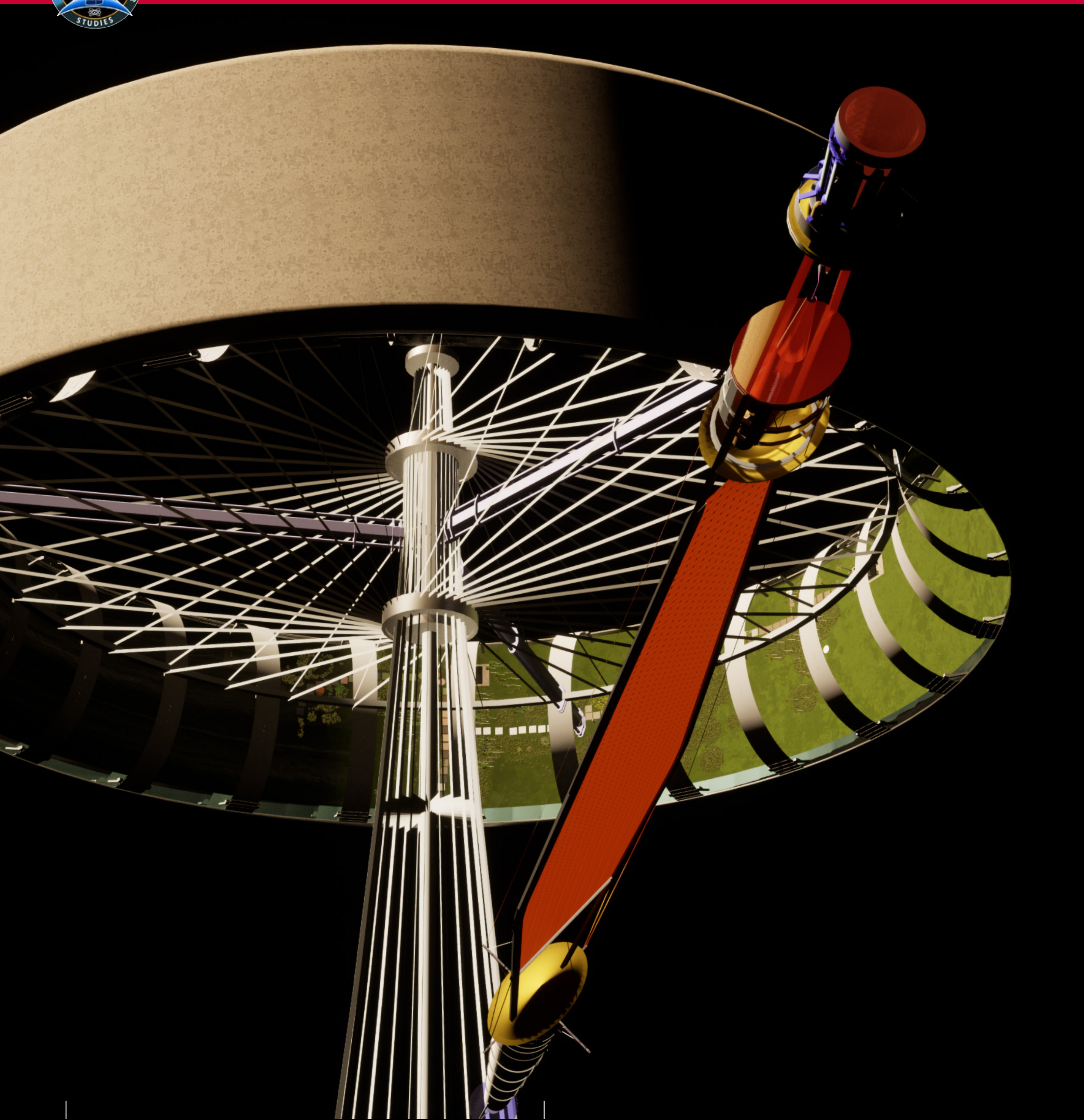
PRINCIPIUM

The Initiative and Institute for Interstellar Studies | Issue 42 | August 2023

SCIENTIA AD SIDERA | KNOWLEDGE TO THE STARS



ISSN 2397-9127 i4is.org

EDITORIAL

Welcome to issue 42 of Principium, the quarterly magazine of i4is, the Initiative and Institute for Interstellar Studies. We have two lead features this time, reports from the Interstellar Research Group biennial symposium, July 2023, at McGill University, Montreal, by Michel Lamontagne and Colin Warn. This 8th Interstellar Symposium is the major interstellar event of the year.

