PRINCIPIUM

The Newsletter of the Initiative for Interstellar Studies
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www.i4is.org

Scientia ad sidera
Knowledge to the stars

Editorial

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

Our Introduction feature for Principium 20 is *Project Lyra: A feasibility study for a mission to the interstellar asteroid 'Oumuamua* by i4is Executive Director Andreas M Hein. We are featuring the i4is Project Lyra strongly in this issue. Our first known interstellar visitor, barren though it may be, is a momentous event and the Project Lyra is typical of our team's ability to bring world-class technical resources rapidly to bear upon issues important to the interstellar community. If you would like to be involved, by technical or by material contribution to our work then get in touch with us via info@i4is.org.

Our front cover this time is by Efflam Mercier (efflammercier.com). We asked him to imagine a crewed mission to 'Oumuamua and the view of the Earth-Moon system at its closest approach to our planet. It did not happen, of course, but we may anticipate that, with progress in human capabilities, it may be possible with a future interstellar object. I hope readers find it as inspirational as I do!

Last time I misattributed that magnificent Sputnik image to our colleague Robert Kennedy. In fact he and others have used it in many contexts, including Wikipedia. I have tried to track down the artist, Gregory R Todd, without success. If anyone knows him then please put me in touch so I can add my thanks to all those he has had and should have had over the years!

Our back cover this time is the three French ExTrA telescopes at the European Southern Observatory, La Silla, Chile. They look for exoplanets transiting across their local star (www.eso.org/public/teles-instr/lasilla/extra).

And we do need to be ready for the next interstellar object so Marshall Eubanks has analysed this in *Preparing for the next Interstellar Object.* Marshall is CEO at Asteroid Initiatives LLC, the Asteroid Prospecting Company, and was a key member of the Project Lyra team.

Our Interstellar News this time includes some words from Andreas Hein on i4is in 2017, a summary of what Kelvin Long and Rob Swinney did on their recent USA visit including giving addresses at NASA Goddard and the University of Maryland. We also report interstellar-related work including the Primitive Object Volatile Explorer (PrOVE) proposal, upcoming ideas from Darryl Seligman of Yale University and the work of the team at Technical University of Dresden. We celebrate the BIS Scotland relaunch and we'll be working with them to deliver more outreach in Scotland. We have an update on Project Glowworm and finally we enjoy some Christmas tree sailcraft from our major 2017 contributor Dmitry Novoseltsev.

Neal Stephenson has always been an interesting novelist and thinker. This time we consider the astrodynamical side of his latest novel in the first part of *The Orbits of Seveneve*s by new contributor Sander Elvik.

I have always been fascinated by Konstantin Tsiolkovsky and his famous equation. In *Tsiolkovsky - Interstellar Pioneer* I hope to show how his maths, physics and engineering broaden to imagine our interstellar future.

We have two News Features - on work in progress on i4is Project Lyra and the interstellar asteroid generally and on the visit of Pete Worden of Breakthrough Initiatives to the i4is HQ.

'Oumuamua has obvious parallels with the eponymous object in *Rendezvous with Rama* and we recently saw Arthur C Clarke's centenary. Patrick Mahon reminds us of his interstellar vision.

As promised we include a glimpse of our HQ interior concentrating on *Models and art at the Mill.*

Next time we will have *The Orbits of Seveneves - Part 2 - the orbits explained*, a review of *Going Interstellar* - a Baen anthology of new fiction and non-fiction on interstellar travel and a major feature introducing Z-pinch fusion propulsion based on the Project Icarus Firefly concept.

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.

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

Project Lyra: A feasibility study for a mission to the interstellar asteroid ‘Oumuamua

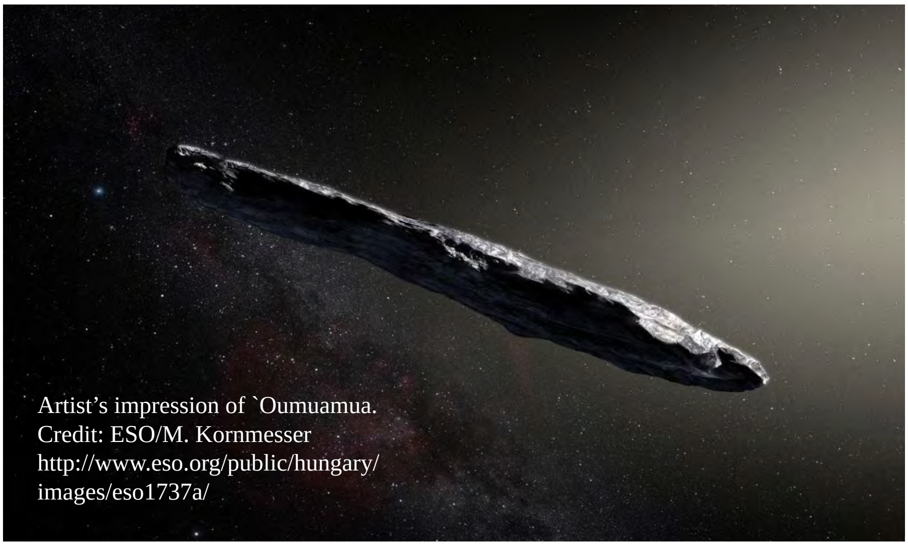
Andreas M Hein

Andreas Hein describes how an i4is technical team responded to the detection of the interstellar asteroid ’Oumuamua. Their paper, *Project Lyra: Sending a Spacecraft to 1I/'Oumuamua (former A/2017 U1), the Interstellar Asteroid* received wide attention and sparked interest in interception of interstellar objects

In 2017, a yet unseen, mysterious visitor from our galaxy has entered our solar system. On October 19th 2017, the University of Hawaii’s Pan-STARRS 1 telescope on Haleakala discovered a fast-moving object near the Earth, initially named A/2017 U1, but now designated as ’Oumuamua [1]. The object’s trajectory is hyperbolic, which means that it is not bound to the solar system. It flew into the solar system from interstellar space and after having been pulled close to the Sun by its gravity, it is now on its way to leaving it again. At its closest approach to the Sun, it had a velocity of over 80 km/s, faster than any object that has been observed in our solar system to date. At this speed, you would get from the Earth to the Moon in 1.3 hours.

Its speed will gradually decrease while leaving the solar system and finally reach about 26 km/s in interstellar space, when it has left the Sun’s gravitational pull.

But this is not the only novelty. It gets far more mysterious. The luminosity change pattern of ‘Oumuamua over time indicates that it has a remarkable shape, never observed before in a small body: It looks like a cigar and has roughly the length and width of the Empire State Building.



Artist’s impression of `Oumuamua.
Credit: ESO/M. Kornmesser
http://www.eso.org/public/hungary/images/eso1737a/

Another mystery: We still do not know what ‘Oumuamua actually is. Is it a comet or an asteroid? First observations indicated that it didn’t develop a cometary tail when it approached the Sun, which means that it is an asteroid. But later publications hypothesized that if ‘Oumuamua has travelled through interstellar space for millions of years, it might have developed a

[1] MPEC 2017-V17 : New Designation Scheme for Interstellar Objects, minorplanetcenter.net/mpec/K17/K17V17.html

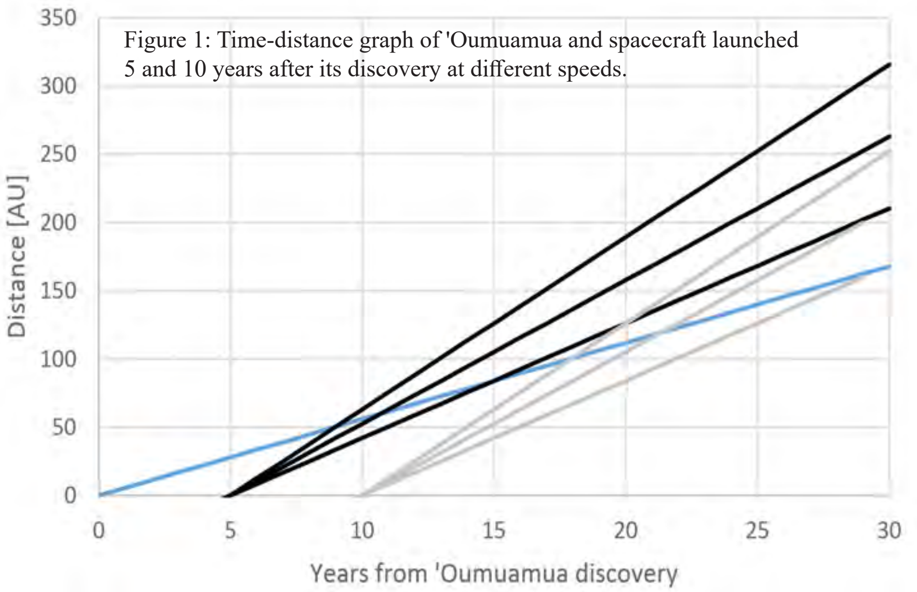


Figure 1: Time-distance graph of 'Oumuamua and spacecraft launched 5 and 10 years after its discovery at different speeds.

"crust" around a potentially icy core, which might explain why no tail was observed. The crust prevented a tail from forming.

From the beginning, discussions about a non-natural origin of 'Oumuamua abound. Due to its odd shape and trajectory, there was a very low probability that this object was actually of artificial origin. A low probability but very high impact event merits further investigation and therefore Breakthrough Listen attempted to capture signals that might be emitted by 'Oumuamua, to no avail.

At this point, it should be clear that 'Oumuamua is probably one of the most exciting objects that were discovered in 2017 and since its discovery, one question has been repeatedly asked: Can we get there? And can we get there with current or near-future technologies? These are exactly the questions the team from i4is asked itself. We immediately formed a team of volunteers (Kelvin Long, Nikolaos Perakis, Adam Crowl, Robert Kennedy, Richard Osborne, Andreas Hein) on the 31st of October, 12 days after 'Oumuamua's discovery and baptised the project "Lyra"; the star constellation in the direction from which 'Oumuamua came from. Intense design activities started during which further external people joined our efforts such as eminent astronomer Marshall Eubanks, former Ariane 4 guidance engineer Adam Hibberd and aerospace engineer Kieran Heyward. What we wanted to know is if we can get to 'Oumuamua within a reasonable timeframe of a few decades with a launch in the next 5-10 years. This much time is realistically the minimum duration for developing an interplanetary spacecraft.

Regarding the first question we wanted to answer, the simplest way of approaching this problem is to assume that 'Oumuamua travels at 26 km/s and now you need to chase it. The later you start the chase, the faster you need to be, as 'Oumuamua will fly farther and farther away from us. The farther 'Oumuamua is away when a spacecraft reaches it, the more difficult will it be to observe it. 'Oumuamua is a very faint object and the farther it gets from the Sun, the more and more difficult it is to collect light that is reflected from it, which means you need a larger telescope that can collect more light. Another disadvantage is that the longer you have to wait for the scientific data to return, the less interesting it gets for scientists to promote a mission. Developing an interplanetary spacecraft already takes about a decade. If it takes further 30 years to get the data, a young scientist is essentially close to retirement when the data arrives.

We can easily visualize this problem. With a time-distance graph, as shown in Figure 1, you can easily see that there are infinite possible trajectories that will reach 'Oumuamua sooner or later. What we do as engineers is to select realistic constraints in order to select the more realistic options. You can easily cut the graph on the x-axis (time) and define the latest and earliest date you want to launch the probe (between 2013 and 2028). If you look at the intersection of the line for 'Oumuamua and the line for the spacecraft you can immediately see when you will reach 'Oumuamua (one to a few decades) and at which distance (100s of astronomical units). The slope of the line is the required velocity (40, 50, 60 km/s) for reaching Oumuamua at a specific time and distance.

Now, the obvious challenge is to reach the required velocities of several dozens of km/s. You need a lot of energy for that. The fastest human-made object is Voyager 1 with a current velocity of about 16.6 km/s at a distance of 122 AU. We need to be several times faster than that. Although challenging, there are ways of reaching such high velocities using existing and near-future technologies. In the following, I present three possibilities that we have considered.

For the first option, we use a mission concept that has been previously proposed by a Keck Institute for Space Studies report for exploring the interstellar medium. It is essentially a rollercoaster ride. The spacecraft is first sent on a trajectory out of the Earth’s gravitational field using a large rocket, for example the Falcon Heavy, Space Launch System, or the Big Falcon Rocket. The spacecraft is accelerated to such high velocities that it is not only thrown out of the Earth’s gravity field but has enough energy to fly out to Jupiter. At Jupiter, the planet’s gravity decelerates the spacecraft with respect to the Sun. This manoeuvre is called “sling shot”. The advantage is that it can be used for accelerating and braking spacecraft by using the planet’s gravity. Hence, you get this acceleration and deceleration “for free” without using propellant. The acceleration and deceleration is achieved by a tiny reduction or increase in the orbital energy of the planet. As the mass of the planet is vastly higher than the mass of the spacecraft, it is essentially negligible. To continue, our spacecraft has been decelerated so much by exploiting Jupiter’s gravity field that it is now on a trajectory that it is falling towards the Sun in an almost straight line, an extreme roller-coaster ride, although it takes over a year to fall. Of course the spacecraft will not fall into the Sun but would move away from the Sun once it has passed its closest point to the Sun. The spacecraft gets very close to the Sun, about 3 solar radii or about 1.5 million km. At such a distance, the solar radiation is about 20,000 times higher than what you receive during a sunny day. Converted to Watts per square meters, the power per area is about 15 MW/m². This is higher than the power per area inside a fusion reactor. To avoid the spacecraft melting away, a heat shield is used which is similar to the heat shield of the NASA Solar Orbiter mission, which will fly close to similar distances to the Sun and is currently undergoing testing. Now, at the closest point to the Sun, the spacecraft ignites a solid propellant engine it has been carrying all the way. In orbital mechanics, you get the biggest “bang for the buck” for a rocket engine, if you ignite it at the closest point to the central body. Hence, the whole idea of falling so closely to the Sun is to ignite the engine at the closest point of approach and then to be propelled away from the Sun with the maximum “bang”. The spacecraft flies away from the Sun at the incredible speed of about 370 km/s. At this speed you would get from London to New York in 15 seconds. Note that this is the speed you would need for a mission duration to ‘Oumuamua of 8 years and a launch in 2021. The spacecraft will have a velocity at infinity of 55 km/s and is therefore much faster than ‘Oumuamua with 26 km/s. The spacecraft would fly past ‘Oumuamua in 2029, taking images using a telescope at a distance from the Sun of 69 AU (Earth-Sun distances). At this point ‘Oumuamua will be a black object in front of the blackness of space. Where the human eye would fail, a telescope and other instruments will suck in the electromagnetic waves that are nevertheless emitted by ‘Oumuamua. The data will then be sent back to Earth with an antenna powered by nuclear radioisotopic generators, a chunk of Plutonium whose heat is transformed into electricity. Finally, the data is transformed into images. What will we see?

It is important to note that all technologies that are used for this mission concept already exist today. The Falcon Heavy is scheduled for a launch in 2018, the heat shield will soon be launched into space with the Solar Orbiter probe, solid rocket engines are routinely used in space, and the spacecraft itself could be based on the heritage of the New Horizons probe that has flown past Pluto.

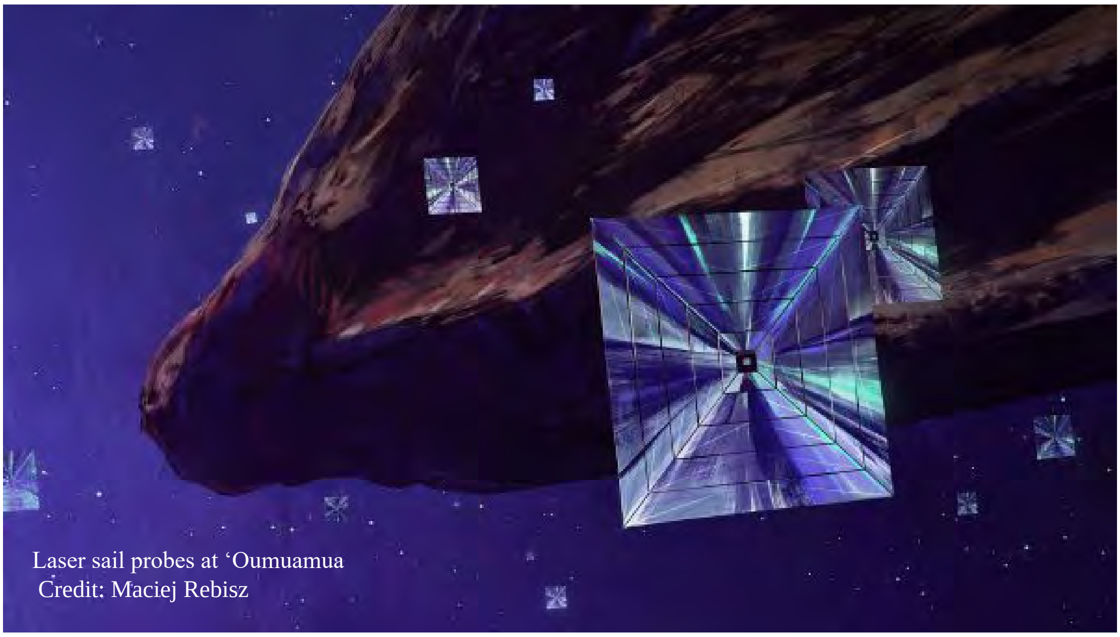
An alternative to this “conventional” mission is to use more advanced technologies. “Advanced” means here that these technologies have not yet been flown in space but laboratory experiments have shown that they work in principle. One possibility is to use laser sail-propelled spacecraft. Laser sail-propelled spacecraft use a laser sail, which is essentially a thin, reflective surface that reflects the photons of the laser beam. The photons exchange momentum with the sail and the spacecraft is accelerated. Think about a sail ship and replace the wind by photons and the sail by a reflective surface. In 2016 Breakthrough Starshot announced the development of a laser-sail propelled interstellar mission, based on a terrestrial laser infrastructure with a beam power of several dozens of GW and gram-sized spacecraft that are accelerated to 20% of the speed of light. Now, could we downscale this infrastructure to launch a spacecraft to ‘Oumuamua? The spacecraft would be launched into space, manoeuvred into the line of sight of the laser infrastructure based on Earth and are then “shot” away by the laser. We did calculations on such a downscaled infrastructure. It turns out that a 2 to 4 MW-class laser infrastructure would be sufficient to accelerate a one gram spacecraft to the same velocity at infinity as the sling shot mission.

