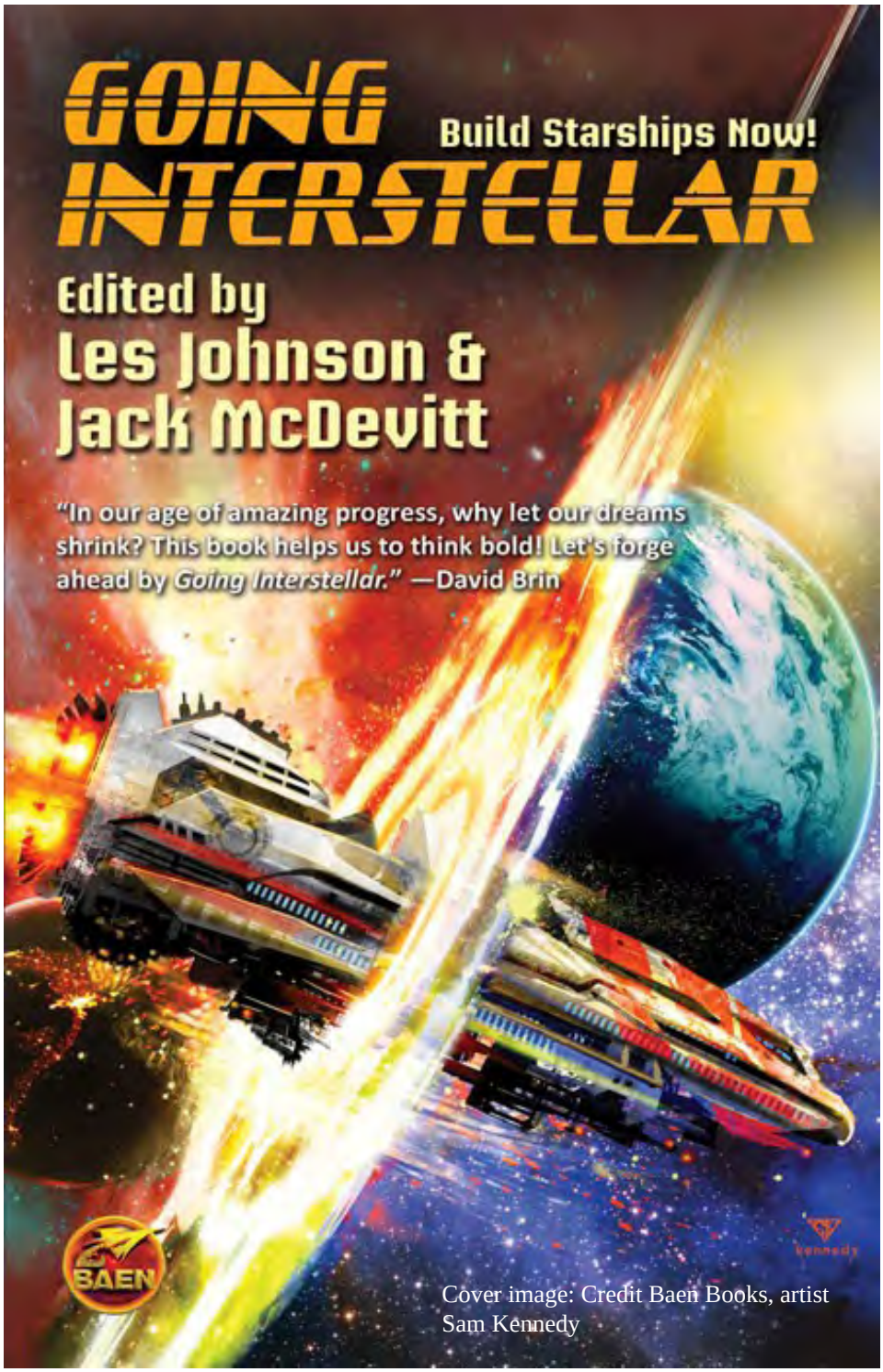
BOOK REVIEW: Going Interstellar – Build Starships Now!

edited by Les Johnson and Jack McDevitt (Baen Books, 2012)

Patrick Mahon reviews an anthology of fiction and non-fiction about interstellar travel.

'Going Interstellar' is a 2012 anthology of newly-written fiction and non-fiction about interstellar travel. It includes four essays on the science and engineering of different propulsion technologies and eight fictional pieces that each take one of those technologies and put it at the heart of a hard science fiction story. The motivation for the book is described in the Introduction, where co-editors Les Johnson and Jack McDevitt explain why they think we need to become an interstellar civilisation. The book is intended to explore that idea through technically feasible science fiction, with the interspersed essays providing a basic briefing for readers on the propulsion technologies that underpin those stories.



Cover image: Credit Baen Books, artist Sam Kennedy

If you were planning a project of this kind, you would be hard pressed to come up with a better pair of editors. Les Johnson is a senior NASA engineer who currently heads the team developing the Agency's first interplanetary solar sail mission and who has also published books of both science fiction and science fact (www.lesjohnsonauthor.com). Jack McDevitt is a prolific and award-winning author of hard science fiction, many of whose novels explore the interstellar question

Further reading

Those readers who find the four non-fiction essays helpful would be well advised to follow them up with further reading such as -

• 'The Starflight Handbook' by Greg Matloff and Eugene Mallove, 1989 (www.wiley.com/en-gb/The+Starflight+Handbook:+A+Pioneer's+Guide+to+Interstellar+Travel-p-9780471619123).

• 'Deep Space Propulsion' by Kelvin F Long, 2012 (www.springer.com/gb/book/9781461406068).

• 'Beyond the Boundary', i4is's 2014 book exploring the science and culture of interstellar spaceflight (www.lulu.com/shop/kelvin-long/beyond-the-boundary/hardcover/product-22522176.html)..

Those who enjoyed the science fiction may be interested to get hold of the 2014 anthology 'Visionary', which includes several pieces by i4is colleagues. It is available from the British Interplanetary Society (www.bis-space.com/eshop/products-page/merchandise/books).

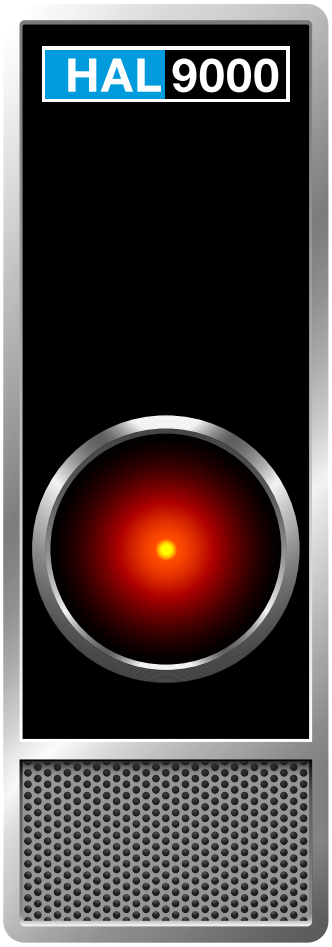
(www.jackmcdevitt.com).

One of the many things I like about The Initiative for Interstellar Studies is that it promotes artistic responses to the interstellar question with just as much energy as it puts into exploring the science and engineering of getting to the stars. That makes a book like 'Going Interstellar', which mixes science fact with science fiction, a potential 'must have' title for i4is supporters. So, should you all go out and buy a copy right away?