The front cover image this time is a visualisation of a meeting between a fast interstellar vehicle and a slower world ship by Michel Lamontagne. The rear cover image is a view of Saturn in infrared from the JWST. More about both in *Cover Images* inside the rear cover.

We have 10 pages of Interstellar News and 5 pages of our regular summary of relevant peer-reviewed papers in *The Journal of the British Interplanetary Society* (JBIS) and *Acta Astronautica*.

As always we have the i4is members' page and our regular call to action, *Become an i4is member*.

We have not been able to review *Conflicting Models for the Origin of Life* - more volunteer reviewers needed!

Next time, P43 in November, will have a first report on this year's International Astronautical Congress, IAC23, as previewed in this issue and a review of papers and presentations from IRG23, the 8th Interstellar Symposium, initially reported in this issue.

Current FTL thinking by Dr Dan Fries, Deputy Head of the i4is Technical Team, is postponed to P43 in November. He will be working with his i4is colleague, Parnika Singh, editor of our Members Newsletter.

More details on P43 in *Next Issue* at the end of this one.

And if you would like to help with any part of ***Working towards the real Final Frontier*** then please take a look at our poster, full-size on page 15. There's lots to do!

And please promote our work by printing and displaying i4is posters, see pages 26 and 36.

If you have any comments on Principium, i4is or interstellar topics more generally, we'd love to hear from you. Write us an interesting - or challenging - letter and we'll publish!

MEMBERSHIP OF i4is

Please support us through membership of **i4is**. Join the interstellar community and help to reach the stars! Privileges for members and discounts for students, seniors and BIS members. More about this in *Become an i4is member* this issue and at i4is.org/membership.

Members have access to:

- **Networking:** i4is.org/members/networking-opportunities
- **Principium preprints:** i4is.org/members/preprints
- **Videos:** i4is.org/videos

Please print and display our posters - all our poster variants are available at i4is.org/i4is-membership-posters-and-video.

KEEP IN TOUCH!

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

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

Follow us on Twitter at **@I4Interstellar**

And seek out our followers too!

Contact us on email via info@i4is.org

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

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

CONTENTS

LEAD FEATURES

NEWS FEATURES

INTERSTELLAR NEWS

REGULARS

IRG23 - the first two days

Michel Lamontagne

Michel is a long standing contributor to interstellar studies and to the work of i4is. Here he recounts his impressions of the first two days of IRG's 8th Interstellar Symposium 2023, the biggest event of the year in interstellar studies. This is the first time this IRG (formerly TVIW) event has taken place outside the USA,

We will have a detailed summary of each presentation in our next issue, P43 in November 2023. .

1 Introduction

After the opening ceremony, the presentations started with one of the patrons of the event, the Canadian Space Agency. John E Moores presented some of the projects the CSA are working on, that might eventually have some Interstellar applications. In particular Canadarm 3, Starchip, the Infrared Imager of the James Webb Space Telescope (JWST) and Canada's participation in the Osiris Rex Asteroid sample return mission.

The following presentation was from another patron, the International Academy of Astronautics, IAA. The IAA president described theT IAA membership and structure: Basic Sciences, Engineering Sciences, Life Sciences and Social Sciences. He then gave the podium to a star speaker, the astronaut (and former Governor General of Canada) Julie Payette.

The inspirational Julie Payette (this image 2017 at Rideau Hall). Credit: Wikipedia

Julie Payette got her bachelor's in electrical engineering from McGill, and was happy to return to her Alma Mater for the event. She showed a genuine interest in the Interstellar question, and was seen listening attentively for a number of later talks. In particular, many students went up to meet her in the breaks between the talks, and she shared career advice with them, and how passion tended to pay off with results, sometimes in the most unexpected ways. In particular, how choral singing was instrumental in her astronaut career!

Julie Payette's talk was quite inspirational, in particular about the importance of human presence in space. After her talk, Julie Payette was presented an achievement award by the IAA, previously given to John Glenn and Valentina Tereshkova, so she is in prestigious company!

Les Johnson, one of the pillars of the IRG organization, was awarded an Honorary IAA membership for his exemplary involvement in research and science outreach.