However, one gram is obviously not much. If we would like to launch a CubeSat-class (1 kg, 10 cm cube) spacecraft, we would need about 2 to 4 GW of laser power. But what's the advantage of building a large laser beaming infrastructure to send a chip-sized or a 10 cm cube to 'Oumuamua? First, this could be an opportunity for a mission that can be done with a smaller version of the Starshot beaming infrastructure, providing a justification for these intermediate infrastructures before the full-scale interstellar-capable infrastructure is operational. Second, the real advantage is the flexibility of such an infrastructure of launching spacecraft to promising targets without much advanced warning. Imagine a "mothership" with 3-4 CubeSats in space. Once the next interstellar asteroid is detected, the mothership releases the CubeSats which are then launched towards its target within days, thereby minimizing the time between discovery and data return. Compare that with the mission based on conventional technologies before. It takes years to perform the manoeuvres to get the spacecraft up to speed.

Let us summarize. As you have seen, there are ways of flying to 'Oumuamua. We could either use existing technologies or technologies that are currently under development. Who will be first to unravel the secrets of 'Oumaumua? Or will we be too late? In that case, let us prepare for the next interstellar object!

The Lyra paper is *Project Lyra: Sending a Spacecraft to 1I/'Oumuamua (former A/2017 U1), the Interstellar Asteroid*

Andreas M Hein, Nikolaos Perakis, Kelvin F Long, Adam Crowl, Marshall Eubanks, Robert G Kennedy III, Richard Osborne
arxiv.org/abs/1711.03155


Laser sail probes at 'Oumuamua
Credit: Maciej Rebisz

About Andreas Hein and the team

Dr *Andreas Hein* is Executive Director of the Initiative for Interstellar Studies (i4is) and chairs its technical committee. His PhD is from the Technical University of Munich (TUM). He is a Researcher / System Architect - Autonomous Driving System of Systems at CentraleSupelec, Paris. *Kelvin F Long* is President of i4is and founded the organisation with Rob Swinney in 2012. He is the author of *Deep Space Propulsion: A Roadmap to Interstellar Flight* (Springer, 2012) and is a member of the Advisory Committee of Breakthrough Starshot. *Robert Kennedy* is President of i4is-USA. He is Senior Systems Engineer at Tetra Tech and co-founded the Tennessee Valley Interstellar Workshops (TVIW). *Marshall Eubanks* is CEO at Asteroid Initiatives LLC, the Asteroid Prospecting Company, and has held senior positions at JPL and the Internet Engineering Task Force (IETF). *Nikolaos Perakis* is a postgraduate at TUM working on a PhD in combustion modelling and simulation of rocket engines. *Richard Osborne* **is a Systems Consultant and rocket scientist. He has worked for many companies in space technology including Reaction Engines and Commercial Space Technologies. He is a Council Member of the British Interplanetary Society. *Adam Crowl* is Project Officer at Queensland Health, Australia. He is the author of numerous papers on interstellar flight and was a member of the original Project Icarus study group. *Adam Hibberd* is a freelance software engineer and musician/composer. He worked on software for Ariane 4 guidance and Airbus flight simulation at EASAMS and other aerospace companies.** *Kieran Hayward* **is an Avionics Validation Engineer at Thales Alenia Space UK. He has an MSc in aerospace engineering from Cranfield University.**

Sir Arthur C Clarke Centenary Celebrations

Thoughts on a mighty imagination and his envisaged interstellar object by Patrick Mahon

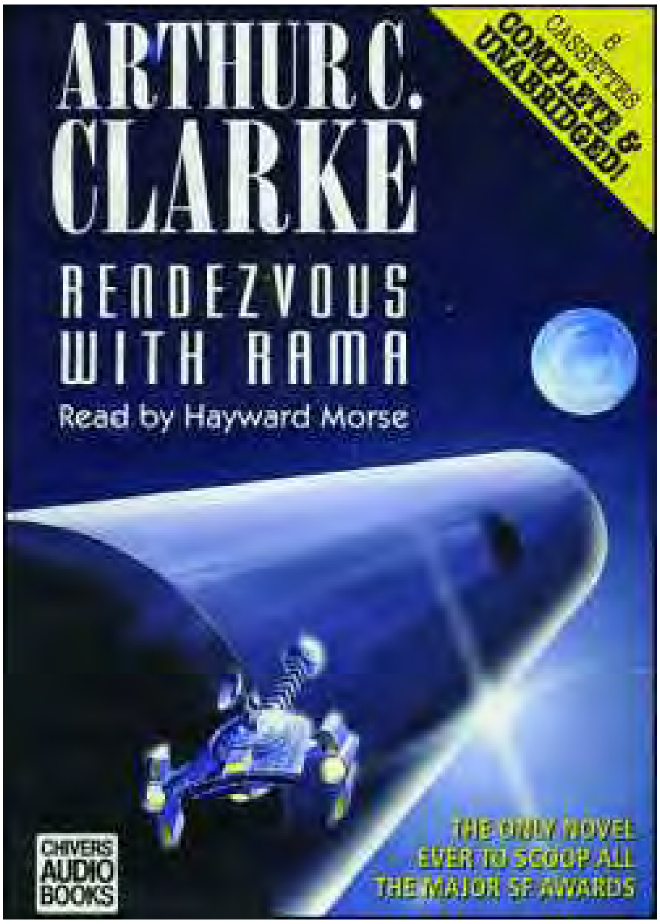
The name of Sir Arthur C Clarke FBIS is, I imagine, a familiar one for most i4is supporters. Clarke's science fiction novels are filled with realistic portrayals of the science and engineering of spaceflight, while his collaboration with Stanley Kubrick on the 1968 film '2001: A Space Odyssey' led to the creation of one of the most iconic spacecraft designs in film history, 'Discovery' – a model of which is on display at i4is HQ.

Although Sir Arthur is sadly no longer with us, 16 December 2017 marked the centenary of his birth. This anniversary was marked by several organisations, including our friends at the British Interplanetary Society, who held a dinner to celebrate Clarke's life at the end of the 'Reinventing Space' conference in Glasgow in late October , and whose Christmas Get Together included an illustrated talk about Sir Arthur by BIS Fellow and special effects designer Mat Irvine, who knew him well. BIS also dedicated the 50th issue of their e-magazine 'Odyssey' to Clarke in November.

Clarke was an active and involved member of BIS for much of his life, joining at the age of 18, becoming a Fellow and twice serving as Chairman.

What makes the centenary of Clarke's birth particularly relevant to the current issue of Principium is the resemblance between the interstellar asteroid 'Oumuamua and the alien spaceship featured in his 1973 novel 'Rendezvous with Rama'. For those who haven't read it, the story focuses on a mission to rendezvous with and study a long, cylindrical object after it enters the solar system from interstellar space. Sound familiar?

Unfortunately, that's where the similarities end. Rama is a huge alien spaceship, over 50 kilometres long and 20 kilometres in diameter. 'Oumuamua is only around 180 metres in length[1], nearly 300 times smaller than Clarke's ship. In addition, attempts by the Breakthrough Listen project to detect any artificial signals emanating from it have been unsuccessful, and the current consensus is that 'Oumuamua is an interstellar asteroid of natural origin, rather



Book covers almost invariably show the interior of the Rama object - where much of the action takes place. This rare exception is an ancient audiobook (on cassettes). Credit: Chivers Audio Books

[1] Estimates of length vary from 180m (www.noao.edu/news/2017/pr1706.php) to about 1km (www.nature.com/articles/nature25020)

than an alien spacecraft. Even so, the first detection of an interstellar visitor to our solar system shortly before the centenary of Sir Arthur's birth seems singularly appropriate.

Rama may be the most topical of Clarke's creations right now, but it is far from being the only one relevant to i4is. Those who have attended one of our 'Starship Engineer' courses will be familiar with several of Clarke's other fictional spacecraft and related technologies, all of which are based on sound engineering principles. A small subset would include:

- Solar sails – the use of sunlight to accelerate a large reflective sail was explored in Clarke's 1963 short story, 'Sunjammer' (later renamed 'The Wind from the Sun').
- Fusion propulsion – Clarke's first published novel 'The Sands of Mars' (1951) includes a plausible fusion-powered passenger liner which travels between the Earth and Mars.
- Quantum vacuum energy drive – in 'The Songs of Distant Earth' (1986), Clarke wanted to show a realistic form of interstellar travel at sub-light speed, as a contrast to the fantastical faster-than-light space drives of 'Star Trek' and 'Star Wars'. He posited a futuristic but conceivable propulsion system based on using the quantum zero-point energy which pervades all space, an idea which was the subject of much academic speculation at that time.
- Space Elevators – the construction of a super-strong orbital tower, reaching from the surface of the Earth up into space, so that people and cargo could travel to and from geostationary orbit without the need for chemical rockets, thus massively reducing the cost of space travel, was explored at length in Clarke's 1979 novel 'The Fountains of Paradise'.

For me, the centenary of Clarke's birth provides an opportunity to give thanks for the life of someone who wrote science fiction that was always informed by science fact – gained initially through being awarded a First Class honours degree in Mathematics and Physics by King's College London in 1948, following his wartime service in the RAF.

I have recently dug out my copies of several of the books listed above, and am re-reading them with great pleasure. If you want to explore some novels which depict interstellar spacecraft realistically I'd recommend Clarke as an excellent starting point.

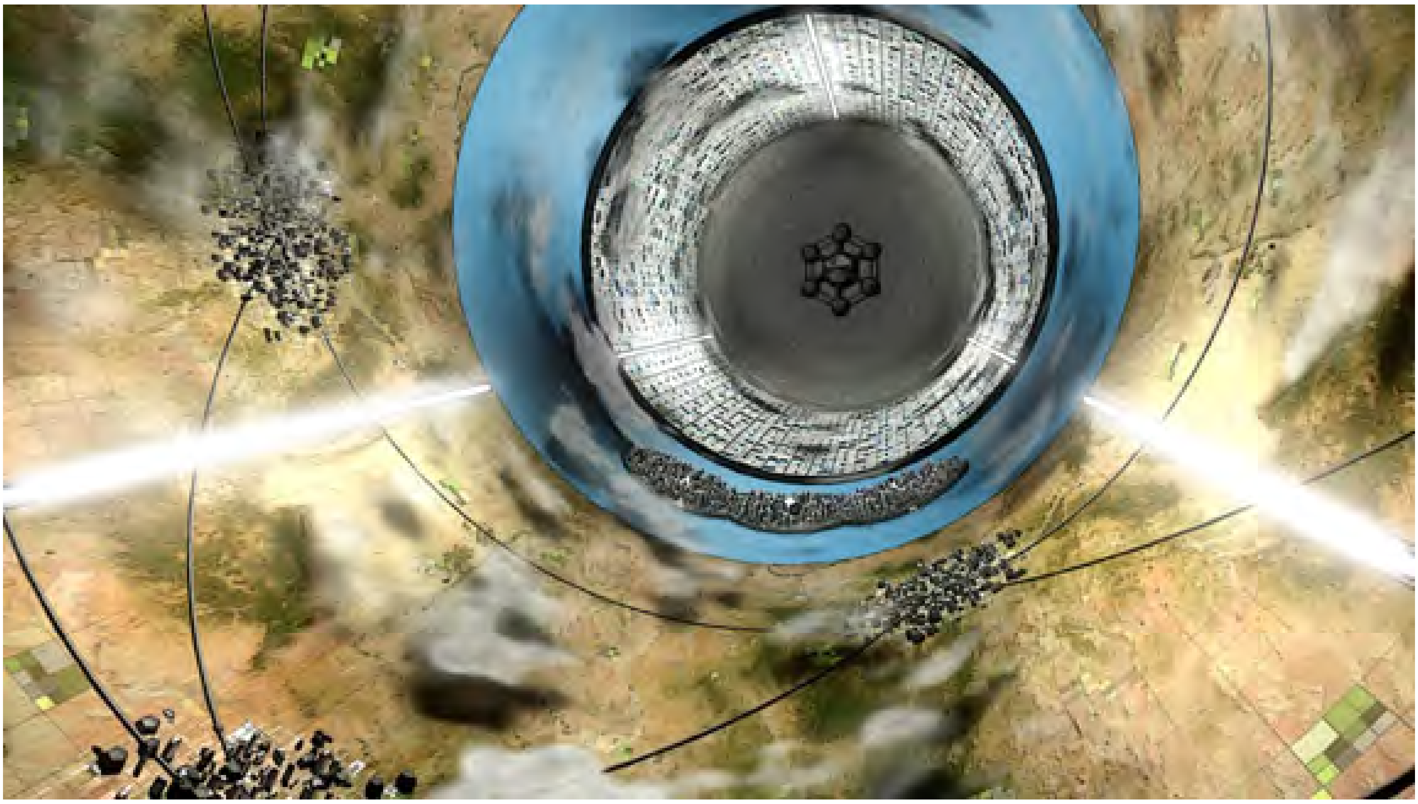


Image was created using descriptions from the original Rendezvous with Rama and its sequel Rama II. 3D artist: James A Ciomperlik. Credit: Monomorphic at English Wikipedia

Interstellar News

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

i4is in 2017

Our Executive Director, Andreas Hein, reminds us of the achievements of the Initiative for Interstellar Studies in the past year -

- The opening of our HQ, which makes us the first dedicated interstellar organization with a building. The opening event in itself has been an unforgettable experience with Apollo astronaut Al Worden.
- We had the honour to welcome Pete Worden, the Executive Director of the Breakthrough Initiatives to our HQ in November and hear about their latest activities. More in Patrick Mahon's report in this issue.
- i4is-US has organised the Foundations of Interstellar Studies Workshop in collaboration with the New York City College of Technology. We spent four marvellous days with presentations spanning the whole width of interstellar propulsion technologies.
- Project Lyra: Our concept study for reaching the interstellar asteroid 'Oumuamua has been a huge success with over 40 websites (Scientific American, Buzzfeed, MIT Technology Review, Universe Today, etc) in more than six languages featuring our project. Even the London Review of Books has picked up the project. i4is.org/what-we-do/technical/project-lyra/
- Andromeda Study: Our Andromeda probe study from 2016 has been featured by the MIT Technology Review and The Times.
- The Interstellar module at the International Space University (ISU) which we delivered for the second year.
- We had numerous educational events in schools and colleges throughout the year.
- Principium is enjoying a larger and larger readership within the interstellar community.

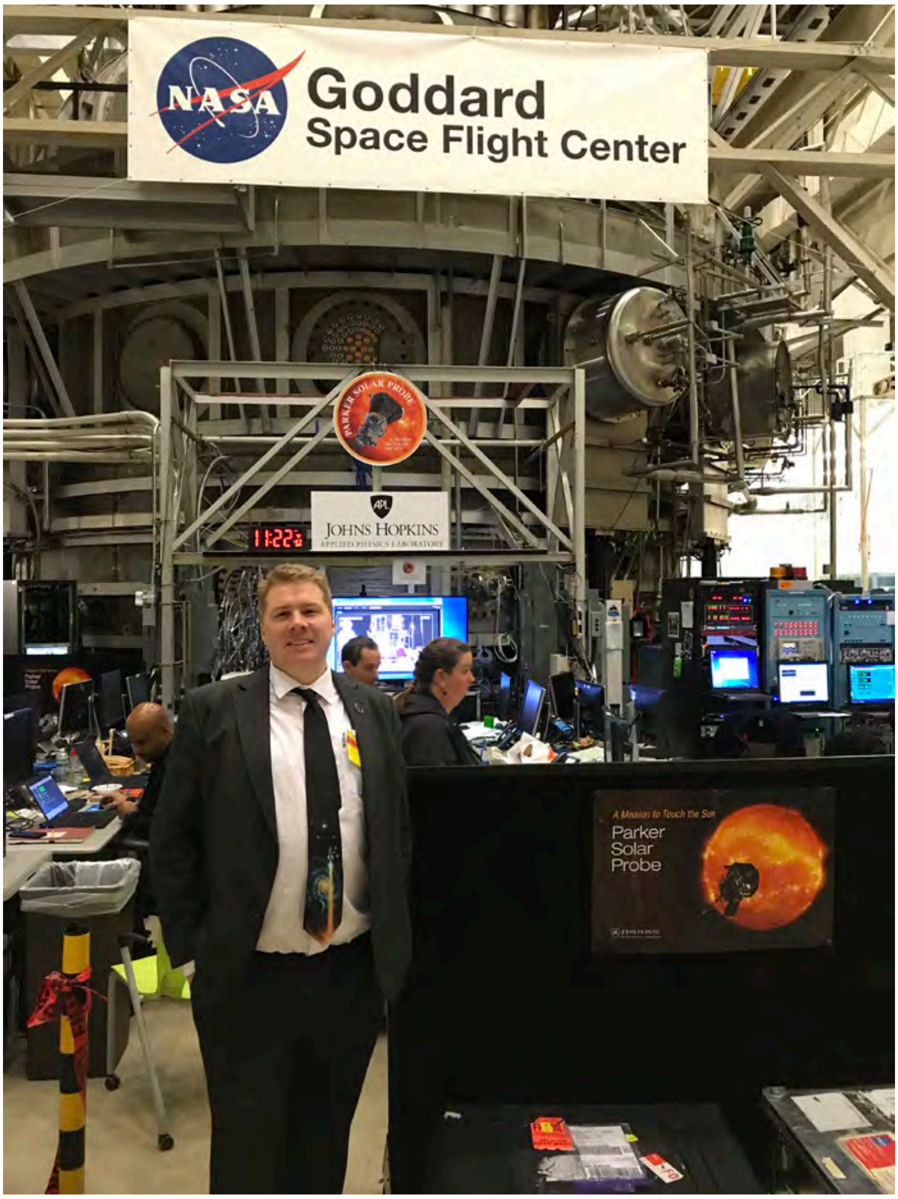
Kelvin & Rob in the USA

i4is President Kelvin F Long and Deputy Director Rob Swinney were in the USA again in recent weeks. Kelvin spoke at NASA Goddard Spaceflight Center (GSFC) on *Interstellar Flight - The Benefits to Astronomy and Astrophysics.* He also addressed the University of Maryland AIAA chapter associated with the aerospace department on *The Application of Extreme Aerospace Engineering to Interstellar Flight.*

There was an opportunity to observe a full scale test of Wide Field Infrared Survey Telescope (WFirst), a proposed space telescope with some exciting objectives from exoplanet imaging to gravitational physics wfirst.gsfc.nasa.gov.