I'll start with the non-fiction. Somewhat perversely, for a book focused on technical feasibility, the four essays on different interstellar propulsion technologies appear in increasing order of near-term feasibility, starting with the most challenging.

Dr Greg Matloff (who will be familiar to many i4is supporters as a member of our Advisory Council and co-host of our New York workshop last year), discusses the use of antimatter as a propulsion fuel. Matloff summarises the physics of antimatter, both in theory and experiment, before considering how you might build a rocket engine to use it as a fuel. There are several major problems to overcome, including how to create more than a few particles of antimatter at a time, how to store it safely once created, and how to deal with the huge amounts of heat generated during antimatter annihilation, so that your spacecraft doesn't melt. Matloff's essay explains all these issues clearly and concludes with a helpful set of references for further reading.

The second essay is also by Matloff and it focuses on nuclear fusion, the process which powers our own Sun. This is introduced through Einstein's famous equation $E = mc^2$, indicating that a small amount of mass can be converted through nuclear processes into a large amount of energy. Matloff then discusses the wartime development of nuclear fission and fusion in the A (atom) and H (hydrogen) bomb respectively. We have now found ways to harness nuclear fission for peaceful energy production. The same cannot be said for nuclear fusion, although it remains the subject of intensive experimental research. When we do finally learn how to harness fusion for energy generation, it will be an attractive technology for interstellar spaceflight, due to the huge amounts of energy that can be generated from relatively small amounts of onboard fuel. Matloff goes on to discuss the main engineering approaches to achieving fusion in the lab, and briefly summarises the various projects that have taken a serious look at the use of fusion as an interstellar propulsion technology, including Project Daedalus, Project Icarus and the Bussard ramjet.



The Eye of HAL, the supposedly infallible AI in *2001: A Space Odyssey*.

Credit: By Grafiker61 - Own work, CC BY-SA 4.0, commons.wikimedia.org/w/index.php?curid=46424786.

Next comes an article dedicated to Project Icarus, written by the then-Project Leader, Dr Richard Obousy. He covers the origins of Project Icarus as a redesign and updating of Project Daedalus, noting the central role of i4is President Kelvin Long in initiating the project, and name-checking several other i4is colleagues along the way. Obousy then summarises the various parallel objectives of the project, including updating the Daedalus design, training a new generation of interstellar engineers, and moving from proof of concept to practical design.

The final non-fiction essay is by anthology co-editor Les Johnson. It discusses solar and beamed energy sails, starting with the history of solar sails in fact and fiction, before moving on to their potential value as a propulsion technology for interstellar missions. This either requires a close approach to the Sun, given the inverse square law, or the use of a high power collimated laser as a substitute for solar photons. The essay concludes with a useful single page diagram illustrating a potential roadmap for moving from near-term solar sail demonstration projects right through to future interstellar probes.

Now I'll turn to the eight stories which illustrate how these interstellar propulsion technologies might work in practice.

The first story is *'Choices'*, the second piece written by Les Johnson. The action takes place on board an antimatter-powered colony ship headed for Epsilon Eridani. Astronaut Peter Goss is woken from a rather horrible hibernation dream to find that the real world is no better. The ship's AI has awoken him because he is now the most senior living officer on board and it needs him to make a vital decision. First, though, he'll need to solve the mystery of where his superiors have disappeared to. Johnson weaves an intriguing and entertaining tale here, warning about one of the many risks that could befall any long duration interstellar mission if we don't think carefully enough beforehand.

Next up is hard SF giant Ben Bova, whose *'A Country for Old Men'* is set on humanity's first manned interstellar spacecraft, a scientific survey vessel powered by hydrogen fusion, the fuel collected using an onboard Bussard ramscoop. They are headed for exoplanet Gliese 581g, twenty light years away, to search for signs of life. The ship is carrying two hundred scientists in cryonic suspension, along with a skeleton crew of twelve who have agreed to remain awake throughout the fifty-year journey to deal with any unexpected events. When the ship's AI starts to power down several non-essential systems, nobody seems to care - except for the grouchy resident astrophysicist Dr Alexander Ignatiev, whose studies since launch have led him to an alarming conclusion about these power problems. Can he persuade his fellow crewmates to believe him over the supposedly infallible AI? There are shades of *2001: A Space Odyssey* in the set-up here, but Bova has been writing this kind of SF for years, and his experience shows.

This is a classic hard SF story which poses a technical problem and requires the characters to solve it using real science. However, in case this sounds too dry, it's worth noting that the story includes an engaging subplot which shows the crew to be a bunch of real people with emotional wants and needs, making you want them to succeed when the chips are down.

'Lucy', by co-editor Jack McDevitt, is one of the most fascinating of the stories in this anthology, as the protagonist is not a human but an Artificial Intelligence. The story is set in a medium-term future, where NASA has developed a fusion-powered spacecraft, the Coraggio, and sent it out to the Kuiper Belt on a test mission to observe an asteroid called Minetka. The ship has no human crew but is being commanded by an advanced new model of AI called Lucy. And as the story starts, Mission Control has just lost contact with her. Already under political and public pressure over the perceived high cost of space travel, NASA can ill afford to lose its latest spacecraft. The Administrator demands an urgent rescue mission, sending out Coraggio's sister ship under the control of Sara, an older model of AI who has proved herself reliable on previous missions. Will Sara manage to find Lucy in the depths of the Kuiper Belt and, more importantly, bring her back? McDevitt has done a brilliant job of making us care about the fate of not one but two AIs. Indeed, at times the AIs seemed to me the most interesting of the characters, when their continued emotional engagement with, and commitment to, interstellar exploration is contrasted with the almost total lack of interest demonstrated by the general public back on Earth.

Dr Charles E Gannon takes a very different approach in his story, *'Lesser Beings'*. Set in a far future where humanity has spread to the stars whilst evolving, if that's the right word, into a rigidly class-based and militaristic

Wheel of Time album cover by Gavin Gamboa gavingamboa.bandcamp.com/album/wheel-of-time Credit: Gavin Gamboa (Creative Commons).

system of a few aristocratic families who despise each other and are constantly at war, the story shows what happens when House Shaddock beats House Mellis in the latest war. The consequence is that House Mellis are exiled from the star system in which they have all lived for 350 years. This requires them to recondition the fusion-powered spaceship which brought them there, so that they can head to the next nearest star system, hoping that there will be at least one habitable planet or moon when they get there. The question is whether a society this rigid can possibly promote those 'lesser beings' who have the intelligence and skills to be able to repair the spaceship, let alone navigate it to their potential future home. There are some echoes of Frank Herbert's *Dune* in the social structures* of the invented society that Gannon portrays, but he does it with great authenticity, illustrating a deeply intriguing if rather atypical future vision for humanity.

In *'Design Flaw'*, Louise Marley puts us on board an antimatter-powered cargo ship on a four-month trip from Earth to Jupiter's moon Ganymede, where humanity's first interstellar starship is being constructed. Isabet is a small woman whose specialist job is to crawl through the narrow maintenance tubes surrounding the antimatter containment rings, keeping the propulsion system running. She is constantly subjected to unwanted sexual advances by Dykens, a senior engineer with a chip on his shoulder, but her lowly status onboard means that her official complaints have been ignored. When they get to the starship at Ganymede she helps unload their cargo, and sees an opportunity to get away from Dykens, perhaps for good. He, however, has no intention of letting her escape that easily. This story includes lots of interesting technical details, yet at its heart it's about human relationships and the ways they can be abused. Isabet is a deeply sympathetic main character, so much so that I'd love to find out what happens to her next.

Michael Bishop's novella, *'Twenty Lights to "The Land of Snow"'*, is notable for two main reasons: it's the longest piece in this anthology, taking up fully one-fifth of the book, and the characters in the story do not

* en.wikipedia.org/wiki/List_of_Dune_Houses

come from the western cultures of America and Europe which normally dominate SF stories written in English, but from Buddhist Tibet. We find ourselves onboard the Kalachakra (which translates as 'Wheel of Time'), an antimatter-powered starship that is 82 years into a 106-year journey to Gliese 581g, 20 light years from Earth. The ship has been constructed in order that one thousand Buddhists, including the 21st Dalai Lama, can escape from Chinese-occupied Tibet and set up a colony on the planet they've named Guge. Unfortunately, the Dalai Lama has recently died on board the ship, cause unclear, and seven-year old Greta is woken from hibernation sleep to be told that the adults believe her to be the reincarnation of his sacred soul. This is unwelcome news to Greta, who is quite happy being a normal little girl, and it's also not what many of the resident monks want to hear, given that the Dalai Lama has previously always been male. Are they sufficiently offended by the idea to try and find an alternate candidate for the post? And in the meantime, as Greta gets older, can she get used to her new position, and the responsibilities that come with it? This is an unusual story, partly because the tenets of Buddhism are so central to the storyline, but also because it's quite slow-moving, with little action. This might make it sound boring, but it's not. In fact, I found it a thought provoking account of how an interstellar pilgrimage might actually progress, while the central character, Greta, provides a strong focus around which everyone else revolves. Once again a key plot point, late in the story, revolves around an engineering problem, bringing the details of the particular interstellar propulsion technology chosen here to the very heart of the story. Indeed, there's a rather lovely bonus, in that the story is followed by a picture of the Kalachakra, beautifully drawn by NASA scientist and SF writer Geoff Landis.

The penultimate story is '*The Big Ship and the Wise Old Owl*', by Sarah A Hoyt. Unlike most of the other pieces, this one features a multi-generational, laser sail powered starship intended to take several hundred years to reach a habitable exo-planet in the Alpha Centauri system. Three twenty-year old friends on board uncover a mystery when they realise that the nursery rhymes taught in the kindergarten are subtly different from the original versions held in the ship's databanks. Who has changed them, and how does this relate to the fact that information on how long the ship has been travelling for, and how close they are to their destination, is restricted? This is an excellent piece with three strong central characters, which provides a fascinating illustration of a potential problem for a centuries-long voyage. The plot has some similarities to J G Ballard's 1962 short story 'Thirteen to Centaurus', but Hoyt puts her own individual twist on it.

Multi-award-winning SF author Mike Resnick rounds out the anthology with the shortest of the fictional offerings. '*Siren Song*' tells the tale of the Great Regatta of 2237, in which five nuclear fission or fusion-powered spaceships race around the solar system against a single solar sail-powered competitor, the Argo. When the Argo falls behind the others, its Captain decides to catch up by taking a detour through the most densely populated part of the asteroid belt, with surprising results! This piece doesn't really qualify to be in the anthology, as it's about interplanetary, rather than interstellar, travel. However, it provides such an amusing end to the book that I'm more than happy to overlook this.

So, does this anthology's mix of fiction and non-fiction work? I'd say yes. Those with a detailed knowledge of all the main types of interstellar propulsion technologies may not learn a huge amount from the four essays, but for the rest of us they offer an excellent primer on the science and engineering of starships, enabling readers to understand more fully the technical challenges that generate key plot points in many of the stories.

I'll conclude with a simple suggestion: if you're interested in the science and the fiction of interstellar travel, order yourself a copy of 'Going Interstellar'. You won't be disappointed.

About Patrick Mahon

Patrick Mahon is Deputy Editor of Principium, and i4is Programme Manager. He 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. As well as reviews, he writes science fiction in his spare time.

BOOK REVIEW: Rendezvous with Rama, by Arthur C. Clarke (Gollancz, 2006 [1973])

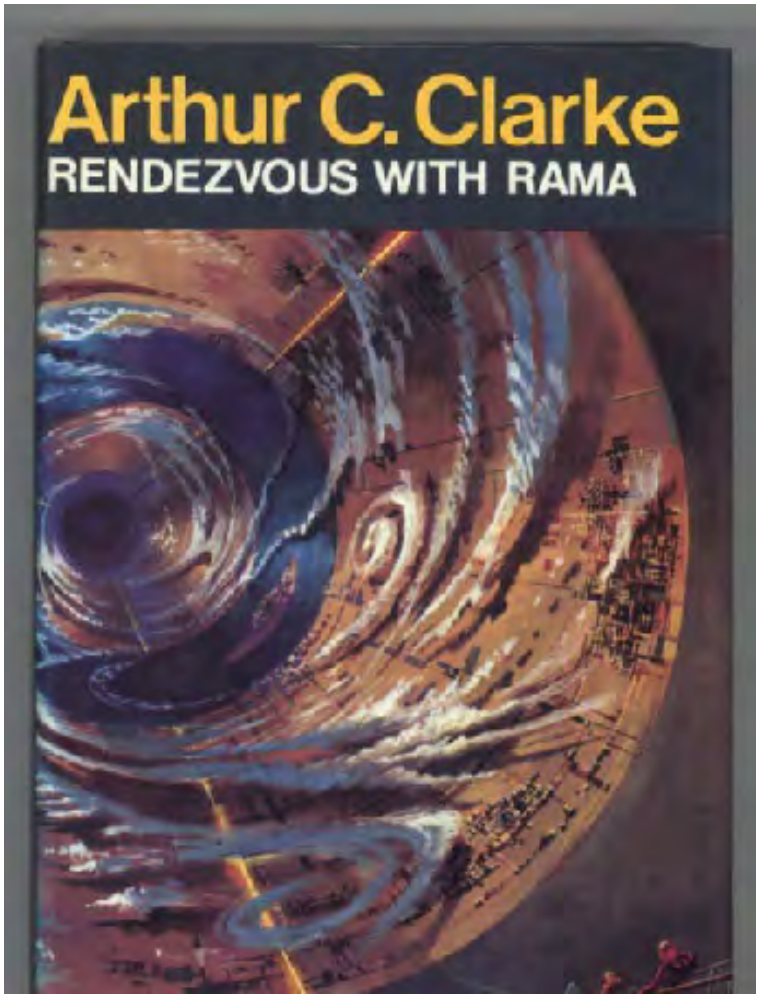
Reviewed by Patrick Mahon

The interstellar asteroid ‘Oumuamua produced much early speculation centred on its unusual shape and the analogies with Clarke’s novel. Here our Principium Deputy Editor reviews the book in the light of this, our first known interstellar visitor.

In the last issue of Principium I reported on the celebrations, in and around December 2017, to mark the centenary of Sir Arthur C Clarke’s birth. In that article I referred to several of Clarke’s novels in which realistically-portrayed spacecraft feature prominently, suggesting that these might provide interesting reading matter for i4is supporters. My starting point in that discussion was the huge alien ship which briefly visits our solar system on a hyperbolic trajectory in Rendezvous with Rama, and its parallels with, and differences from, our recent interstellar visitor, ‘Oumuamua.

Not having read Rendezvous with Rama before, I took my own advice and got hold of a copy. What follows are some thoughts on the story, seen from the perspective of someone interested in the science and engineering of spaceflight.