Here is Kelvin at GSFC witnessing the vacuum chamber thermal testing of the Parker Solar Probe spacecraft due for launch to the Sun in July.

At closest approach it will be travelling at approximately



Twitter illustration of a proposed impact mission to ‘Oumuamua. We especially liked the three axis views. Credit: @darryl_seligman - Darryl Seligman, Yale University

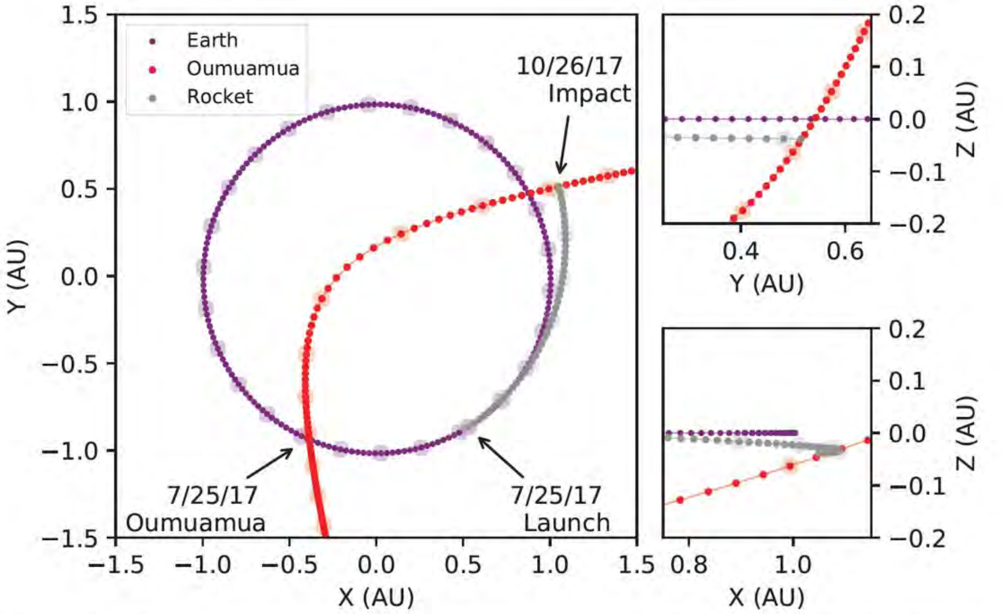


FIG. 7.—: Trajectory of the minimum-ΔV mission interception mission sent on July 25th 2017, which had a flight time of 83.38 days. The trajectories for ‘Oumuamua, the Earth, and the rocket are plotted in red, blue and grey respectively in four day intervals in the smaller circles, while the larger circles are plotted in 28 day intervals. The arrows indicate the positions in space of ‘Oumuamua and the rocket on the launch and interception date, 7/25/2017 and 10/16/2016. Projections in the X-Y, Y-Z and X-Z planes are shown in the left, right upper, and right lower panel respectively.

700,000 km/hr and will require several gravitational "slingshots" around Venus to get closer to the Sun than any previous probe. Recall it takes just as much "push" to get close to the Sun as to get away from it! In December Kelvin also attended the American Geophysical Union which held its fall meeting in New Orleans, Louisiana, at the Ernest N Morial Convention Center. 25,000 delegates attended. For the first time in its history the meeting organized an interstellar session, titled 'from the Heliosphere to Interstellar Exploration Beyond: IMAP and Interstellar Probe'. This was organized by the primary convener Pontus C Brandt from Johns Hopkins University Applied Physics Laboratory. Kelvin F Long presented a *Historical Review of Interstellar Probe Concepts and Examination of Payload Mass considerations for Different System Architectures*. Among the many speakers were Marc G Millis from the Tau Zero Foundation discussing *Long Term Perspectives on Interstellar Flight*, Ralph L McNutt Jnr from Johns Hopkins University discussing *Interstellar Probe: First Step to the Stars* and Anthony Freeman from the Jet Propulsion Laboratory on *The First Interstellar Explorer: What Should it Do when it Arrives at its Destination*.

Kelvin also visited the gravitational wave detector LIGO Livingston near New Orleans

Presentations by Andreas Hein

i4is Executive Director Dr Andreas Hein has presented our Project Lyra work to -

- "Raumfahrtkolloquium der FH Aachen" (30th space symposium of the University of Applied Sciences Aachen) in November 2017
- 22nd Winter Seminar at Bad Honnef in January 2018
- the Paris observatory in December 2017

More interstellar thinking

Much of this issue is devoted to our study of an intercept mission, Project Lyra but others are thinking along similar lines.

The Primitive Object Volatile Explorer (PrOVE) www.lpi.usra.edu/sbag/meetings/jan2018/presentations/1010-Hewagama.pdf is a comet interceptor idea which pre-dates our interstellar asteroid but by lurking at a series of "way-points" could intercept an unexpected visitor.

We have also heard of a paper by Darryl Seligman of Yale University (astronomy.yale.edu/people/darryl-seligman) submitted to AAS Journals around the end of January. Thanks to Marshall Eubanks of Asteroid Initiatives for spotting this. A Twitter image (see above) gives a good illustration of a proposed impact mission to ‘Oumuamua. We look forward to the paper.

We also noticed Developing Revolutionary Propulsion at TU Dresden, a paper from last year's International Astronautical Congress in Adelaide, Australia. Since 2012 there has been a dedicated breakthrough propulsion physics group at the Institute of Aerospace Engineering at Technical University of Dresden, Germany and in this paper they discuss ideas for Propellantless propulsion, the EMDrive and the Mach-Effect Thruster. They are concentrating on the latter and building very sensitive thrust balances to detect the tiny thrusts which may be expected.

Education and Outreach

It was good to re-make contact with Space Studio West London and their enthusiastic students and teachers at their Careers event on 6 February 2018. We are working with their physics and maths departments on new ways of interesting their students in space, interstellar and the physics and maths of space.

We have also been talking to the famous Royal Institution (www.rigb.org)in London about getting involved in their Masterclass programme.

BIS Scotland relaunch

We were not able to be at City of Glasgow College for the relaunch of the Scottish chapter of the British Interplanetary Society on 30 January 2018 so all we can do is congratulate this renewed branch of our good friend and "older sibling", the BIS and signpost them at www.bis-space.com/branches/regional/bis-scotland

The principal movers of this renewal are Graham Paterson of City of Glasgow College and Matjaz Vidmar of the Royal Observatory Edinburgh. You can contact them via scotland@bis-space.com. They are keen to include i4is in their work and we'll be working with them to achieve this in 2018.

All the founding members of i4is are long-established members of the BIS. Why not join this, the world's longest-established space advocacy organisation (www.bis-space.com/eshop/why-join)?

Project Glowworm Update

Project Glowworm has made significant progress mostly in developing our own ChipSat, a fingernail-sized spacecraft. The project is currently in its early phase of development but we aim at rapidly entering hardware development in 2018. Here are some of the results from 2017 and plans for 2018 -

- ISU white paper on ChipSat-based interstellar mission. Professor Chris Welch from the International Space University and Rob Swinney of i4is working with a group of ISU Masters' students has completed a report on how ChipSats could be used for a minimal interstellar mission that requires minimal funding.
- ISU white paper on foldable structures for ChipSats: Another report by ISU students addresses how small foldable structures could be used for enhancing the capabilities of ChipSats.
- Glowworm mission ISU Individual Project: Chris Welch (ISU) and Nikolas Perakis (i4is) are currently supervising an Individual Project on different mission architectures for the final Glowworm mission (laser CubeSat + laser sail ChipSat). The project is going to be completed in the first half of 2018, resulting in a report and a paper for the International Astronautical Congress.
- Minimal ChipSat interstellar mission ISU Individual Project: Another Individual Project, supervised by Chris Welch (ISU) and co-supervised by Elena Ancona (i4is) is addressing how a ChipSat could be sent out of our solar system using minimal resources. The project is also going to be completed in the first half of 2018, again resulting in a report and a paper for the International Astronautical Congress.
- We are also reaching out to other universities and the Chipsat community to establish mutual ways of working.
- We have started working on developing a ChipSat prototype that we can use for testing basic functionalities of our ChipSat and to gain practical experience with them.

If you would like to get involved please contact our technical team via the usual address info@i4is.org and tell us how you can help.

Christmas Sailcraft

A little belated but we thought you would like the Christmas tree from Dmitry Novoseltsev (Дмитрий Новосельцев). Dmitry gave us a vast vision of possible futures in his piece *Engineering New Worlds: Creating the Future* in P17-19. Here we see his more playful side. Lets adopt his idea for a Christmas tree decorated with solar sails, laser sails, E-sails and magsails of different designs. Maybe for a children's Christmas party or adult New Year celebrations next year?

The Initiative for Interstellar Studies

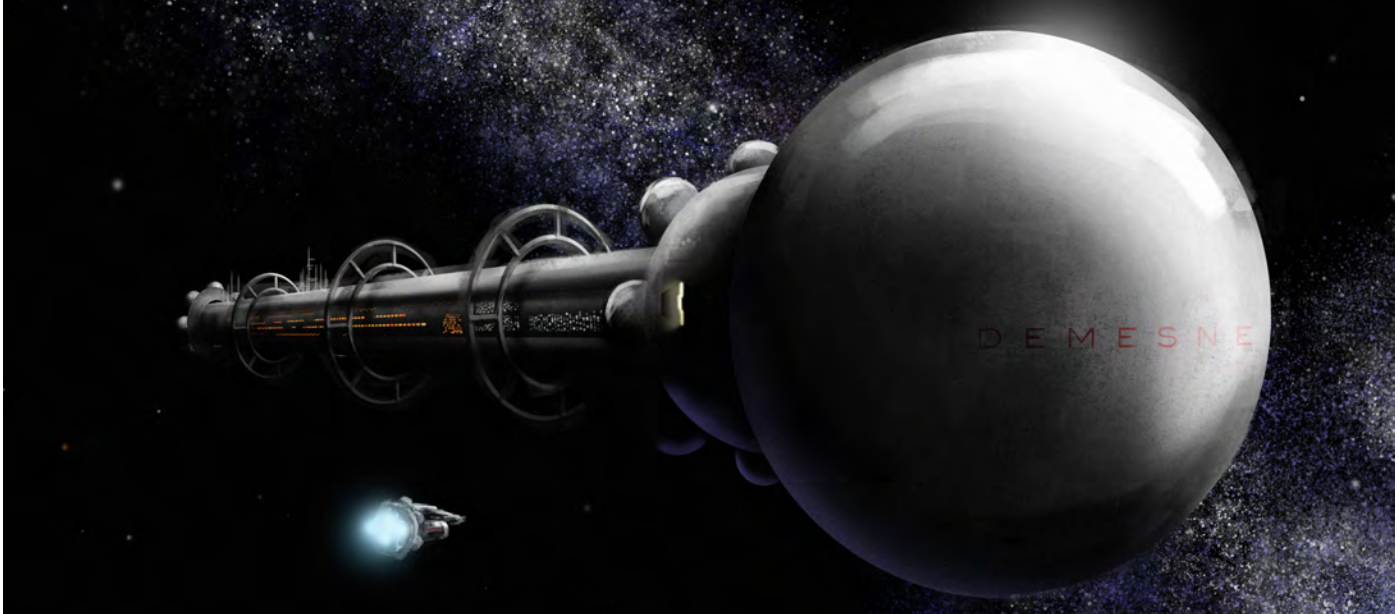


image: ©ALEX STORER

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 is just some of our team -

- **Dr Andreas Hein: i4is Executive Director, System Architect & Engineer**
- **John Davies: Project Manager & Editor, Principium, the i4is quarterly**
- **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: i4is Education Director, Project Leader, Project Icarus**
- **Terry Regan: creator of the BIS Daedalus model and the i4is 2001 Monolith**
- **Tishtrya Mehta: Astrophysics Researcher**

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

Web: i4is.org
Twitter: @I4Interstellar
Facebook: InterstellarInstitute
Principium:
tinyurl.com/principium

NEWS FEATURE
Dr Pete Worden, Breakthrough Initiatives, at i4is HQ

Patrick Mahon

Our Principium Deputy Editor was privileged to be present at a historic meeting and public lecture by Dr Pete Worden, former Director of the NASA Ames Research Centre, Mountain View. He is now the Executive Director of Breakthrough Initiatives, and specifically of Breakthrough Starshot, with which i4is has been associated since its launch.

On Monday 20 November 2017, i4is HQ received a visit from Dr Pete Worden, former Director of the NASA Ames Research Centre in California, who is now the Executive Director of Breakthrough Initiatives, the set of interstellar challenges launched by US/Russian billionaire Yuri Milner and Professor Stephen Hawking in July 2015. Dr Worden was on a whistle-stop tour of Europe, so we were delighted that he found time in his busy schedule to meet with i4is's leadership, discuss our work and give a public lecture.

Pete Worden has had a long and varied career. After gaining a PhD in astronomy he joined the United States Air Force, where he worked for nearly thirty years on the Strategic Defence Initiative and many other space-related programmes, rising to the rank of Brigadier General. After retiring from the USAF, Worden became a Professor of Astronomy at his alma mater, the University of Arizona, before becoming the Director of NASA Ames in 2006, a role he held for nine years before leaving NASA to join the Breakthrough Initiatives.

Intense discussion at the Mill. LtoR Angelo Gonovese, Rob Swinney, Patrick Mahon, Stefan Zeidler, Pete Worden. Credit: Kelvin Long

Pete arrived at lunchtime and, following a quick tour of the building and a sandwich, he spent the afternoon meeting with several members of the i4is team, including Kelvin F Long, Rob Swinney, Angelo Genovese, Stefan Zeidler, Terry Regan and Patrick Mahon. Pete was briefed on i4is's current projects, including Project Lyra, Project Glowworm, Project Dragonfly and our education programme, and, in turn, told us about the latest developments at the Breakthrough Initiatives. Our President, Kelvin Long, took the opportunity during these meetings to present Pete with a copy of the i4is book 'Beyond the Boundary' and an i4is lapel pin, both of which were warmly received.

Following a tea break, Pete then delivered a public lecture in the grand conference room. He prefaced his remarks by showing a short video address delivered to a recent Chinese space conference by Breakthrough Initiatives Board member Stephen Hawking, in which Hawking explained why he believes that humanity should develop the capability to travel beyond the solar system and colonise planets around other stars. [Editor's note: See the review of 'A Search for a New Earth' in P19 for further details of Hawking's arguments.] He co-founded the Breakthrough Initiatives to do the early research and development work that will be a necessary precursor to any manned interstellar flight capability in the coming centuries, aiming to answer three fundamental questions: is there other life in the Universe? If so, is any of it intelligent? And is it possible for mankind to develop the technology to enable travel between the stars?

Pete summarised the four main projects that fall under the banner of the Breakthrough Initiatives:

- Breakthrough Listen – a $100 million programme of astronomical observations, searching for evidence of intelligent life beyond Earth. It will look for artificial radio or optical signals coming from the 1,000,000 nearest stars, the plane and centre of our own galaxy, and the 100 nearest galaxies.
- Breakthrough Watch – a multi-million dollar astronomical programme to develop Earth- and space-based technologies that can find Earth-like planets in our cosmic neighbourhood, to see if they host life. This will start with observations of the Alpha Centauri system.
- Breakthrough Discuss – an academic conference focused on life in the Universe and novel ideas for space exploration. The last one took place at Stanford University in April 2017.
- Breakthrough Starshot – a $100 million research and engineering programme aiming to demonstrate proof of concept for a new technology, enabling ultra-light unmanned space flight at 20% of the speed of light, ultimately laying the foundations for a flyby mission to Alpha Centauri within a generation.