The basic plot is simple enough. In 2131, a large object is detected coming towards the inner solar system. When its orbit is computed, it becomes clear that it is not a comet or an asteroid permanently bound to the solar system, but an interstellar visitor whose hyperbolic orbit will see it flash past the sun and planets just once, before it heads off again into deep space. It also has an unusual light curve, suggesting that it’s not just an ordinary lump of rock tumbling on its own axis but something much more regular. That’s enough to persuade those in charge to send a small space probe on a flyby mission, to see



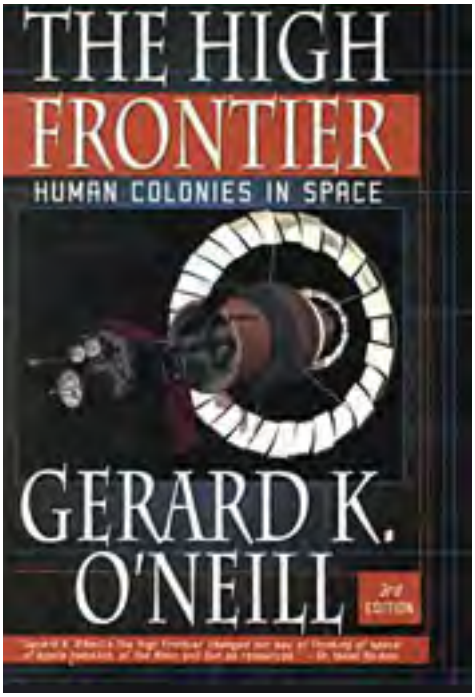
Bruce Pennington's cover for the original UK edition of Rendezvous with Rama, 1973. Credit: Artist & Gollancz
Current UK edition: Orion Books
www.orionbooks.co.uk/books/detail.page?isbn=9780575077331.

what the object is in more detail. The encounter, some five months later, proves extraordinary: the object, now christened Rama after the Hindu deity, turns out to be a hollow cylinder, some 50 kilometres in length and 20 kilometres in diameter. It is clearly artificial in origin, and thus represents humanity's first contact with alien technology.

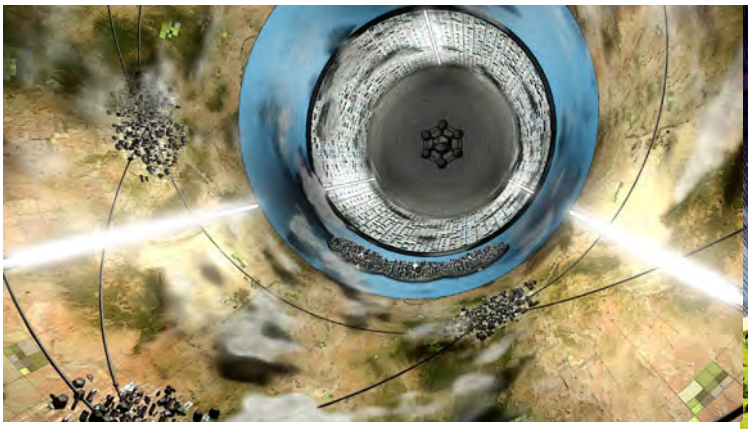
Armed with this information, the authorities order William Norton, Commander of the manned survey vessel Endeavour - the only crewed spacecraft in the solar system whose current position makes catching up with the extraterrestrial visitor possible - to rendezvous with Rama. Having done so, Norton and his crew have just three weeks to explore the interior of the lifeless alien spacecraft before they must leave it, since its point of closest approach to the Sun would melt their own vehicle. What they find inside Rama is a series of mysteries, the unravelling of each of which only leads to more questions. Can Norton work out who the Ramans were, and why they aimed their ship at our solar system, before he is forced to abandon it forever?

Putting the technicalities to one side for a moment, Rendezvous with Rama strikes me as classic Clarke. He proposes a situation which only makes sense within the genre of science fiction - in this case, first contact with an alien civilisation through one of its artefacts - and then builds an exciting adventure story around it, filled with surprises, cliffhangers and close shaves, almost all of which are a direct scientific or engineering consequence of the scenario he has presented us with. As so often with Clarke's novels, plot generally trumps character, although he does explore his main characters' lives a little more here. For example, we find out that Commander Norton has two wives and families - one on Earth and the other on Mars - but Clarke is at pains to emphasize that this is normal for the times, and that there is nothing underhand going on; the arrangement is an open one and his wives are friendly to each other. Nonetheless this is principally a novel about the exploration of alien technology, not a reflection on the human condition. Read on that basis, I think it's a great success.

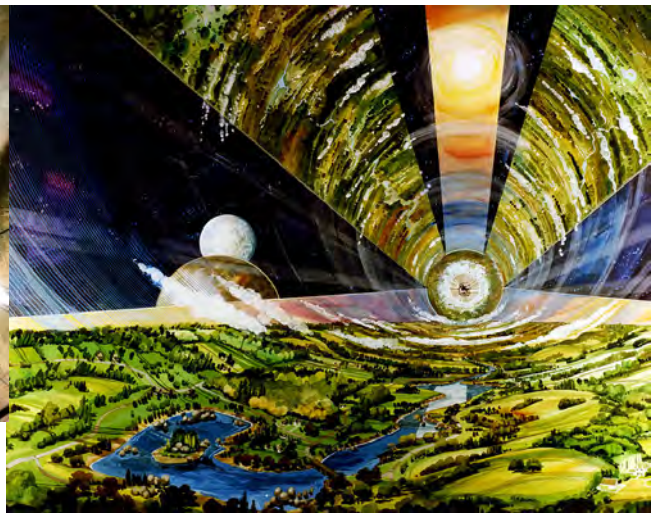
So, which aspects of Rendezvous with Rama are going to be of particular interest to i4is supporters? In the interests of space, I'll focus on just four - although there are several others that I could have included as well. First, there's the question of how hard it is for Norton and his ship to get to Rama in the first place. We're told in the book that they have to borrow fuel from three sister survey ships in order to be able to accelerate to a high enough velocity to catch up with, and then



The High Frontier - Human Colonies in Space, Gerard K O'Neill, 3rd Edition, Apogee Books (2000)
ISBN 9781896522678.
www.cgpublishing.com/Books/Highfrontier.html.



Impression of the interior of Rama
Credit: Monomorphic at English Wikipedia [Public domain], via Wikimedia Commons.



Interior of an O'Neill cylinder
Credit: Rick Guidice, NASA Ames Research Center; color-corrector unknown.

match speeds with, the visitor. This is because Rama, as a one-time visitor to the solar system, is travelling on a rapid hyperbolic orbit round the Sun. This is principally an energy issue: if an object with relatively low speed and energy comes into the Sun's gravitational field of influence, the likely outcome will be a fiery death as it falls into the Sun's outer layers. If the object has high enough speed and energy, it can avoid that fate and end up orbiting the Sun in a periodic, elliptical orbit. However, if its kinetic energy is too high to be captured by the Sun, it travels instead on a one-shot hyperbolic orbit, where the Sun's gravity is enough to bend its path at closest approach, but not enough to hold onto it, and it shoots off into interstellar space once more, never to be seen again. That is the fate of Rama, here, and of our recent, real-life interstellar visitor 'Oumuamua also. This explains why sending a space probe to fly past 'Oumuamua, let alone rendezvousing with it, presents such a challenge, as i4is's Project Lyra has demonstrated [1]. With current chemical propulsion technologies, accelerating a probe to a high enough speed is very hard. We need better, faster propulsion technologies if we're to stand a good chance of successfully sending a mission to the next 'Oumuamua. This issue was considered in detail by Marshall Eubanks in the last issue of Principium [2].