Pete Worden addresses the meeting. Credit Kelvin Long


Kelvin, Pete and Angelo. Credit Patrick Mahon

Expanding on the last of these, Pete explained that the key problem for interstellar, rather than interplanetary, flight was speed. The fastest probes we have yet launched from the Earth are the Voyager spacecraft, and these would take tens of thousands of years to get to our nearest neighbour, Alpha Centauri. The chemical rockets we currently use simply aren't up to the challenge. Breakthrough Starshot is instead investigating an alternative approach: laser-powered solar

Angelo explains i4is technical team laser sail propulsion and chipsat work. Credit Kelvin Long

sails, where a powerful laser is focused on a large reflective sail carrying a tiny, low mass payload known as a ‘chipsat’. Freed from having to carry, and accelerate, their own fuel, such craft have the potential to reach very high speeds. [Editor’s note: This is, of course, the same propulsion technology that is at the heart of i4is’s own Project Glowworm.]
He noted that one possible destination for an early solar/ laser sail technology demonstrator mission could be Saturn’s moon Enceladus, to follow up the Cassini mission’s recent discovery of a sub-surface ocean of liquid water.
There followed a brief question and answer session, during which Pete was asked for more detail about the possible mission to Enceladus, his views on colonising Mars, and what he believes to be the key challenges to achieving interstellar travel. i4is President Kelvin F Long thanked Pete for his inspiring lecture, and soon afterwards Pete was whisked away by taxi, headed for the University of Cambridge, where he was scheduled to see Lord Martin Rees, the British Astronomer Royal who is, like Kelvin, a member of the Breakthrough Initiatives’ advisory committee.
It was a great pleasure to host Dr Pete Worden. We thank him for his time and insights, and hope to see him at our headquarters again in the near future.


Relaxing in The Swan at the end of an exciting and highly productive day. LtoR Rob Swinney, Angelo Genovese, Gill Norman (Executive Secretary, BIS), Terry Regan, Sue Morris, Patrick Mahon, Kelvin Long, Stefan Zeidler.

About Patrick Mahon
Patrick Mahon is Deputy Editor of Principium and Programme Manager, i4is.

The Orbits of Seveneves

A book review with a touch of orbital dynamics

Sander Elvik

Sander reviews Seveneves by Neil Stephenson, a fiction by an acclaimed writer who has a strong technical backgound.
This is part one of two. The second part, explaining the orbits and trajectories, will appear in the next issue of Principium.

> ***"Why didn't they just send everything up here?"***
> ***"Plane-change maneuvers are expensive. It's not too bad if the only thing plane-changing is Sean and Larz and a Drop Top, but it would be ridiculously wasteful to send the whole expedition package up here only to plane-change later." Dinah didn't mention the other reason, which was that the biggest part of Sean's package was so screamingly radioactive that it couldn't be allowed anywhere near them.***
> ***"Okay. But we're still talking geocentric, right?"***
> ***"Correct, we're still just a few hundred miles high."***
> ***"So, how do they get from the rendezvous point to a heliocentric situation?"***
> ***"There's a bunch of different ways to do it," Dinah said, "but if I know Sean he'll go through the L1 gateway."***

And so starts the description of the orbital mechanics that are in play for Sean and his crew on the *Ymir*, off on a private, improvised mission to improve the odds of humanity surviving the inevitable doom that has been brought upon the Earth.

Seveneves, by Neal Stephenson is a science fiction novel with a very realistic feel to it. The book is divided into three parts, of which the first two read like a technology thriller. Although no date is used, the book is set in the near future. A reader with more than average interest in space, such as the readers of Principium, can enjoy recognizing current orbital hardware, see a certain NASA mission having been completed, and observe further progress in the New Space capabilities.

By almost immediately making it clear that the Earth is doomed, and giving a tight but uncertain timeline for its demise, Stephenson ensures you keep turning the pages. In the first part, we follow the main characters of the story as they work their roles in the preparations to make a safe haven for humanity outside the atmosphere. The tension builds up relentlessly by both the race against a loosely defined clock, and by the new challenges being introduced along the way. These are not only the fictional challenges the characters need to deal with, but also the ones the readers are allowed to come up with by themselves. Time and time again, parts of the plan unfolding are introduced and you find yourself thinking "hey, that is cool, but how then about…" And again and again Stephenson proves the thoroughness of his work by addressing these issues as well, but a bit further on in the book.

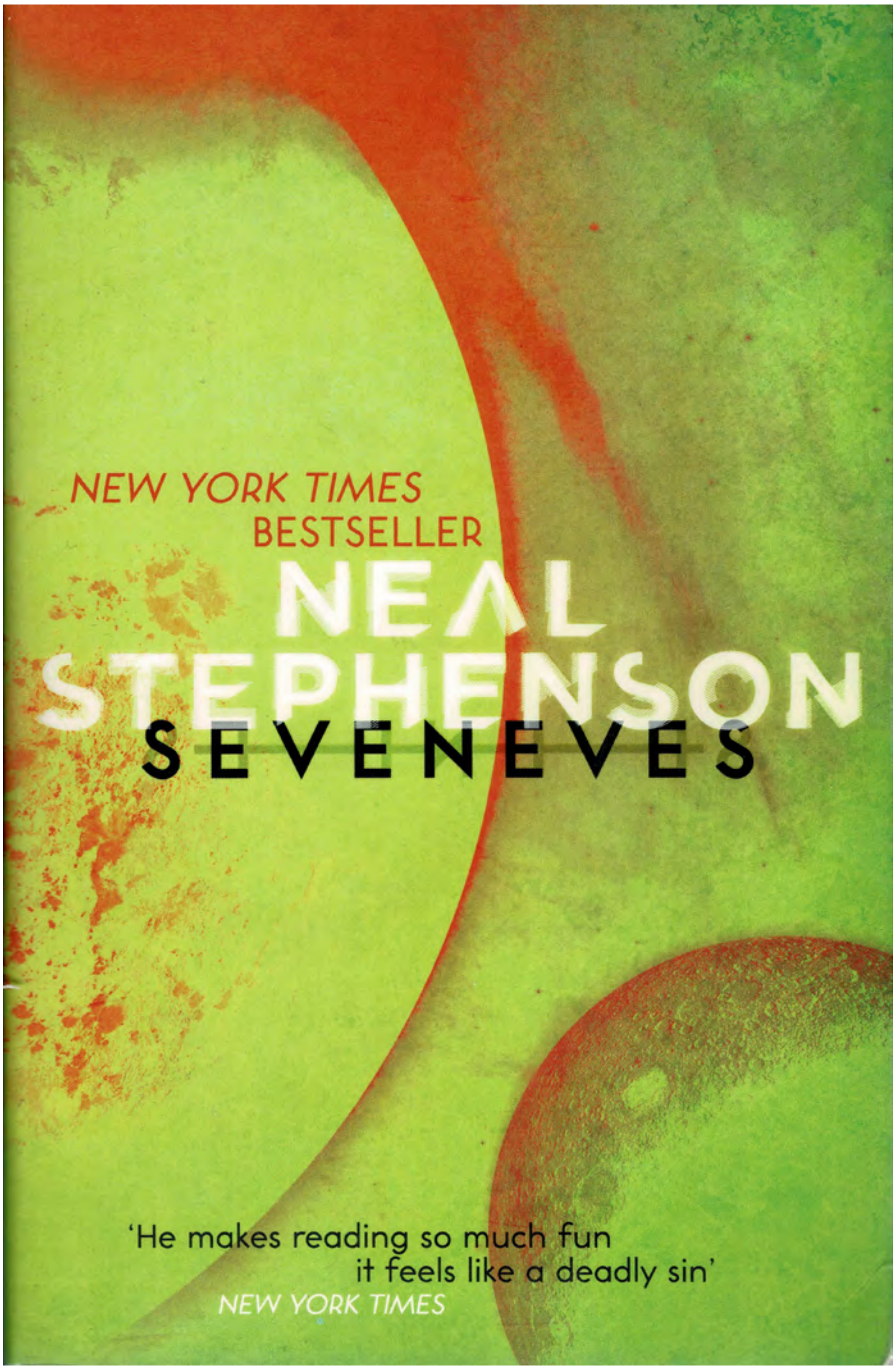
Although the presence of technology is made very explicit in the book, it is often more of a backdrop in which the tale is told. Just like contemporary technology usage is. Being a work of science fiction however, new strides in technology are required to meet the need of the characters, such as long term provision of energy, waste reuse and food production. While the latter comes to play a pivotal role in the story, unfortunately none of the three are discussed in significant detail. At the time of the events in the book, important strides have been set in robotics however, and these play an interesting and entertaining role throughout the book. But the real focus of the book is on orbital dynamics, starting with the traditional orbits that current space travel technology work with.

"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 centres of gravity could coincide."

Hence the basics of orbital parameters and their influence on formation flight in space is introduced by one of the main characters of the book: Doc, a "famous astronomer and science pundit". Stephenson has put much effort into making the real effects of orbital mechanics play an important role as the story is told. More or less all variations come into play, such as the basic class book circular low-earth orbit. Particularly interesting is how large orbital structures behave under the stresses of a low-earth circular orbit and the implication for formation flying, both of which play important roles in the story. Being thorough in his use of orbital dynamics, Stephenson also elegantly weaves into the story the aspects of orbital rendezvous, the matter of plane changes and the impact of an orbit's inclination on the location of launch facilities on the ground. Even tethered flight and atmosphere skipping is touched upon.

Stephenson then broadens the subject to elliptical orbits, using them in a very action packed and exciting part of the book, where the team flying a spacecraft is faced with "so many imponderables, a well-managed aerospace engineering project would have called a halt to all further work and devoted several years to analysing the problem down…" Their challenge is to match their highly elliptical orbit to a circular low-Earth orbit, but by rather unconventional means. The author takes the reader through the delicates of ΔV (delta vee), apogee and perigee, the matter of changing these and the effects on orbital periods, the time it takes a spacecraft to make a full orbit.

In the citation used in the introduction of this review, he also throws in the very imaginative notion of the "L1 gateway". Although maybe the L2 gateway would inspire the readers of Principium more, as it is our way out of the solar system.



UK cover
Credits: Cover layout design ©HarperCollinsPublishers Ltd 2016

Unfortunately, the specifics of this branch of orbital dynamics do not receive as much scrutiny by Stephenson as they deserve. 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 the gravitational influence of two celestial bodies, like the Earth and the Moon.

Stephenson's orbital work is accurate, but at times brief or tightly interwoven into the story. To be able to grasp the finesse of what is described, good visual imagination power or some pre-knowledge comes in handy. Though it remains entertaining either way.

And rest assured, the book is by no means an introduction to orbital dynamics only. Despite all good intentions by the powers at work in the novel, politics finds itself a way to orbit as well. This provides for some attractive conflicts. Often the wisdom of knowledgeable subject matter experts is challenged by strongly opinionated politicians, backed by social media influencers. Luckily, it is only the survival of the human species which is at stake...

The outcome of these conflicts echoes on in part 3 of the book, which takes place 5000 years later, and form the new backdrop of the story. Of course humanity by now have mastered Clarke's space elevator. There are grand space stations in orbit and several ingenious ways for people to travel between them and the Earth. One of which uses 19th century whip technology.

Neal Stephenson at Science Foo Camp 2008

The role of orbital dynamics diminishes in this part of the book. The reader's curiosity as to what happened to humanity in the five millennia between part 2 and part 3 is rewarded piece by piece as the story further unfolds. It makes for a very rewarding read, but being more heavily a work of fiction and less a technology thriller as the first two parts, it is also a different read.

In conclusion: a great read that will, if you like me like to read in bed, deprive you of some hours of sleep. However, you will be awarded with an excellent tale of space travel and the joy of orbital mechanics.

Seveneves by Neal Stephenson is a science fiction novel and was published in 2016 by Harper Collins Publishers (ISBN: 978-0-00-813254-5). It counts 867 pages and can be found in various online stores with a list price of 14.99 USD. UK price £9.99.

Neal Stephenson

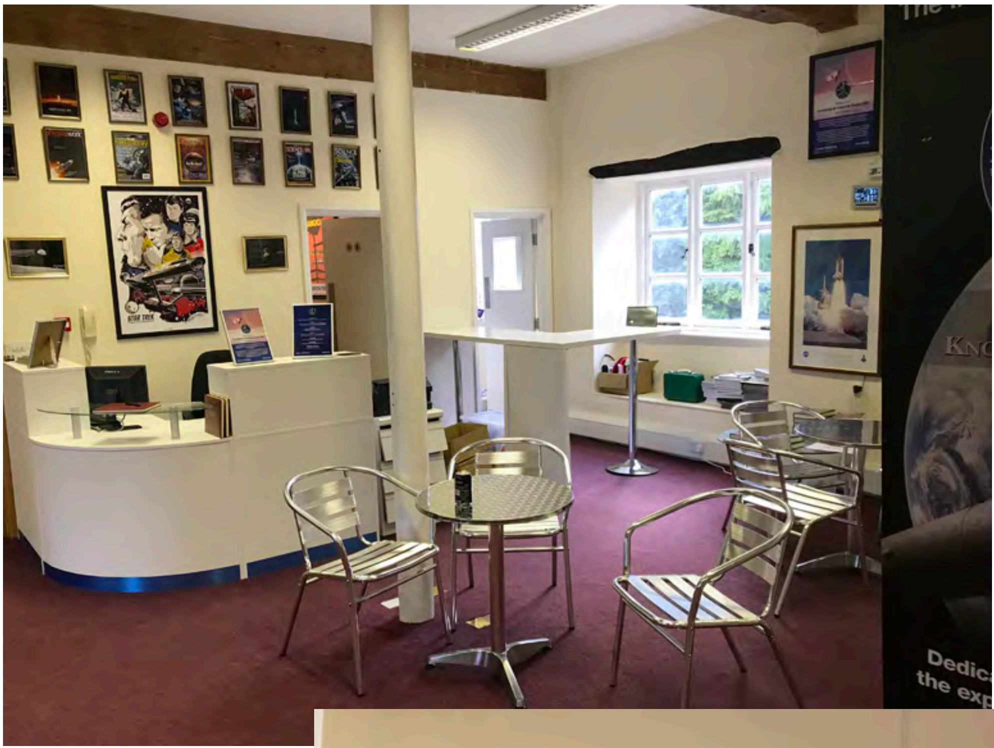
Stephenson was born on October 31, 1959 in Fort Meade, Maryland, US, and had his first novel published in 1984. Many of his books combine high-tech themes with sociological ideas. Among other prizes, his novel Cryptonomicon (2013) won the Prometheus Hall of Fame Award, and Seveneves was nominated for the Hugo Award for Best Novel, a prize he'd previously won in 1995.

About Sander Elvik

Sander Elvik is a Systems Engineer and Systems Integrator based in The Netherlands, specialised in mission critical facility infrastructure for data centres. He holds a Masters in Aerospace Engineering from Delft University of Technology.

Models and art at the Mill

The Initiative for Interstellar Studies has always cherished the imaginative as an inspiration and sometimes even an exemplar of what we are striving to achieve. Our headquarters, informally "The Mill", give us an opportunity and a location to show visual imagination in all its forms. Here is a small sample of what you will see when you visit The Mill. Chosen to show the diversity of what we have gathered.
There is far more and we'll be showing more of our collection in later issues of Principium. But there is no substitute for seeing it yourself - so come and visit us either at one of our of events or by pre-arrangement. You can always reach us on info@i4is.org.



The reception and bar features a display of magazine covers, a Star Trek poster by Joshua Budich and on the right a NASA poster showing a Shuttle launch. Relax with coffee and a snack or wander further and see more...

Opposite the bar you will find globes of the Moon, Mars and Earth and portraits of UK space travellers - European Space Agency astronaut Tim Peake (Soyuz TMA-19M and ISS, 2015) and Project Juno cosmonaut Helen Sharman (Soyuz TM-12 and Mir space station, 1989).

Terry Regan holding the finished Discovery model (*2001: A Space Odyssey*) with Rob Swinney. Much enhanced from a kit model it now hangs in our HQ.

"To Boldly Go" by Joshua Budich www.joshuabudich.com/star-trek "I was honored when CBS asked me to participate in their *Star Trek: 50 Artists. 50 Years* Art Exhibition".

Star Trek has been an inspiration to all at i4is.
Here a specially significantly named starship, USS Kelvin.

The BIS Project Daedalus Fusion Starship model was sponsored by i4is and built by Terry. Normally residing at BIS, HQ, London, but loaned to i4is on special occasions.

Terry also led the team which built our 2001 monolith. Here Rob and Terry move half of it into storage in our HQ basement.

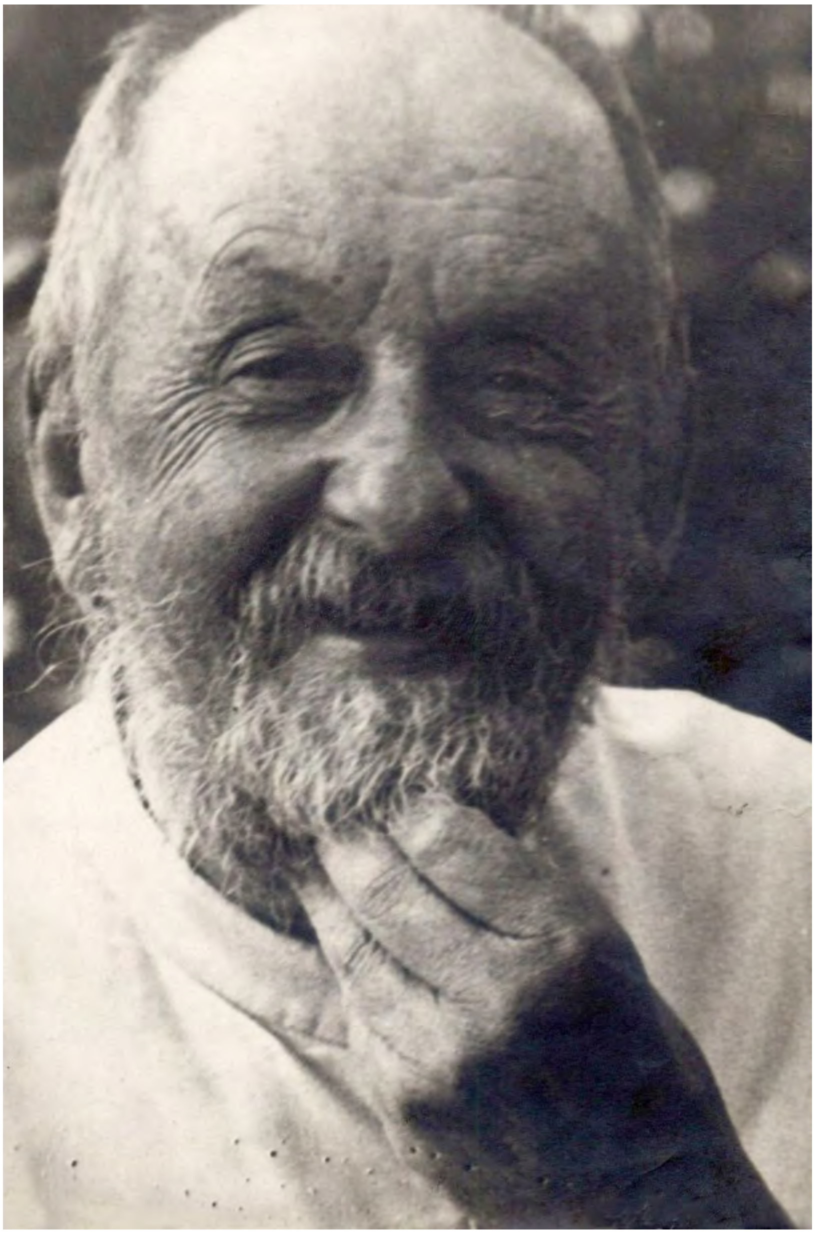
Tsiolkovsky - Interstellar Pioneer

John Davies

Principium Editor John Davies considers one of his heroes and his contribution to rocketry and the interstellar endeavour.

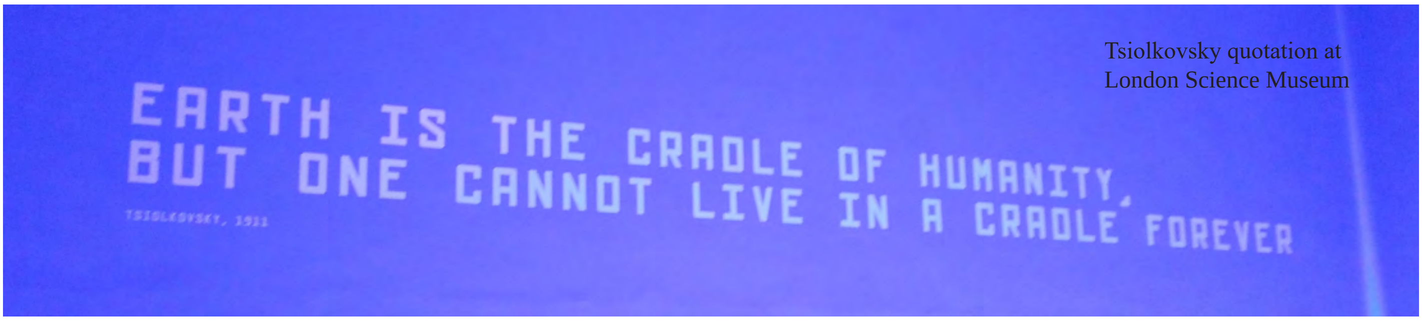
Introduction

I first encountered Konstantin Eduardovitch Tsiolkovsky (Константи́н Эдуа́рдович Циолко́вский) in my early teens. I was reading popular books about space travel following on from the adventures of Dan Dare "Pilot of the Future" in the UK comic Eagle. I read books like The Conquest of Space and Rockets, Missiles and Space Travel, both by Willy Ley and The Exploration of Space by Arthur C Clarke. And others now forgotten, by me at least! Amongst the Goddards and Von Brauns I came across a mention of a mysterious Russian, Tsiolkovsky; A man with a long beard and small glasses who was around at the time of Jules Verne and H G Wells but who did "real space", if only in calculation. I later discovered that he wrote science fiction too.



Konstantin Eduardovitch Tsiolkovsky - without the long beard and small glasses! Credit Archive of Russian Academy of Sciences.

He's been around my space career, both professional and amateur, ever since. Most recently I have done some work for schools with his famous equation but I was especially struck last year with this quotation which was blazed across the exit room of the exhibition, Cosmonauts: Birth of the Space Age, at the London Science Museum "Earth is the cradle of humanity, but one cannot live in a cradle forever". I was aware of Tsiolkovsky as a visionary as well as a mathematician and engineer but I had an impression that he had had



Tsiolkovsky quotation at London Science Museum an interstellar vision. I decided to investigate. This article is the result.

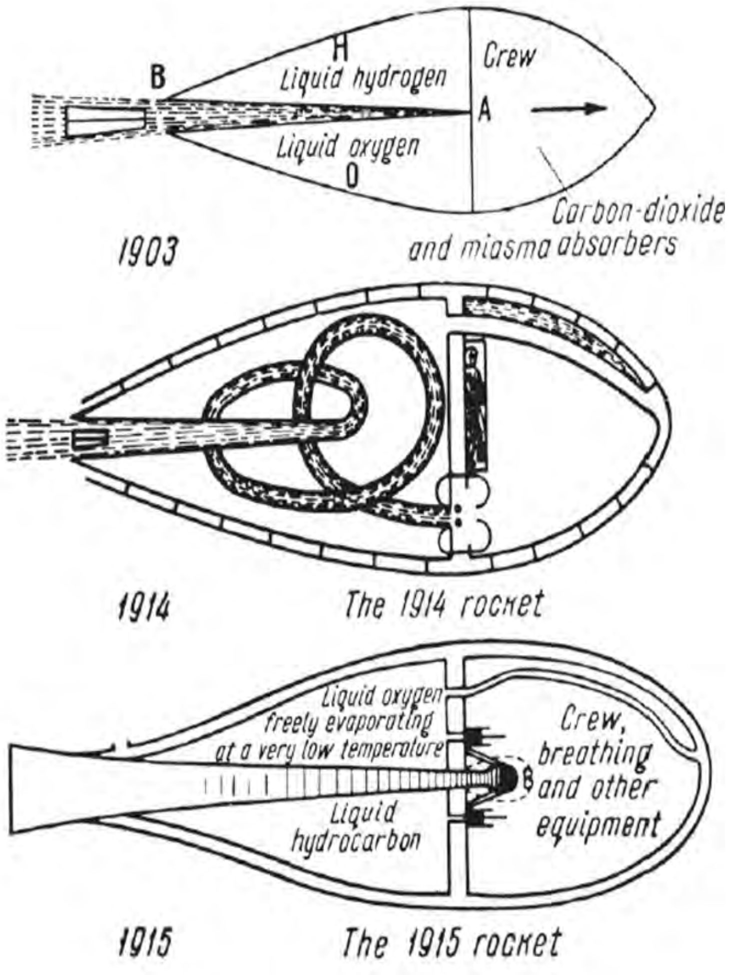
My wider sources are referenced in the text but you may be especially interested in the final sections of this piece, Biographies and Works (of Tsiolkovsky). The latter is a translation of his papers which has been especially useful.

Tsiolkovsky was driven throughout his life by that Onward and Upward urge which drives many of us, great and small, to consider the future of our species beyond its beautiful cradle. His vision extended to the stars but his mathematical and engineering intellect also drove him to dream too of "explosive pipes" governed by equations to enable us to get there.

Brief Biography

To set the scene, here are the main facts and milestones of Tsiolkovsky's life (culled from the Biographies listed below and online sources) -

- Konstantin Eduardovich Tsiolkovsky, Константи́н Эдуа́рдович Циолко́вский
- Born 1857 in Izhevsk, Ryazan Province, Russian Empire, son of Eduard Ignatyevich Tsiolkovsky and Mariya Ivanova Yumasheva
- Early life - made deaf by an infection at age 9 and took to private study
- Work - Aerospace Engineering, Mathematics, Physics, Philosophy, popularisation of all these through writings including science fiction
- Profession - Schoolteacher
- First international recognition - from the Society for Space Travel, Germany, Herman Oberth wrote to Tsiolkovsky in 1929: "You have kindled a fire, and we shall not let it die out, but will bend every effort to make the greatest dream of mankind come true." (see Biographies: Sokolsky)
- Death 1935 in Kaluga, Russian SFSR, Soviet Union. Age 78.



Tsiolkovsky's drawings of liquid fuelled rockets showing how his thinking evolved.
Credit: ESA / Museum of Flight, Seattle.

The Equation

Amongst his numerous achievements, both visionary and practical, perhaps his most famous, simple and striking result is the Ideal Rocket Equation. This defines the performance of all reaction-propelled vehicles from fireworks to fusion rockets.

The equation first appears in "Investigation of World Spaces by Reactive Vehicles (1903)" (see Works below). The date is important in the title because he uses the same title in later works - which also used the equation. Tsiolkovsky wrote the equation -

$$\frac{V}{V_1} = \ln\left(1 + \frac{M_2}{M_1}\right)$$

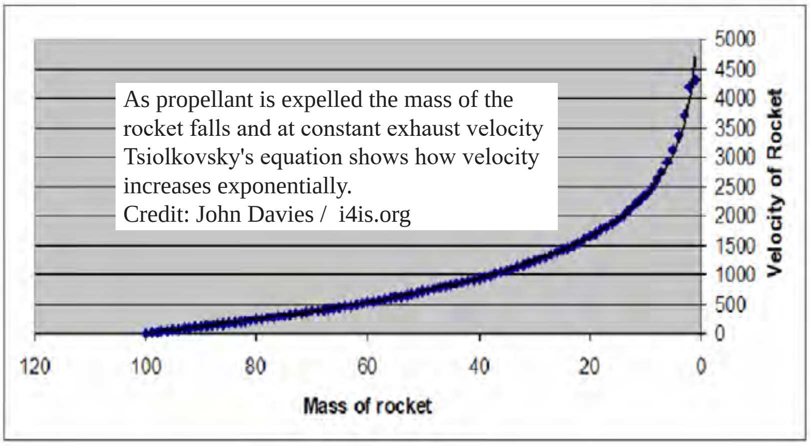
Where V is added velocity, V_1 is exhaust velocity, Tsiolkovsky writes "Let us denote the mass of the vehicle and everything it contains, with the exception of the supply of explosives, by M_1; the total mass of explosives by M_2"

A bit of algebra shows this to be equivalent to our more usual -

$$\Delta v = v_e \ln \frac{m_0}{m_f}$$

Where m_0 is total initial mass and m_f is the final mass.

Tsiolkovsky used conservation of momentum to derive the equation but a simpler though much less rigorous derivation can be done directly from Newton's Second law (using computing notation).



As propellant is expelled the mass of the rocket falls and at constant exhaust velocity Tsiolkovsky's equation shows how velocity increases exponentially.
Credit: John Davies / i4is.org

Newton's Second law - force equals mass times acceleration -

$f = m*a$

Transposing

$a = f/m$

Integrating acceleration against the time from initial to final velocity and mass from initial mass to final mass - with force kept constant and directly proportional to the exhaust velocity of the rocket (since the exhaust velocity does not change)

$\int a\,dt = f * \int (1/m)\,dm$

Performing the integrations - noting that the indefinite integral of 1/x is ln x (log to base e of x)-

Change in velocity = exhaust velocity * ln (initial mass/final mass).

Which is the equation as we usually quote it today.

I stress again that this is not a rigorous derivation but it may be helpful in showing how Newton leads to Tsiolkovsky.

Having noticed that any derivation of the equation requires integration and that this is not taught in UK schools except to science specialists I developed an incremental solution using a spreadsheet, Please contact me if you would like details.

Tsiolkovsky's objective was to achieve spaceflight. His motivation was practical but like all good engineers he used mathematics and physics wherever they assisted his objective. His equation gave us the fundamental limits of "reactive vehicles". Physics can set frustrating limits to engineers. American engineer-astronaut Don Pettit expressed this frustration in "The Tyranny of the Rocket Equation" (www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny.html) and Scotty put it more generally but very succinctly, telling Captain Kirk "I canna change the laws of physics!"

Imagination

Tsiolkovsky was not only concerned with the "nuts and bolts" of leaving the earth and getting to other parts of the universe, he also had visions of the future of humanity and sentient beings in general. Here the themes of cosmism much discussed during his time and especially in Russia, overlap with the practical scientist and engineer. Here's a quote from "Investigation of World Spaces by Reactive Vehicles" (1911-1912) -

> *At the present time, the more advanced layers of humanity strive to put their life in frameworks that are more and more artificial. Does not this represent progress? The fight against inclement weather, high and low temperatures, the force of gravity, beasts and harmful insects and bacteria—do not all these activities create about man a situation that is purely artificial?*
>
> (see Works below for source)

Here his philosophy opposes the reaction of cultural critics like John Ruskin (1819 – 1900) who lamented the artificiality of industrial civilisation.

> *In ethereal space this artificiality will simply be extended to the very limit, but then man too will find himself in conditions that are most favourable for him.*

Here Tsiolkovsky sees our species as finding its natural environment in space. What has subsequently been called an "ecological niche".

> *Over the course of the centuries, new conditions will create a new species of beings, and the artificiality which surrounds them will be diminished and perhaps will disappear completely. Wasn't it like this that aquatic animals once crawled out upon the land and little by little turned into amphibians and then into land animals; the latter, but perhaps also the aquatic animals (flying fish, for example) started the line of animals of the air, the flying birds, insects, and bats.*

He envisages a process of gradual change to suit the new conditions. He goes on to argue that "The Reactive Vehicle will save us from calamities that await the Earth" both from catastrophic volcanic activity and from impact of bodies from "stellar space" -

> *If an aerolite several versts [approximately kilometres] across hit the earth, it would kill many people; and this could happen quite unexpectedly, for such an aerolite as a non-periodic comet coming from the murky*

depths of stellar space along a hyperbolic path cannot be foreseen by astronomers much in advance of the catastrophe. People will perish because of earthquakes, rising temperature of the earth and air, and due to a multitude of other causes.

We have, of course, recently seen such a "nonperiodic comet" on a hyperbolic path, the asteroid ‘Oumuamua - discussed elsewhere in this issue of Principium. It was only about half a kilometre in length but NASA anticipates that interstellar objects may be fairly common (www.nasa.gov/planetarydefense/faq/interstellar).

So Tsiolkovsky produced early arguments for moving beyond our planet and solar system. He imagined how we might do it -

Reactive vehicles will conquer limitless spaces for us human beings and will provide two thousand million times more. solar energy than that which humanity has here on earth.

Tsiolkovsky does not "show working" but 2*10^9 times greater than very early 20th century terrestrial energy consumption looks fairly modest! He looks further -

But there is not one sun, there are numberless luminaries and therefore not only limitless space will be captured, but also limit- less energy of the rays of numberless suns will be available for the life of creatures.

That it is possible to reach other suns is seen from the following reasoning: suppose a reactive vehicle is in uniform motion at a velocity of only 30 km/sec, which is 10,000 times slower than the speed of light.

That is the speed of the earth moving round the sun; such also is the speed of certain aerolites, from which it is evident that this speed is possible (without decrease) for small bodies as well. Since from the closest stars it takes light several years to reach us, reactive trains will travel that distance in the course of several tens of thousands of years.

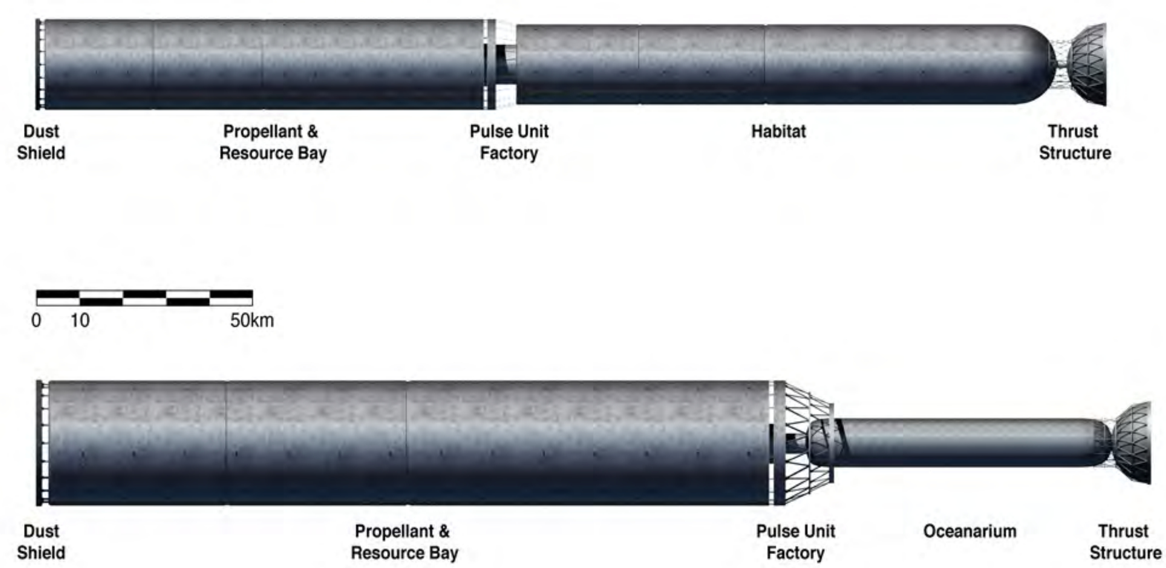
For the life of one person this period of time is of course very great, but for the whole of humanity and for the light-giving life of our sun it is negligible. During tens of thousands of years in its trip to another star, the human race will live by the stores of potential energy borrowed from our sun.