Second, much of the story is concerned with the physical implications for Norton and his crew of finding themselves exploring the interior of a fifty kilometre long and twenty kilometre diameter cylinder which rotates on its long axis once every four minutes in order to provide artificial gravity of around 0.6g at the interior of the spaceship's walls, reducing linearly to zero at the central axis. This aspect of the physics of a rotating habitat is well-known, being extensively explored for example in Gerard K. O'Neill's The High Frontier (1977). However, Clarke considers several other implications of the situation, including for example the need for a large cliff to the 'southern' side of the Cylindrical Sea that bisects Rama (the side nearest the ship's engines), to ensure that when the ship accelerates, the seawater doesn't slosh over the farmland adjacent to it. It's these kinds of practical consequences of spinning your spacecraft to generate artificial gravity that interstellar advocates can learn much about from Clarke's books in general, and this one in particular.

Third, Clarke uses the book to consider other aspects of long duration spaceflight. One I found both intriguing and prescient was the description of one building they explore, where they find three-dimensional, life-sized holographic representations of all sorts of Raman artefacts. They hypothesize that this is a form of computer memory, enabling the ship to manufacture copies of any of the holograms using what we would now call 3D printing. This seems like an excellent solution to the question of how you maintain your onboard equipment in good working order during an interstellar journey that might take many thousands of years - subject, of course, to someone continuing to know how to work the 3D printers themselves.

Fourth, near the end of the story we find out that Rama has a powerful but mysterious propulsion system. If you're interested in fictional explorations of novel propulsion technologies, it's well worth reading the book just for the intriguing details of this 'space drive' that Clarke shares with the reader.

If, like me, you're an i4is supporter who enjoys reading so-called 'hard SF', where science and engineering are central to the story, then I'd say that Rendezvous with Rama should be high on your priority list. The entire story is a rigorous exploration of the physics and engineering of getting to and then exploring this alien spacecraft. If another interstellar visitor like 'Oumuamua should enter the solar system in future, once our spaceflight capabilities have advanced sufficiently to make a manned rendezvous mission a realistic possibility, Clarke's novel could serve as a valuable mission primer. Not bad for a book published forty-five years ago!

References:

[1] A M Hein, N Perakis, K F Long, A Crowl, M Eubanks, R G Kennedy III, R Osborne, Project Lyra: Sending a Spacecraft to 1I/'Oumuamua (former A/2017 U1), the Interstellar Asteroid, arxiv.org/abs/1711.03155.

[2] T M Eubanks, Preparing for the next Interstellar Object, Principium issue 20, February 2018, p.29.

Imagining Interstellar

Art by Efflam Mercier

(words by Efflam Mercier and John Davies)

Principium readers may remember one of our most striking covers. P16 illustrated Andreas Hein's paper on AI probes via the art of Efflam Mercier. Here we show Efflam's art with words based on his own notes - giving a glimpse of his thinking as he creates his beautiful images.

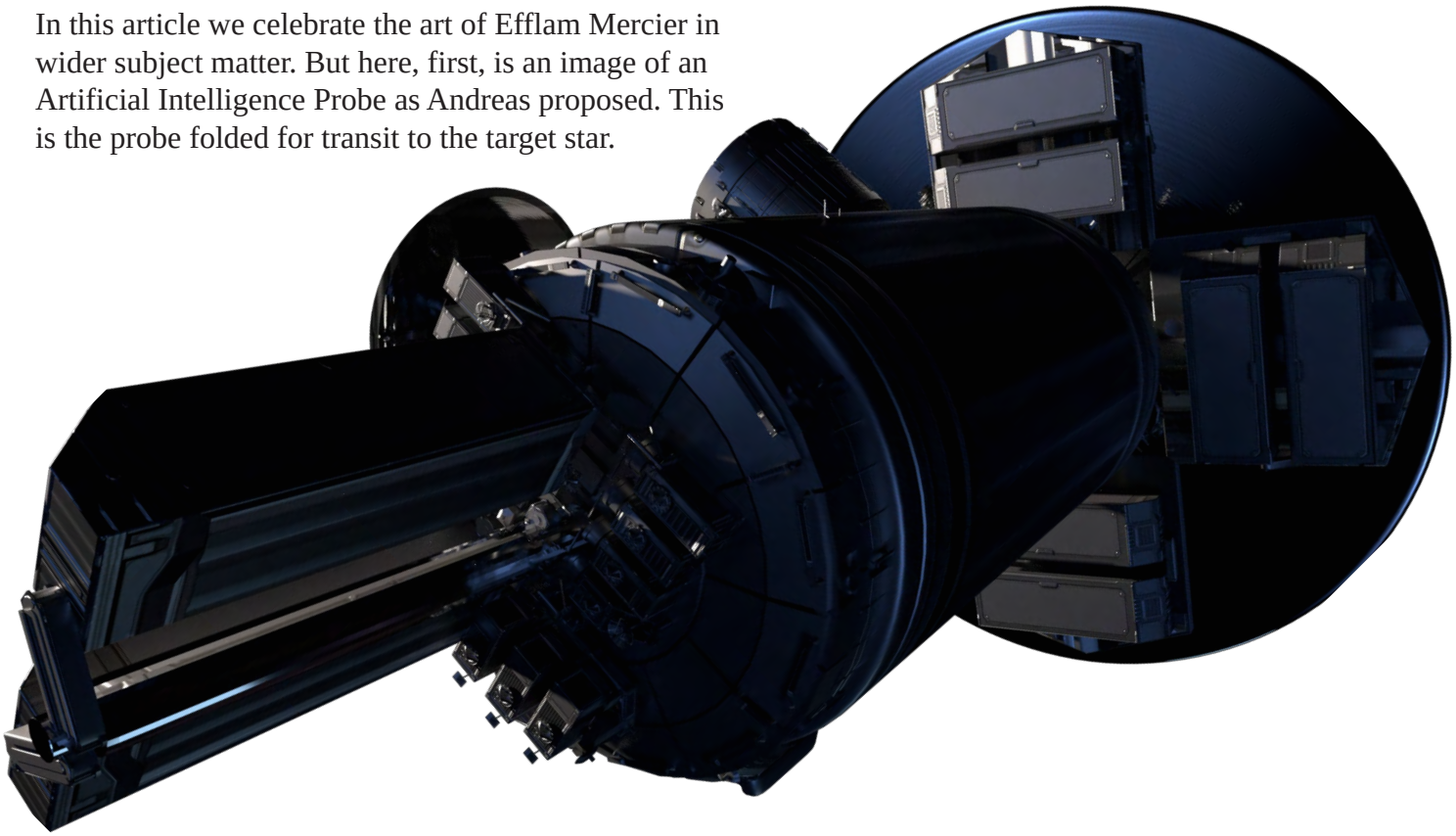
Artificial Intelligence Probes

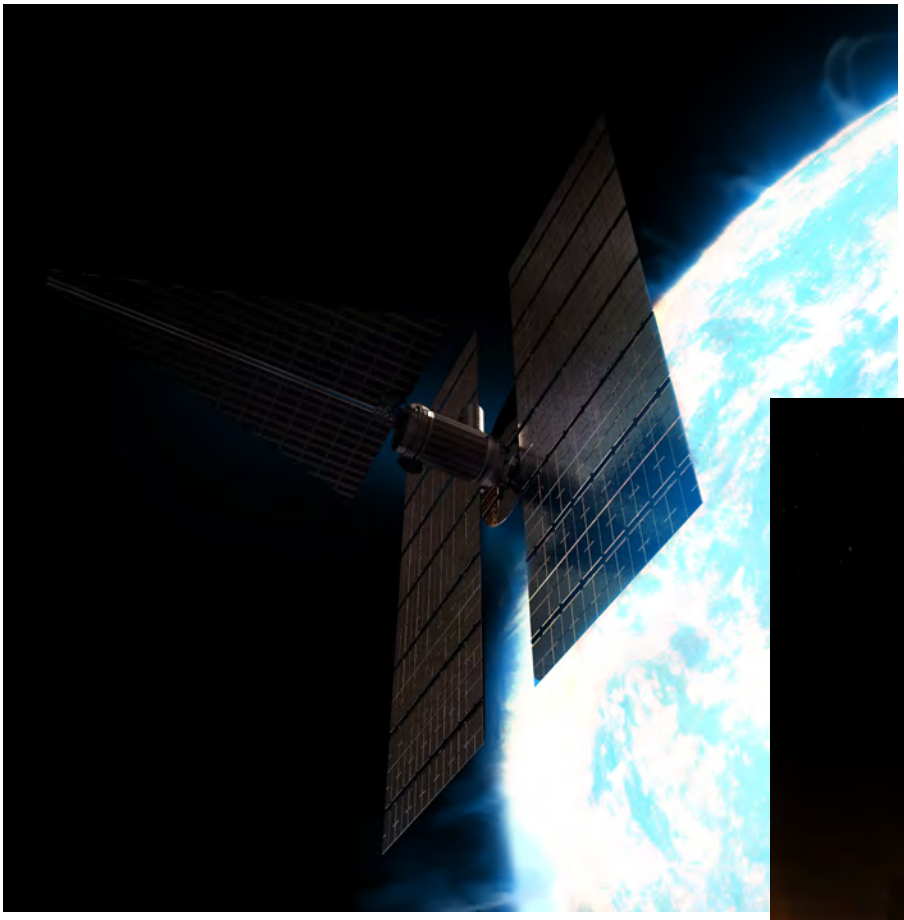
We in i4is have a long established interest in the application of Artificial Intelligence (AI) to the interstellar endeavour. And we love to inspire ourselves and others with the vision of our associated artists.

When Dr Andreas Hein, our Executive Director, wrote his most recent work on AI for interstellar he contacted one of our oldest collaborators, Adrian Mann (www.bisbos.com) for images to illustrate his paper, *Artificial Intelligence Probes for Interstellar Exploration and Colonization*, (www.researchgate.net/publication/311872021_Artificial_Intelligence_Probes_for_Interstellar_Exploration_and_Colonization). Adrian's images have featured in many issues of Principium and on several front covers. On this occasion Andreas also asked a new i4is collaborator, Efflam Mercier (efflammercier.com).

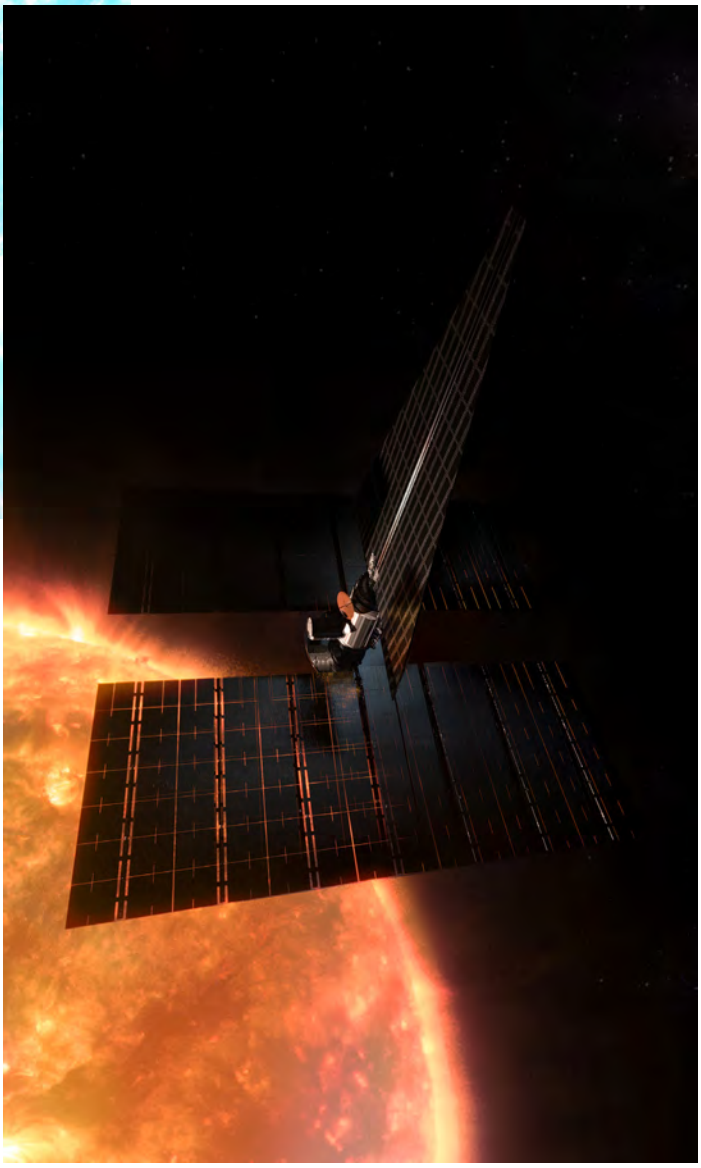
And we featured more of his art in Principium 16, including the front cover.

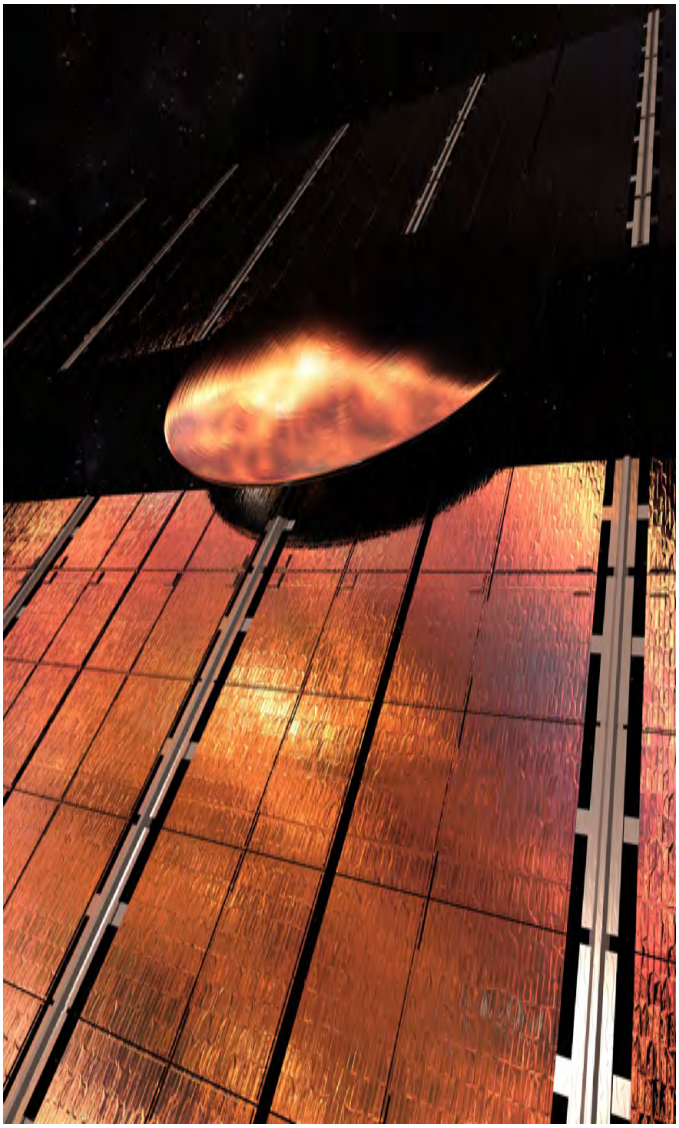
In this article we celebrate the art of Efflam Mercier in wider subject matter. But here, first, is an image of an Artificial Intelligence Probe as Andreas proposed. This is the probe folded for transit to the target star.