There are indeed "numberless luminaries". He remarks that "several tens of thousands of years" will be required to reach the nearest stars at a mere 30 km/sec or 1/10,000 of c but he mentions elsewhere that greater velocities may be obtained by other means, as we will see.

And unless the Bussard ramjet can be made to work then "reactive" worldships will certainly need to "live by the stores of potential energy borrowed from our sun".

If transportation of mankind to another sun is possible, then why our fears about the light-giving span of life of our presently bright sun? Let it grow dim and become extinct! During hundreds of millions of years of its glory and

Bond/Martin Dry and Wet World Ship Concepts, Credit: Adrian Mann / BIS
See 1984 papers including *A. Bond and A.R. Martin, “World Ships – An Assessment of the Engineering Feasibility”, JBIS, 37, pp.254–266, 1984*



brilliance man will be able to build up supplies of energy and emigrate with them to another seat of life.

Tsiolkovsky envisaged an unlimited future for our species. He was sceptical about the contemporary view that the Sun would suffer thermodynamic "heat death" -

The gloomy views of scientists about the inevitable end of all living beings on the earth and its cooling off due to the loss of the heat of the sun should not now have the merits of indisputable truth.

Lord Kelvin and others in the late 19th century expected the Sun to cool as a result of the operation of thermodynamics. We now know that nuclear processes give us reason to expect a much longer, but still finite, life for the Sun.

Tsiolkovsky puts one of the key long-term arguments for human expansion beyond the solar system -

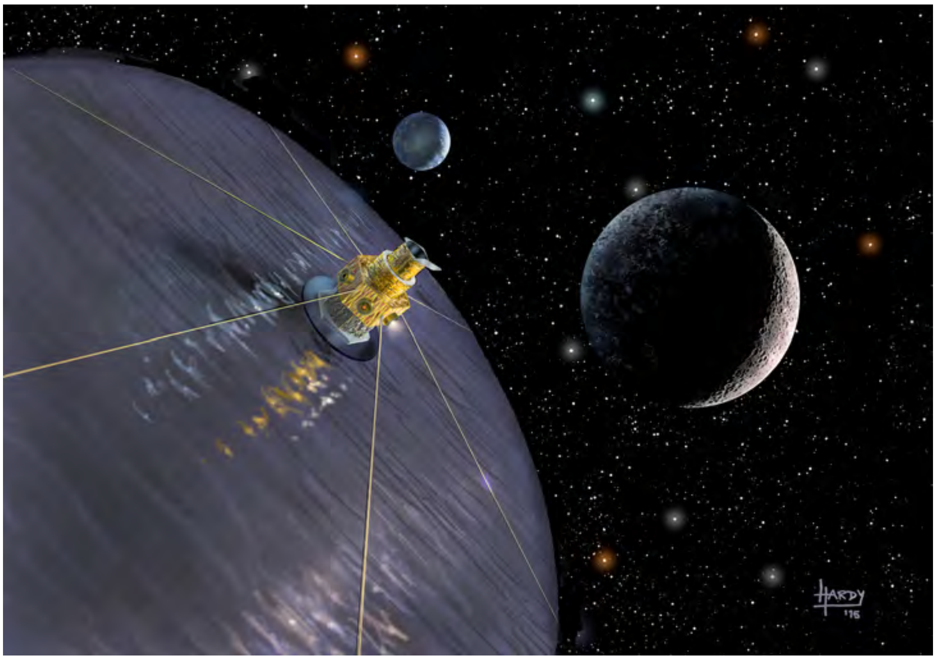
In all likelihood, the better part of humanity will never perish but will move from sun to sun as each one dies out in succession. Many decillion years hence we may be living near a sun which today has not yet even flared up but exists only in the embryo, in the form of nebulous matter designed for eternity and for high purposes.

And he expects us to do even better when "our knowledge and reason will have increased"

If today we are able to believe somewhat in the infinitude of mankind, what will it be like several thousand years from now when our knowledge and reason will have increased?

Though we may now be a little less confident in the influence of "knowledge and reason" in human affairs. But Tsiolkovsky is an optimist

Thus, there is no end to life, to reason and to perfection of mankind. Its progress is eternal. And if that is so, one cannot doubt the attainment of immortality.



First i4is laser-propelled interstellar probe concept, Project Dragonfly
Credit: David Hardy

Interstellar Propulsion

There is currently little dissension from the view that our earliest hope for propulsion of interstellar probes is via some version of high energy external electromagnetic radiation acting on a sail. Tsiolkovsky envisaged this in his paper "The Spaceship" (1924-1926). It is worth quoting at some length. After discussing a number of high energy rocket propulsion ideas he goes on -

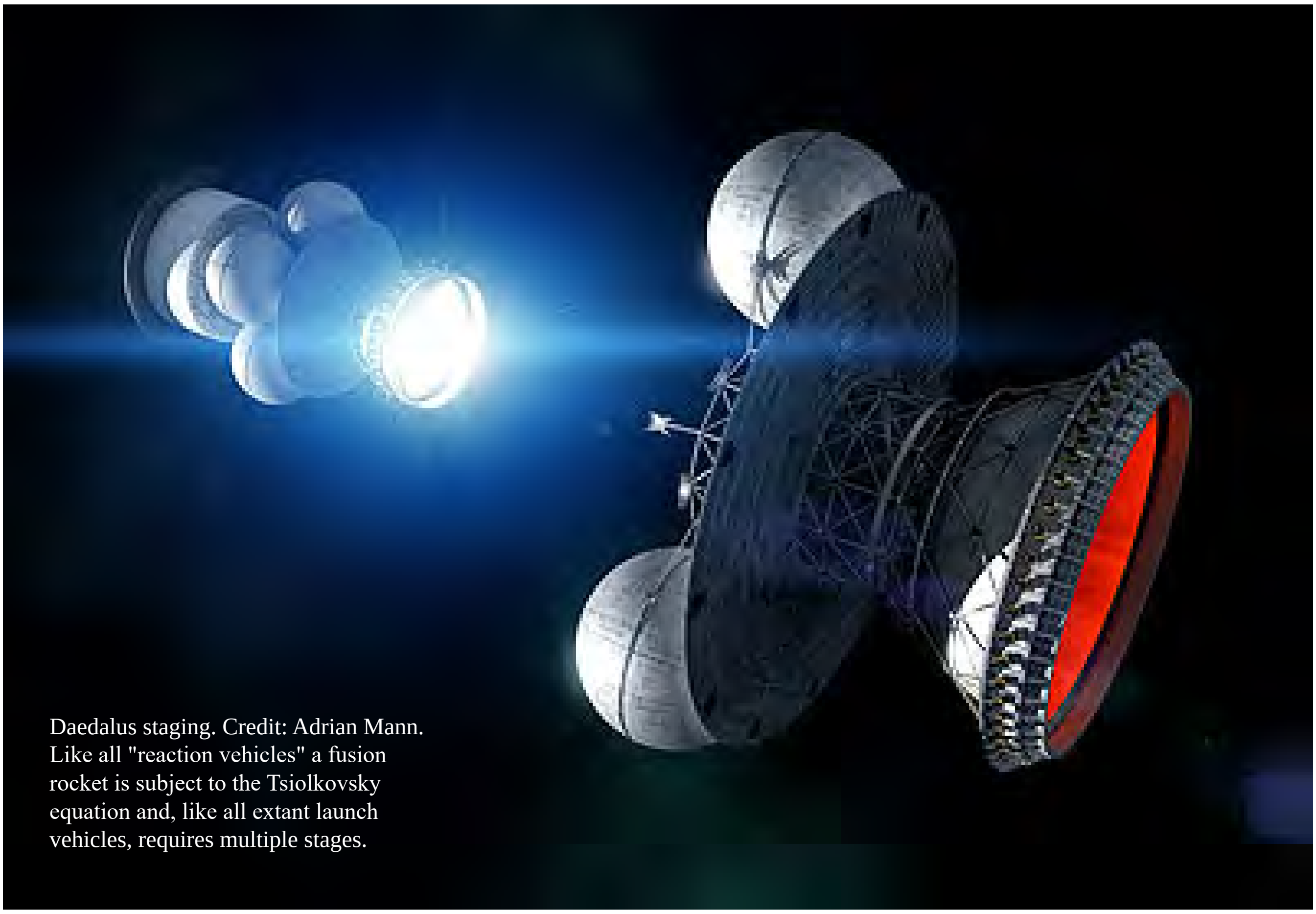
And finally, the third and most attractive method of obtaining speed. This is to transmit energy to the vehicle from outside, from the earth. The vehicle itself need not store up material energy (that is, ponderable energy—in the form of explosive or fuel). The energy is transmitted to it from the planet in the form of a parallel beam of electromagnetic rays of short wave-length. If its size does not exceed a few tens of centimetres, this electromagnetic "light" can be directed as a parallel beam with the aid of a large concave (parabolic) mirror to a flying aeroplane and there perform the work needed for ejecting particles of air or supplies of "dead" material in order to acquire cosmic velocity while still in the atmosphere.

(see Works below for source)

This is beamed power to drive on-board reaction mass. He goes further -

This parallel beam of electric or even light (solar) rays should exert pressure by itself (there can be no doubt that such pressure exists [see note on Lebedev below]) such pressure can give the vehicle a sufficient speed. In that case, one would not need any supplies for ejection. The last method would seem to be the most refined.

Refined indeed - since this avoids the need for reaction mass and makes Tsiolkovsky's own equation irrelevant. This is,



Daedalus staging. Credit: Adrian Mann. Like all "reaction vehicles" a fusion rocket is subject to the Tsiolkovsky equation and, like all extant launch vehicles, requires multiple stages.

of course, the subject of much recent work by several groups worldwide including Lubin's team at UCSB and by the Initiative for Interstellar Studies - and, of course, the major work driven by Breakthrough Starshot. Tsiolkovsky goes on to consider energy sources.

> *Indeed, on the earth we could build a power station of almost unlimited size with the generation of many millions of units of electric energy. The station transmits energy to a flying vehicle which does not need to carry any supplies of special energy (energy to produce speed). The vehicle would only carry passengers and life-support facilities for the trip or for permanent residence in the ether. This would greatly simplify the problem of interplanetary communications and colonization of the solar system.*

The editors of this translation add a footnote to justify Tsiolkovsky's "refined method" -

> *The effect of light pressure was experimentally established by the noted Russian physicist P. N. Lebedev in 1899 (Editors).*

Lebedev's paper is "Untersuchungen über die Druckkräfte des Lichtes" (Investigations on the pressure forces of light) (it.wikisource.org/wiki/Scientia_-_Vol._VII/Die_Druckkr%C3%A4fte_des_Lichtes)

Lebedev describes the effect, supporting Maxwell's conclusion that -

> *…the rays of light must exert pressure on those bodies on which they fall. The fact that this property of light escaped the researchers was easily explained by the exceptionally low behaviour of these forces: Maxwell calculated (1873) that in the clear sky at lunchtime the compressive force of solar radiation on four square meters hardly equals the weight of one-tenth of a gram.*

So, in "The Spaceship" one Russian engineer, Tsiolkovsky, speaks to another, Yuri Milner of Breakthrough Starshot, across 100 years. And to the rest of us as we work towards our interstellar goals.

Our other greatest hope for interstellar propulsion was also anticipated by Tsiolkovsky. Recall that nuclear fission was decades from proof, that fusion was a distant dream and see an inkling of what might be possible in this from "Investigation of World Spaces by Reactive Vehicles" (1911-1912).

First he reminds us of his rocket equation -

> *… it is seen that an increase in [exhaust velocity] brings about a proportional increase in the velocity of the rocket, V2, for the same relative consumption of explosive mate-(M2/M1).*

He then considers the early results from the study of radioactive elements -

It is believed that as radium disintegrates continually into more elementary matter it liberates particles of different masses moving with amazing, unconceivable velocities close to that of light. For example, helium atoms are released here with speeds from 30 to 100 thousand km/sec.

He mentions other particle velocities and goes on -

These speeds (in km) are 6 to 50 thousand times greater than those of gases emerging from the muzzle of our reaction pipe.

So he concludes that his rocket, the "reaction pipe", can employ propellants using similar processes -

.. if it were possible to accelerate the disintegration of radium or other radioactive bodies, and probably all bodies are of this kind, then its employment might yield—all other conditions being equal, see formula (35) [a version of the rocket equation from his 1903 paper]—a velocity of the reactive vehicle such that to reach the closest sun (star) would be possible in 10 to 40 years.

It is a coincidence, of course, that the BIS Daedalus study led to a similar mission duration but clearly Tsiolkovsky was anticipating mission durations which are in the same range as Bond, Martin and the BIS team anticipated many decades later.

He goes on -

Then only a handful of radium, see formula (16) [a different version of the rocket equation from his 1903 paper], would be enough for a rocket weighing a ton to break all ties with the solar system.

All this from a single page in the translation of his paper.

Only someone with the combination of imagination, drive, practical engineering thinking, up-to-date scientific knowledge and mathematical capability could have come up with this intelligent speculation at this time. The world of 1912 was even more unready for this than the ideas of Goddard ("A Method of Reaching Extreme Altitudes" 1919), Oberth (Die Rakete zu den Planetenräumen "The Rocket into Planetary Space", 1923) and the lunar visionaries of the British Interplanetary Society 2 or 3 decades later (BIS Lunar Spaceship, 1939).

Vision

Tsiolkovsky was a dreamer - although a very practical one. Some of his other ideas include -

- All metal airships - lifted by an internal vacuum
- Steering rockets either by using graphite vanes in the exhaust or by pointing the whole rocket motor
- Cooling the outer surface of a high velocity vehicle by circulating fuel through a double skin
- Similarly cooling the rocket motor
- Advocacy of liquid fuel rockets in an era of solid fuel rocketry - in essence larger versions of firework rockets - with suggestions for liquid oxygen and hydrogen as ideal propellants
- The space elevator
- And, as we have seen, the destiny of our species beyond our planet

And he believed that consciousness must exist throughout the universe. We still don't know if we are alone, of course, and Arthur C Clarke remarked that either a positive or a negative answer to this great question would be equally staggering.

Tsiolkovsky's 1911-1912 paper "Investigation of World Spaces by Reactive Vehicles" ends with an exhortation -

Advance boldly, great and small workers of the human race, and you may be assured that not a single bit of your labours will vanish without a trace but will bring to you great fruit in infinity.

May we, mostly "small workers", also retain an optimistic view of our human future!

Biographies

Red Cosmos, K E Tsiolkovskii, Grandfather of Soviet Rocketry, By James T Andrews Ph.D, Texas A&M University Press. 2009, muse.jhu.edu/book/2784

A biography putting Tsiolkovsky into a historical and cultural context.

Konstantin Tsiolkovsky His Life and Work, Arkadiĭ Aleksandrovich Kosmodemyansky. English translation X Danko published Dec 2000 University Press of the Pacific, Honolulu

A more technical biography from a Soviet point of view

The Life and Work of Konstantin E Tsiolkovsky, V N Sokolsky in K E Tsiolkovsky Selected Works

A brief biography included in Selected Works, see below in Sources

There are also many useful sources on the web - here are two I have found most useful -

Konstantin E Tsiolkovsky www.nasa.gov/audience/foreducators/rocketry/home/konstantin-

tsiolkovsky.html

Konstantin Tsiolkovsky: Russian Father of Rocketry, Nola Taylor Redd, Space.com Contributor, February 27, 2013, www.space.com/19994-konstantin-tsiolkovsky.html

Works

My principal source has been -

K E TSIOLKOVSKY Selected Works, compiled by V N Sokolsky, General editor Acad. A A Blagonravov, translated from the Russian by G Yankovsky, University Press of the Pacific, Honolulu, Hawaii, 1968-2004

It contains two background pieces. The first by the great Sergei Pavlovich Korolev, director of the Soviet space programme till his premature death in 1966.