Two images of Andreas' AI probe at its target star.
Given the power demands of a true AGI*, power generation for computing is likely to take place close to the target star to limit solar panel size

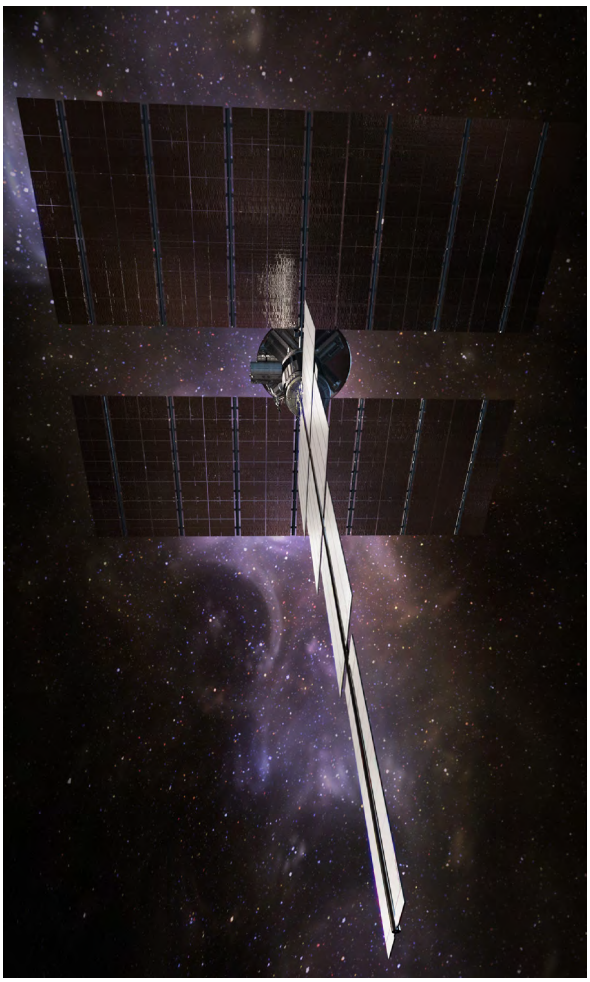


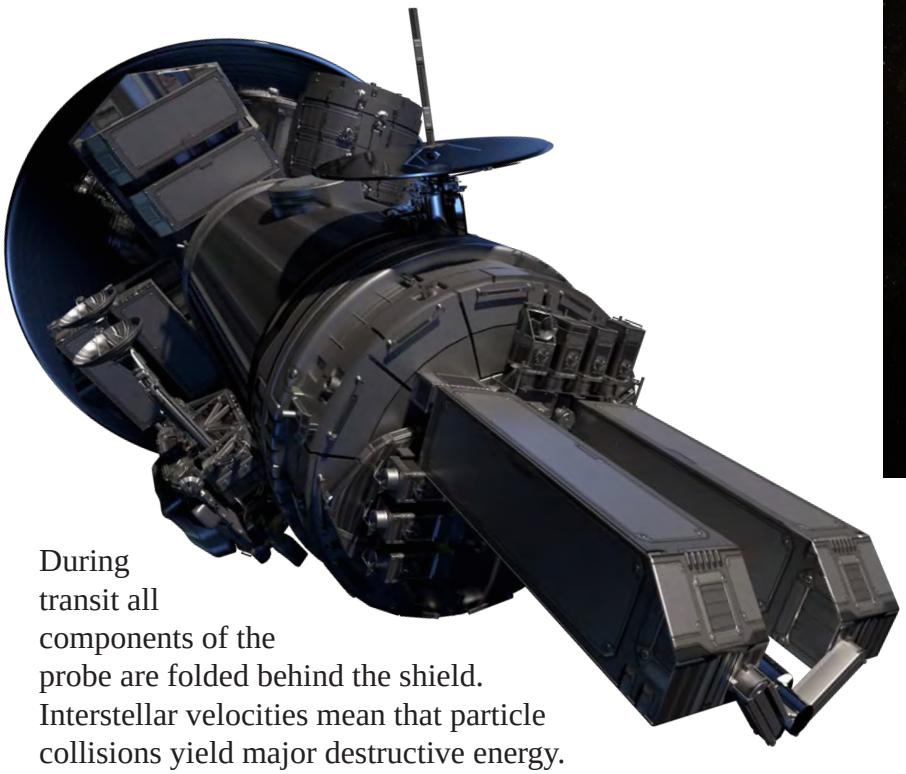


Shield to protect the AI probe from high speed particles during interstellar transits at significant fractions of c (speed of light), as well as particles from the local star.

*Artificial General Intelligence is AI which is capable of intellectual performance equivalent to that a human being. A good introduction to the feasibility of this is in en.wikipedia.org/wiki/Philosophy_of_artificial_intelligence#Can_a_machine_display_general_intelligence?

The AI probe deployed - before alignment to face the target star. Conversely the computing components will need to be both shielded from stellar heating and able to dump the waste heat of computation into the only available sink, the interstellar void whose temperatures are just a few degrees Kelvin. The heat dissipation radiators follow the inverse square law narrowing as they get further away from the circular AI payload.





During transit all components of the probe are folded behind the shield. Interstellar velocities mean that particle collisions yield major destructive energy. On deployment at the target star the same shield faces the star to protect the computational elements from particles and radiation while allowing the probe to be as close to the star as possible for maximum energy production with minimum solar cell mass.

Artistic rendering of an hypothetical Chipsat deployment.

Scientists and engineers all over the world are exploring the possibilities of miniaturisation to reduce the cost of survey and data gathering from low earth orbit, but who knows, maybe one day we could send some to other planets, or even other star systems!

They would be deployed from a Cubesat at 300km altitude, their low ballistic coefficient assuring a safe lifetime of only 2 months and an assured destructive re-entry.

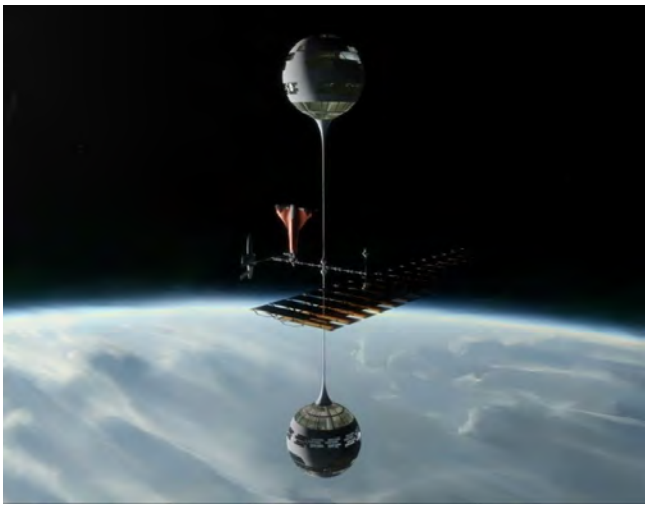
Inflatable “bolo” hab modules

This is an image Efflam created for the Arstation “beyond human” challenge exploring themes of transhumanism and the future of mankind. Efflam wanted to explore a non-conventional space habitat interior, slightly inspired by the “bolos” of *Seveneves* (see also the second piece by Sander Elvik elsewhere in this issue). A system where two or more inflatable hab modules are acting on each other as counterweights, providing artificial gravity for long duration flights at small RCS thruster fuel costs. Those habs would have to be modular in nature in order to be able to remodel the space depending on if you’re in microgravity or simulated gravity.

Here’s an excerpt from the accompanying story :

Beyond human : Arrival at Luhman WISE-1B

"Earth is the cradle of humanity, but one cannot live in a cradle forever." Konstantin Tsiolkovsky
Entry // 1 : Arrival at Luhman WISE-1B
Final mission report...Arrived at Luhman WISE-1B, we are about to deorbit.
Status : only 14 survivors of the initial 50 member crew, Sarah is now the commander. Running out of water, (we had to convert some to propellant after a leak) crew is heavily dehydrated. The terraforming equipment has been destroyed in a meteoroid collision.
Prof. Hamel R. has ended his life after the loss of the terraforming equipment. Morale is low about the losses but everyone is excited about landing. We will not be able to complete the primary mission. We are keeping a picosat in orbit, hopefully we can bounce a signal from the ground and transmit survey information for the secondary mission.
Tell the Earthlings we'll send some nice pictures.



On the topic of rotating counterweights, this is a concept for a hotel in low Earth orbit (LEO).
The docked space planes would use a small percentage of leftover fuel for station-keeping boost.
The solar panels could be folded in the direction of the air drag to reduce ballistic coefficient during night cycles, then open up again when the drag to power output ratio is favorable.
At some point if access to LEO becomes cheap enough, we will start to see more and more branded content in space; this is a logical next step in a capitalist society. The first real example of this being the Tesla roadster sent by SpaceX to the trans-Neptunian region. We could one day see a Coca Cola / Apple branded luxury spaceplane in rose gold. (Efflam really dislikes this color and hopes it becomes one of those things that people will point at and laugh when they talk about the 2010’s).

Hypothetical Astronaut looks from ‘Oumuamua to the Earth-Moon system at closest approach
This picture was created for the cover of P20. Often in space images, what’s missing is the human scale. And so even though it is improbable, Efflam finds that the addition of an astronaut always gives a sense of melancholy to images. It’s the story of humanity beyond the cradle, where the human civilization will have to step up to the challenge of sustainable development and managing resources on multiple planets at a time.
The Earth and Moon are to scale at the closest approach of ‘Oumuamua.

About the artist
Efflam Mercier is a 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.

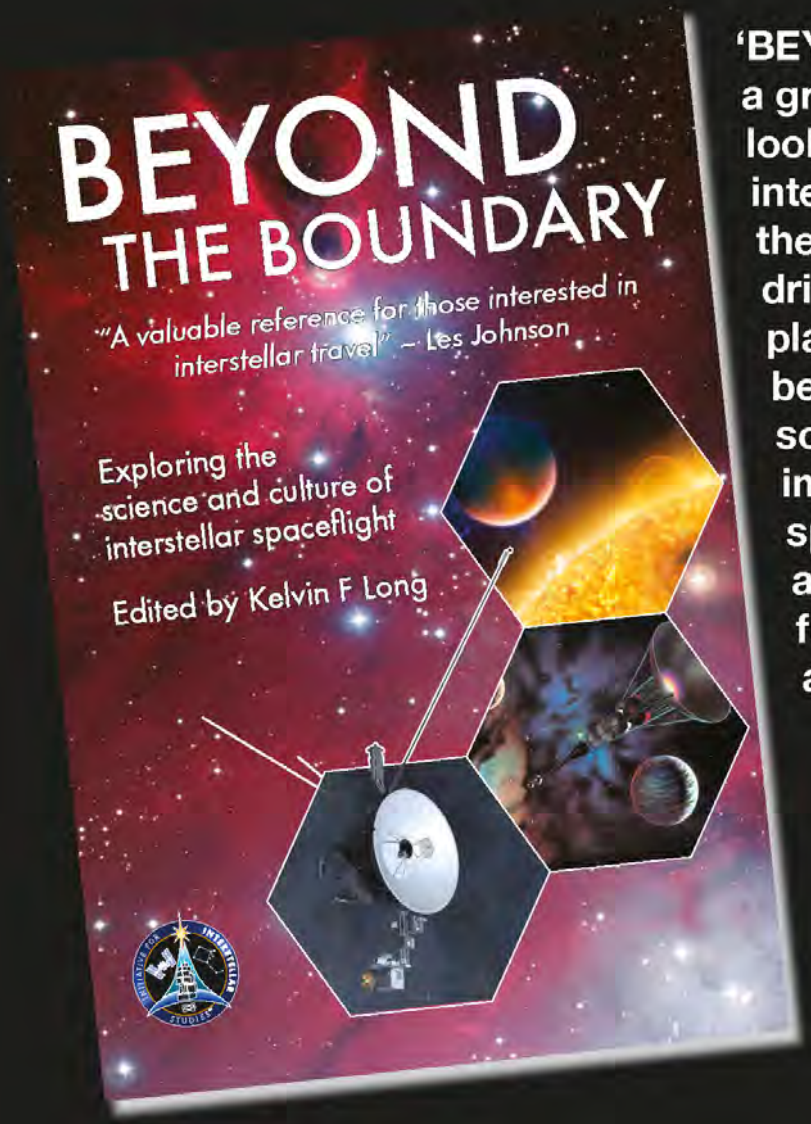
NEXT ISSUE

Z-pinch and Icarus Firefly
Nomadic Planets and Interstellar Exploration
More about the October IAC conference

We'd love to hear your thoughts on Principium, the Initiative or interstellar flight in general. Email - info@i4is.org - or come along to Facebook(InterstellarInstitute), Twitter (@I4Interstellar) or LinkedIn to join in the conversation.

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.

- 448 pages, hardback edition
- Featuring 21 chapters written by i4is' interstellar experts
- Topics as diverse as propulsion technology, exoplanets, art and SETI

www.i4is.org

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.

Editor: John I Davies
Deputy Editors : Andreas Hein, Patrick Mahon
Layout: John I Davies

The Initiative for Interstellar Studies is a pending institute, established in the UK in 2012 and incorporated in 2014 as a not-for-profit company limited by guarantee.
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Scientia ad sidera
Knowledge to the stars

Front cover: TU Delft E|A|S (Evolving Asteroid Starships) project
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Back cover: Gaia mapping the stars of the Milky Way
Credit: ESA/ATG medialab; background: ESO/S. Brunier

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