> On the Practical Significance of the Scientific and Engineering Propositions of Tsiolkovsky in Rocketry - S P Korolyov, 1957

The second the short biography already cited above -

> The life and work of Konstaniin E Tsiolkovsky, V N Sokolsky

- and the following works by Tsiolkovsky-

- From the manuscript "Free Space", 1883
- Tsiolkovsky's First Description of his Wind Tunnel, 1897
- Investigation of World Spaces by Reactive Vehicles, 1903
- Investigation of World Spaces by Reactive Vehicles, 1911-1912
- Investigation of World Spaces by Reactive Vehicles, Supplement to first and second parts, 1914
- The Spaceship, 1924-1926
- A High-Speed Train, 1927
- Cosmic Rocket Trains, 1929
- A New Aeroplane, 1929
- Reactive Aeroplane, 1930
- To Astronauts, 1930
- Semi-Reactive Stratoplane, 1932
- Reaching the Stratosphere, 1932
- Astroplane, 1932
- The Astroplane and the Machines That Preceded It, Manuscript dated 1933
- Maximum Rocket Speed, From the manuscript dated 1935

Conclusion

I have only touched on the range of work produced by this remarkable member of our species. There is much more to say. We lack a thorough technical/scientific biography, at least in English or English translation. And I have said nothing of his science fiction - which was deliberately didactic and inspirational.

I would welcome additions, corrections and comments from Principium readers.

Sergei Pavlovich Korolev (Серге́й Па́влович Королёв)
Credit: London Science Museum

John I Davies is a retired software engineer and mobile telecomms consultant. He was briefly in the UK space industry with small parts in an early design study for the Hubble telescope and in the last stages of the ultimately cancelled European ELDO launcher. His main work has been in communications software and in mobile data communications. He has been active in the Initiative for Interstellar Studies since soon after its foundation in 2012. He is a career-long member of the British Interplanetary Society.

Preparing for the next Interstellar Object

T M Eubanks*

Marshall Eubanks, CEO of Asteroid Initiatives LLC and a key member of the i4is Project Lyra team, considers the challenges of intercepting and examining future interstellar objects.

The recent discovery of the first high velocity hyperbolic object passing through the Solar System [1], 1I/2017 U1 'Oumuamua (or simply 1I), opens the possibilities of near term interstellar missions, not to distant stars, but to considerably closer objects passing through the solar system. Material orbiting in the galaxy tests to migrate widely over time and thus 1I, or any other visiting InterStellar Object (ISO), would likely have formed very far from the solar system in both space and time, in another solar system or maybe independently from stellar outflows or ejecta in interstellar space. These objects are thus likely to be very different from any solar system asteroid, and from each other; determining their composition in detail would thus be of intense scientific interest. 1I is, however, an asteroidal ISO, not emitting any gas to inform astronomers about its composition; in situ spacecraft exploration will be necessary to determine details of the structure and chemical composition of this or any other asteroidal ISO. This note describes how spacecraft exploration of asteroidal ISOs can be accomplished based on what has been learned from efforts to design a mission to 1I. Two basic types of such missions have been proposed to date, pursuit missions, where a spacecraft would be sent to chase and catch up to an ISO after its discovery, and prepositioned missions, where spacecraft would be launched and positioned in stable orbital regions, such as at Lagrange points, in advance of the discovery of any particular ISO. The prepositioned spacecraft would then wait and attempt to intercept ISOs in the inner solar system, should some be discovered and pass within range. It is not realistic to expect that a heavy lift booster would be kept on standby to send a probe to a incoming ISO on short notice, and it is highly unlikely that even a very active interstellar comet would be detected much before one year before its perihelion passage, and so any mission initiated after the discovery of a new ISO will inevitably be a pursuit mission. Prepositioned missions are a newer idea offering a number of advantages but also some formidable technical challenges; more attention will be paid here to pursuit missions.

1. Introduction

1I is a difficult, but not impossible, target for a spacecraft mission with existing technology. 1I was only discovered after its perihelion (closest approach to the Sun) and is rapidly leaving the solar system on a hyperbolic orbit, with a velocity "at infinity" (i.e. far from the Sun), v_∞, of 26.3 km s^{-1}, or ~5.5 Astronomical Units (AU) per year, where one AU is the distance between the Earth and the Sun. 1I will thus be many AU from the Sun by the time any probe could be launched to overtake it; such a probe would need a v_∞ considerably larger than 1I's to have a reasonable mission duration. 1I will, for example, be at a distance of 36.2 AU on July 18th, 2023. A probe with a v_∞ of 6.5 AU per year would have a closing velocity of only 1 AU per year, and would take roughly 36 years to flyby 1I if it started its pursuit on that date. A more reasonable mission duration of under 18 years would require a $v_\infty \geq 7.5$ AU per year, or ≥ 36 km s^{-1}. This is substantially faster than the fastest human spacecraft to date, Voyager 1, which has a v_∞ =16.86 km s^{-1}. The various propulsion technologies capable of pursuing and reaching 1I deep in the

* Asteroid Initiatives LLC, P.O. Box 141, Clifton Virginia 20124, tme@asteroidinitiatives.com

outer solar system have been surveyed by Hein et al. [2]; these technologies can be in principle applied to any incoming asteroidal or cometary ISO. With chemical rockets the necessary velocities require a combination of gravity assists together with powered Oberth maneuvers close to the Sun to gain orbital energy; these complicated orbital maneuvers inevitably restrict the timing of such flyby missions even if a heavy lift booster, such as NASA's Space Launch System (SLS) [3] were dedicated to the mission.

2. Finding More Interstellar Asteroids

1I/'Oumuamua was discovered on October 18 by Pan-STARRS1 with a visual magnitude of 19.8 at a distance from Earth of ~0.208 AU [1]. 1I photometric observations [4, 5, 6] reveal an average absolute visual magnitude of about 23, a tumbling non-principal axis rotation with rotation periods of ~8.1 - 8.3 hours and surprisingly large magnitude changes of > 2 magnitudes during a rotation period. 1I was discovered by one of the three most capable current asteroid surveys, the others being the Mt. Lemmon Survey, and the Catalina Sky Survey. These surveys in aggregate have a total survey time of about 30 years; a naive estimate for the detection rate of 1I type objects would thus be ~0.03 yr^{-1}.

The upcoming Large Synoptic Survey Telescope (LSST) will reach a limiting survey magnitude as faint as r = 24.5, and so should be able to detect an incoming ISO with a photometric magnitude comparable to 1I at a distance of ~ 1 AU, possibly several months before perihelion. The LSST survey should have a depth per unit time better than one order of magnitude better that the existing surveys, leading to a naive estimate of a discovery rate for interstellar asteroids of ~0.2 per year [7]. Cook et al. [8] looked at constraints on the number density of interstellar comets and concluded that the LSST could detect as many as 1 or as few as 10−4 interstellar comets per year (with the primary uncertainty being the uncertainty in their number density). The discovery rates of both sorts of ISO are thus still quite uncertain; it is not clear if the next decade will lead to the discovery of no ISOs, a few, or potentially a flood. Hopefully, this uncertainty will be resolved by the middle of the next decade, when the LSST should be in full operation.

3. Likely Velocities of Visiting Interstellar Objects

As objects with densities comparable to solar system bodies and diameters »1 cm will not be significantly perturbed by drag from the Interstellar Medium (ISM) even on billion year time-scales [9], the v_∞ of an incoming ISO provides a strong indication of which galactic population it belongs to. The Sun and most of the nearby stars are in the galactic thin disk, orbiting very close to the plane of the galaxy. The relative velocities of objects in the thin disk are effectively randomized by mutual gravitational interactions, with nearly Gaussian velocity dispersions with a root mean square (rms) in the galactic plane of ~40 km s^{-1} relative to the Local Standard of Rest (LSR)*, together with a rms of only 16.5 km s^{-1} for the W velocity component (the velocity in the direction orthogonal to the galactic plane) [10]. (Note that these velocities are all relative to the local orbital motion of ~255 km s^{-1}

Table 1: Velocity Vector Components in the galactic U, V, W system, where U is radial, V is along the direction of galactic rotation, and W is orthogonal to the galactic disk. The final column provides the vector magnitude . The 1I inbound velocity is of course the incoming velocity of the asteroid relative to the Sun; the other velocities are thus expressed as the velocity of the LSR relative to the Sun. [10] provides the standard deviation of the stellar velocities, which is also included. The final row provides, as a reference, the difference of the 1I and Gaia DR1 velocity estimates.

Source	**U km s^{-1}**	**V km s^{-1}**	**W km s^{-1}**	**|v| km s^{-1}**
1I inbound [13]	-11.33 ± 0.07	-22.38 ± 0.08	-7.63 ± 0.09	26.18
New Hipparcos Reduction[10]	-7.5 ± 1.0	-13.5 ± 0.3	-6.8 ± 0.1	16.9
NHR standard deviation [10]	32.6	22.4	16.5	
Gaia DR1 [14]	-8.19 ± 0.74	-9.28 ± 0.92	-8.79 ± 0.74	15.18
1I - Gaia DR1	-3.14 ± 0.74	-13.10 ± 0.92	1.16 ± 0.75	13.52

* the mean motion of material in the Milky Way in the neighborhood of the Sun (en.wikipedia.org/wiki/Local_standard_of_rest)

about the center of the galaxy.) Stars (and presumably thus also asteroids and comets) from other populations also speed through the galactic disk, with typical rms relative velocities of ~50 -100 km s^{-1} for objects from the thick disk, and ~300 km s^{-1} for objects from the galactic Halo [11]. Intergalactic asteroids and comets are also a possibility; these would be expected to have velocities relative to the Sun > 500 km s^{-1} [12]. All of these higher velocity objects should have near random inclinations, and thus on average large velocities out of the galactic plane.

Table 1 provides, in galactic coordinates, the inbound 1I v_∞, together with recent determinations of the LSR velocity and, for reference, the difference between the 1I inbound velocity and the recent Gaia DR1 LSR determination [14]. 1I has an incoming v_∞ of ~26.3 km s^{-1}, largely in the galactic plane.

This velocity is quite consistent with it being a long term resident of the galactic thin disk, but is much too small for it to be a thick disk or halo object. Clearly, with existing or near term technology, pursuit missions will not be able to reach thick disk or halo objects, as these should have v_∞ > 100 km s^{-1}, and it is reasonable to assume that any potential pursuit target will be a thin disk object. Prepositioning missions are not subject to the same limitations, and seem to be the only way at present to explore high-velocity objects from outside the thin disk at close range.

The incoming velocity vectors of thin-disk visitors to the solar system are likely to be in the galactic plane with v_∞ ~ being on average close to the velocity of the local standard of rest (16.9 km s^{-1}, but with a variation of about 40 km s^{-1}). If a new visitor is a thin disk object, the chances thus are roughly equal that it will have a smaller or a larger v_∞ than 1I; only the objects with a comparable or smaller outgoing v_∞ are likely to be reachable with near term space flight technology. The directions of the outgoing velocity vectors will be changed by their passage near the Sun, and will be effectively randomized with respect to the ecliptic. The effective outbound inclination (the angle between the outgoing v_∞ vector and the plane of the ecliptic) will thus also be an important factor in mission planning, as only targets that happen to have relatively small effective outbound inclinations are likely to be reachable by a pursuit mission.

4. Pursuit Missions

To reach an ISO in a pursuit mission using chemical propulsion within a reasonable amount of time would require both a launch reasonably soon after perihelion passage and a spacecraft $v_\infty \gtrsim 35$ km s^{-1}. Attaining this velocity with chemical propulsion is only possible in practice with a combination of gravity assists, at a minimum a Jupiter or Saturn gravity assist to remove almost all of the spacecraft's orbital angular momentum and leave its velocity vector pointing almost directly at the Sun, followed by an Oberth maneuver (an impulsive velocity change) at the time of the closest approach to the Sun [15, 16]. After perihelion passage and the Oberth maneuver the probe would execute a ballistic pursuit, possibly decades long, to catch up with and flyby the target. Pursuit missions thus depend in practice on a favorable planetary alignment, with Jupiter (or potentially Saturn) being at a longitude suitable for a gravity assist for the pursuit.

Figure 1 shows the complicated trajectory required for a sample pursuit mission to a body with the same timing and velocity as 1I, but assumed for simplicity to be entirely in the ecliptic plane. This sample mission involves a launch in the Spring of 2021 into a high-energy transfer trajectory reaching Jupiter a little over 1 year later, an unpowered Jupiter gravity assist to remove most of the probe's orbital angular momentum so that it drops in close to the Sun, where an Oberth maneuver, with a δV * of 3.2 km s^{-1}, would be performed only 2.4 million km from the Sun on July 18th, 2023, yielding a v_∞ = 43.2 km s^{-1} and a flyby in late 2040. Solar shielding at least as good as that for the Parker Solar Probe [17] would be required to survive the close passage by the Sun during these Oberth maneuvers (at the minimum distance of this sample mission the solar flux would be over 5 Megawatts per square meter, almost 4000 times the flux here at the Earth).

Note that there are two fairly small angles in the trajectory shown in Figure 1, one being the angle between the incoming and outgoing velocity vectors at Jupiter, and the second, called the opening angle, being between the incoming and outgoing velocity vectors at the Sun. The latter angle (~ 30° for this particular trajectory) sets a stringent limit on the effective inclination range that can be targeted by these maneuvers. To fall from Jupiter to close to the Sun the orbital angular momentum must be

* Delta V - the change in velocity required. See *Tsiolkovsky - Interstellar Pioneer* elsewhere in this issue for Delta V as provided by rockets. There are other ways of achieving Delta V, of course, including laser propelled sails

quite small (5.4 AU km s^{-1} in this case), which means that the Jupiter gravity assist cannot provide any significant velocity out of the ecliptic and the incoming velocity vector will be close to the ecliptic plane. The out-of-plane velocity required to reach high inclination targets thus must come from the Oberth maneuver, which typically have a small opening angle, or from a subsequent second giant planet gravity assist, which requires a possible but unlikely favorable alignment of two planets.

The particular Oberth maneuver shown in Figure 1 thus cannot reach objects with effective outbound inclinations ≳30 degrees unless a giant planet happens to lie at the correct longitude for a second, post-Oberth, gravity assist. Of course, the opening angle resulting from the Oberth maneuver can be changed, but only at the cost of other mission parameters.

Let ψ be half the opening angle (technically, the angle between the perihelion vector and the outbound v_∞ vector), and δV be the velocity imparted by the rocket thrust in the Oberth maneuver (i.e. along the velocity vector at perihelion). Then, for a relatively small v_∞

$$v_\infty \sim \frac{4\ \delta V}{\psi} \quad (1)$$

where ψ is of course in radians. Equation 1 shows an inverse relation between v_∞ and ψ; a larger v_∞ can be obtained by a closer passage by the Sun, which results in a narrower hyperbolic trajectory and a smaller ψ angle. To reach a large effective outbound inclination (i.e. a large ψ) requires either reducing v_∞ by moving the Oberth maneuver further from the Sun (which would increase the mission duration) or increasing δV (by using either larger rockets or a less massive payload, or both).

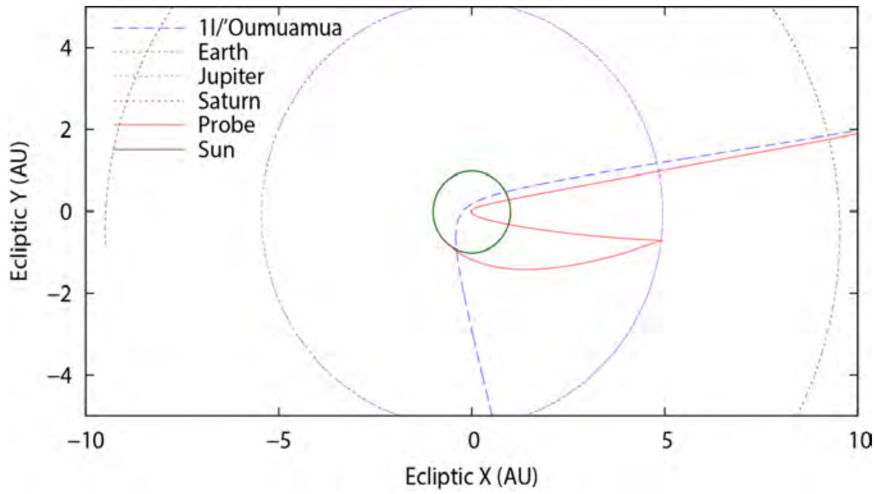


Figure 1: An intercept trajectory for an object in the ecliptic, but otherwise with the orbital parameters of 1I/'Oumuamua. After a launch into a fast Jupiter trajectory in April 28, 2021, the probe would execute an unpowered gravity assist at Jupiter on May 22, 2022, passing within 30,000 km of the Jupiter surface, followed by a 3.2 km s^{-1} Oberth maneuver near the Sun (at 3.5 $R_\odot$ [sun radii])on July 18th, 2023. This combination of maneuvers would allow a heavy lift booster, such as NASA's SLS [3], to deliver a 500 kg probe to the target with a fast flyby in early 2043. Credit: Marshall Eubanks.

The combination of realistic limits on mission duration and rocket size will mean that high velocity and high effective inclination ISOs will not make good pursuit targets. By combining the velocity and inclination restrictions it is thus possible to predict that only roughly one quarter of the ISOs found are likely to be suitable targets for a pursuit mission.

It is fortunate that the first one found, 1I, happens to be a suitable pursuit target and it is very unclear when the next such target will be found.

5.The End of the Chase; Finding the Target in a Pursuit Mission

ISO pursuit missions will be unusual in that they will almost certainly be " flying blind," aimed at a target that neither the probe nor any terrestrial or space telescope can see for most of the duration of the mission. Unfortunately, radar or lidar will not help with target detection at distances of millions of km; target detection will have to be performed optically or in the near-IR with a telescope or telescopes carried on the pursuit probe. The terminal navigation problem for 1I, for example, will be severe; with an absolute magnitude of ~22 magnitude, 1I will be very dim as it recedes from the Sun, and an intercept in the late 2030's or early 2040's would be based, with present data, on ephemeris information from 2017-2018, leading to ephemeris uncertainties of many 10s or even 100s of thousands of km.

The apparent magnitude, m, of an asteroid depends on its absolute magnitude, H, the distance between the body and the observer, d_{BO}, and the distance between body and the Sun, d_{BS}. Ignoring the phase factor, which will be effectively a constant in the geometry of a pursuit mission, the apparent magnitude is given by

$$m = H + 2.5\ log_{10} \frac{d_{BO}^2\ d_{BS}^2}{1AU^4}. \quad (2)$$

If the spacecraft has a telescope with a limiting magnitude of m_{SC} then the target can be detected at a distance

$$d_{BO} = \frac{1}{d_{BS}} 10^{\frac{m_{SC}-H}{5}} \quad (3)$$

with both d_{BO} and d_{BS} being measured in AU. Equation 3 encapsulates the discovery difficulty that a pursuit mission will face. 1I, for example, has an absolute magnitude that varies between ~ 22.5 and 25 depending on its rotational phase [5, 6]. A 40 cm optical telescope in space should be able to detect a object with a predictable motion at m_{SC} ~23.5. As the exponential factor in Equation 3 would thus be near zero on approach to 1I, and as d_{BS} would be of order 100 AU or more even for high energy Oberth maneuvers, 1I would not be detected until the spacecraft is a few hundredths of an AU, or a few million km, away, a day or two at best from the time of the fast flyby*. As the target ephemeris uncertainty at that point is likely to be ~50,000 km, the probe will need a terminal guidance δV of order 0.5 to 1 km s^{-1} in order to do a close flyby of the target, releasing a small impact probe to generate vapor for spectral analysis. As the communication Round Trip Time (RTT) at that time would be > one day, the probe would have to detect the target, perform terminal navigation, execute the terminal guidance maneuver and target the impact probe entirely autonomously, without any active feedback from its controllers on Earth.

6. Prepositioning Spacecraft

It is possible that small spacecraft could be prepositioned in the inner solar system at relatively stable locations, such as Lagrange points, to attempt ISO flybys in the inner solar system, as has been proposed for comets [18]. These spacecraft, not having any particular launch windows, could be launched on a "space available" basis, or under a program such as the NASA Small Innovative Missions for Planetary Exploration (SIMPLEx) program (part of SALMON, Stand Alone Missions of Opportunity). Prepositioning would avoid launch scheduling problems and decades long pursuit times. However, to have a good probability of success, such a mission would likely need a δV capability of order 1 - 5 km s^{-1}, in order to traverse distances of order 0.1 AU in times of order of a few months. Prepositioned spacecraft will likely need be small to lower costs, which seems in tension with the δV required on such missions. This interesting possibility would clearly benefit from a detailed design study for the ISO case, as intercept mission characteristics will be considerably different for interstellar asteroids than for long period comets.

7. Conclusions

We now know for certain that interstellar asteroids exist and from time to time come through the solar system; it is inevitable that missions will eventually be mounted to directly observe these scientifically interesting bodies. There is much that can be done to prepare for the next such visitor before its discovery. A program to send future probes to future visiting ISOs would benefit from finding numerous such objects, finding them as early as possible, and improving the technology available to reach them. Clearly, anything that would substantially improve the depth and number of asteroid surveys should improve the chances of finding interstellar objects; these surveys should make sure that their software allows for the high angular rate of motion of ISOs when they are close to the Earth. Solar electric propulsion rapidly loses effectiveness as probes on fast hyperbolic orbits move away from the Sun; pursuit missions would benefit from the availability of high-specific impulse (ISP) propulsion, such as nuclear-electric rockets, that do not require the availability of solar power. Pursuit missions will require a very high level of independence in the flyby spacecraft, and thus will benefit from the development of spacecraft autonomous operations. ISO missions are likely to make use of impacting sub-probes to gain information about composition in the absence of cometary activity. These hypervelocity impacts would produce a significant amount

* The question of the limiting magnitude of a spacecraft telescope is a complicated one, as it depends on more than just the size of the telescope. Other factors include the nature and temperature of the detector, the stability of the platform and the length of maximum duration of exposures. The latter is exemplified by the increased exposure time for the Long Range Reconnaissance Imager (LORRI) on the New Horizons spacecraft which added an apparent magnitude (from 20 to 21) to the sensitivity of the imager as it headed out beyond Pluto (www.planetary.org/blogs/emily-lakdawalla/2018/0124-new-horizons-prepares-for-2014mu69.html). Note that such magnitudes are logarithmic - en.wikipedia.org/wiki/Apparent_magnitude - and this more than doubles the sensitivity of the imager.

of Extreme Ultraviolet (EUV) radiation on very short time scales, and these missions would thus benefit from improvements in flash EUV spectroscopy. Prepositioned missions to intercept ISOs are at present poorly characterized and are at a low overall Technical Readiness Level (TRL); these missions thus require basic work to improve their TRL before they can be seriously proposed.

Acknowledgements.
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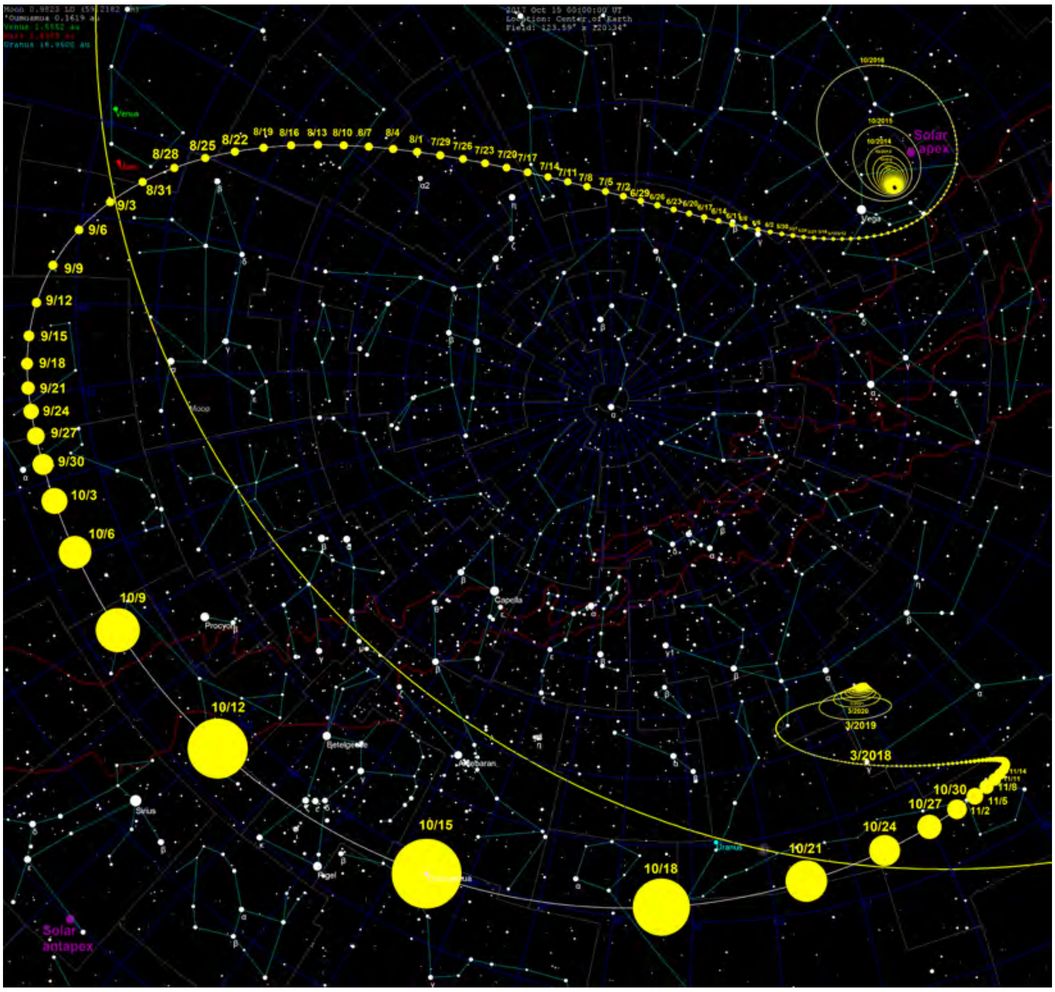

Apparent trajectory of 'Oumuamua as seen from Earth (from en.wikipedia.org/wiki/'Oumuamua) showing origin in Lyra, closest approach to Earth in October 2017 and destination in Pegasus.
See front cover of this issue for a hypothetical view of the Earth-Moon system at closest approach of 'Oumuamua.

Image credit:Tomruen/Wikipedia (trajectory data from JPL Horizons, ssd.jpl.nasa.gov/horizons.cgi?find_body=1&body_group=sb&sstr=3788040)

About Marshall Eubanks

Marshall Eubanks is CEO at Asteroid Initiatives LLC, the Asteroid Prospecting Company, and has held senior positions at JPL and the Internet Engineering Task Force (IETF). He holds a Master of Science (M.S.) in Physics and an M.S. in Planetary Physics from the Massachusetts Institute of Technology.
Asteroid Initiatives is dedicated to exploring the economic potential of Near-Earth asteroids.
Email address: tme@asteroidinitiatives.com (T.M. Eubanks)
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NEWS FEATURE
Work on the interstellar asteroid and i4is Project Lyra

John Davies and Andreas Hein

Principium editor and i4is Project Lyra team leader consider the present state and future of ’Oumuamua and Project Lyra.

The Initiative for Interstellar Studies, i4is, announced Project Lyra on the 30 October 2017, 11 days after the discovery of 1I/’Oumuamua by the team at the University of Hawaii’s Pan-STARRS 1 telescope. The goal of the project is to assess the feasibility of a mission to 1I/’Oumuamua using current and near-term technology and to propose mission concepts for achieving a flyby or rendezvous. On 8 Nov 2017 i4is published the first paper *Project Lyra: Sending a Spacecraft to 1I/’Oumuamua (former A/2017 U1), the Interstellar Asteroid* arxiv.org/ftp/arxiv/papers/1711/1711.03155.pdf

Early work and reception

Recall that ’Oumuamua has a hyperbolic excess velocity of 26 km/s. This is much faster than any object humanity has ever launched into space. Voyager 1, the fastest object humanity has ever built, has a hyperbolic excess velocity of 16.6 km/s. As it enters interstellar space ’Oumuamua covers 5.5 AU/year. In other words it is travelling fast enough across the diameter of Earth's orbit more than twice a year. To reach it is a challenge close to the technical limits of our current civilisation.

Project Lyra and the initial paper of 8 November 2017 received a great deal of attention including mentions in scientific publications-

- **IEEE Spectrum**: *How We Could Explore That Interstellar Asteroid* spectrum.ieee.org/tech-talk/aerospace/space-flight/how-we-could-explore-that-interstellar-asteroid
- **Scientific American**: *SpaceX’s Planned Giant Rocket Could Chase Down Interstellar Asteroid* www.scientificamerican.com/article/spacex-rsquo-s-planned-giant-rocket-could-chase-down-interstellar-asteroid/
- **Universe Today**: *Project Lyra, A Mission to Chase Down That Interstellar Asteroid* www.universetoday.com/137960/project-lyra-mission-chase-interstellar-asteroid-1/

There are also many references to Project Lyra in popular and "serious" press and in academic papers.

Research on ’Oumuamua and interstellar objects

Here is just a small sample of published work -

The SETI Institute explains some remarkable findings *The Three Surprises of 'Oumuamua* www.seti.org/three-surprises-of-oumaumau notably that `Oumuamua is tumbling, unlike most asteroids in our Solar System and that given its elongated shape this means that it is almost certainly a solid object, unlike some of the "rubble pile" irregular objects in the Solar System.

There is a **fine animation of the hyperbolic path of `Oumuamua within the solar system** by video originator "Tomruen" at - commons.wikimedia.org/wiki/File:Oumuamua_trajectory_animation.gif based on trajectory data from JPL Horizons.

The **American Astronomical Society (AAS)** has a January 2018 *Update on an Interstellar Asteroid* by Susanna Kohler, aasnova.org/2018/01/19/update-on-an-interstellar-asteroid.

A couple of highlights from the AAS piece-

- Jason Wright (The Pennsylvania State University) demonstrates via a series of calculations that no known solar system body could have scattered ‘Oumuamua onto its current orbit - nor could any still unknown object bound to our solar system. The paper is *On Distinguishing Interstellar Objects Like 'Oumuamua From Products of Solar System*

Scattering iopscience.iop.org/article/10.3847/2515-5172/aa9f23/meta

• Gregory Laughlin (Yale) and Konstantin Batygin (Caltech) argue that its current passage, if it's not a fluke, suggests the presence of an enormous number (1027) of such objects in our galaxy alone — enough to account for two Earth-masses of material for every star in the galaxy.

They also argue that flinging asteroids like 'Oumuamua out into interstellar space isn't easy. The necessary multi-body interaction requires the system to contain a giant and long-period planet like Neptune or Jupiter and suggests that every star in the galaxy may host a Neptune-like planet at a Neptune-like distance.

The Laughlin/Batygin paper is *On the Consequences of the Detection of an Interstellar Asteroid* iopscience.iop.org/article/10.3847/2515-5172/aaa02b/meta

Looking for origins of the asteroid, a paper *1I/2017 U1 ('Oumuamua) is Hot: Imaging, Spectroscopy And Search Of Meteor Activity* by Quan-Zhi Ye et al (Caltech, University of Maryland, University of Western Ontario) arxiv.org/pdf/1711.02320.pdf

It suggests -

• The velocity and trajectory of 'Oumuamua is consistent with a typical interstellar object (ISO) given the velocity distribution of the local stellar population, but they found no definite star of origin

• A scan of stellar close approaches to the nominal trajectory with the Gliese star catalogue (Gliese & Jahreiß 1991) also reveals no obvious candidates in the immediate vicinity of the solar system

• A travel time of 10^{13} years (10,000,000,000,000 years!) at a speed comparable to its relative motion through the solar neighbourhood.

Manasvi Lingam and Abraham (Avi) Loeb look at *Implications of Captured Interstellar Objects For Panspermia and Extraterrestrial Life* arxiv.org/pdf/1801.10254.pdf. They estimate the capture rate of interstellar objects by means of three-body gravitational interactions for Sun-Jupiter system and the Alpha Centauri A&B binary system concluding that the radius of the largest captured object is a few tens of km and Earth-sized respectively. They look at the implications of this model for the transfer of life by means of rocky material by objects captured by this "fishing net" of the Solar system.

Avi Loeb is Professor at the Center for Astrophysics, Harvard, and chairs the Advisory Committee for the Breakthrough Starshot Initiative.

At the more speculative end of things N Chandra Wickramasinghe of University of Buckingham, UK, and international collaborators suggest a vindication of his work with Fred Hoyle, the Hoyle-Wickramasinghe theory of the origin and evolution of cosmic life in *Oumuamua (A/2017U1) – A Confirmation of Links between Galactic Planetary Systems* in Advances in Astrophysics tinyurl.com/ACoLbGS

For other papers and the latest publications try - scholar.google.com and search for Oumuamua.

Where do I find out more?

The i4is website has *Project Lyra – A Mission to 'Oumuamua* i4is.org/what-we-do/technical/project-lyra which summarises the project and includes links to six videos and 41 media mentions.

There is a Project Lyra Wikipedia page en.wikipedia.org/wiki/Project_Lyra. Please feel free to edit (but kindly avoid anonymous editing!)

Coming soon

i4is president Kelvin F Long and other members of the Lyra team are working on a paper discussing the potential for an artificial origin of 'Oumuamua. They conclude, as have other authoritative experts, that this is highly unlikely.

However given -

• the curious shape of the object

• therefore the parallels with Arthur C Clarke's story

• the exploratory purpose of Project Lyra

- they have called their paper, *Rendezvous with 'Oumuamua*.

Look out for announcements on our website, Twitter and Facebook.

Future of Project Lyra

Work on Project Lyra continues and we are currently working on refined mission scenarios, including the potential for advanced technologies such as laser, solar, electric sails for acceleration and magnetic and electric sails for deceleration that may allow for a rendezvous with 'Oumuamua. Furthermore, we have also started using trajectory otpimization tools for finding optimal trajectories to 'Oumuamua using the Oberth maneuver (powered slingshot at the Sun). Furthermore, our public outreach continues with Project Lyra features to appear in the Dutch technology magazine KIJK and the French astronomy and aerospace magazine "Ciel et Espace" (Sky and Space).

NEXT ISSUE

The Orbits of Seveneves - Part 2 - the orbits explained
Book review 'Going Interstellar' - a Baen anthology new fiction & non-fiction on interstellar travel
Z-pinch and Icarus Firefly

We'd love to hear your thoughts on Principium,
the Initiative or interstellar flight in general.
Email - info@i4is.org - or come along to
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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
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The Initiative for Interstellar Studies is a pending institute, established in the UK in 2012 and incorporated in 2014 as a not-for-profit company limited by guarantee.
The Institute for Interstellar Studies was incorporated in 2014 as a non-profit corporation in the State of Tennessee, USA.

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Front cover: Hypothetical Astronaut sees Earth-Moon system from ‘Oumuamua,
Credit: Efflam Mercier, efflammercier.com
Back cover: ExTrA telescopes at La Silla
Credit: ESO/Emmanuela Rimbaud

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