A short break was followed by a keynote speech from Frank Tipler, American mathematical physicist and cosmologist "The Ultimate Rocket and the Ultimate Energy Source, and Their Use in the Ultimate Future". Tipler presented the results of an experiment purporting to show proof for some of the cosmological equations of his Omega point theory [1]. The theory points to the use of vacuum energy as a propulsion mode and energy source, and although quite abstract, the presentation was certainly entertaining.

I missed the following presentation, Joseph Gottlieb "Should we colonize (interstellar) space?", having been called away on mundane matters from my day job. I did get to hear most of Claudio Maccone's presentation of some of his work on gravitational lensing: "Human Interstellar Expansion driven by Gravitational Lensing". In particular, how gravitational lensing could be used as an amplifier for SETI communications. Maccone proposed that the gravitational focus might be explored for signs of Interstellar communications, as the lens allows for communications at much reduced power levels.

Claudio Maccone delivers his talk on Gravitational Lensing
Credit: Dr René Heller

[1] See en.wikipedia.org/wiki/Omega_Point - see also *the Hart-Tipler argument against the existence of extraterrestrial intelligence* (en.wikipedia.org/wiki/Hart%E2%80%93Tipler_conjecture) and *Self-replicating probes and SETI*, in Principium 38, August 2022, page 13 (i4is.org/principium-38/). Dr Tipler's most famous work is the book *The Anthropic Cosmological Principle.* Oxford University Press (1986), Frank J Tipler and John D Barrow..

Alan Stern, Stephane Linter and Setthivoine You - Helicity team reporting their work in development of a fusion drive Credit: Michel Lamontagne

The author also presented his ideas on using lenses as bilateral communication systems, and how these could exist already between a multitude of stars, but be unseen by us until we ourselves reached the gravitational lens focal point.

Lunch was followed by a one hour panel, that was more fundamentally a presentation, by Alan Stern, Stephane Linter and Setthivoine You of the current status of the work at Helicity, a company dedicated to the development of a fusion drive in the near future. Alan Stern, building on his long experience as a NASA project leader (notably New Horizons) presented what new missions might be achievable with a fusion drive. Stephane Linter presented the business plan for the company, and how they might achieve a progressive roadmap towards fusion, in particular an interesting 'augmented ion drive' mode, based on Solar Electric Propulsion (SEP) and some fusion gain. The roadmap aims for a test prototype in space by 2032. Setthivoine You presented some of the hardware built at this time, and the simulations done for the fusion reactions. The fusion mechanism, pulsed magneto inertial fusion, a form of magnetized target fusion, is an interesting intermediate between ICF and tokomak type magnetic fusion that lends itself to a rapid development path where injectors could be combined into larger and larger engines, eventually reaching high thrusts and significant neutron and Bremsstrahlung absorption in a simple package. The focus of the company is now on preparing a first prototype, that they hope will validate the mathematical modelling. They are also targeting Deuterium-deuterium fusion at first, as that fusion fuel is much more accessible than others.

After the afternoon coffee break, Alex Gmerek presented an "Astrobiology payload for Interstellar missions". Although clearly developed for exploration of the Solar system the instrument suite presented by Gmerek provide an interesting number of functions in tiny packages, suitable for cubesat missions, or very low mass Interstellar explorers.

This presentation was followed by Victor Toth's "Look before you leap: Using the solar gravitational lens to explore exoplanets". The extreme difficulties of actually implementing gravitational lensing, the technical problems involved in reaching the focal line, navigating to the correct position and extracting the information from the annular image that the gravitational lense creates were all covered in detail. The precision needs to be very high, in the order of hundreds of meters, and Toth presented some ideas on how to achieve that precision.

The Outreach event. Trevor Kjorlien at the podium Les Johnson, Alan Stern, AJ Link, Erika Nesvold, Philip Lubin . Credit: Michel Lamontagne

The evening outreach event "Interstellar Travel: Are We Ready?" was held before a large audience at the McGill Leacock building. Les Johnson, AJ Link, Alan Stern, Philip Lubin, Erika Nesvold, Trevor Kjorlien. Trevor asked this panel a number of open questions, with particular emphasis on how Interstellar travel might be achievable in the future, and why thinking about it today could bring immediate benefits. AJ Link was particularly interesting as he challenged the audience on the accessibility of space to disabled people, and the need to outreach towards all the communities that might usually be omitted from space research.

About the Author

Michel Lamontagne, Ingenieur senior principal chez CIMA+, is a bit of a "Renaissance Man" - visionary, artist and practical engineer. He holds first and masters degrees from Université du Québec à Chicoutimi and has been a mechanical engineer in many aspects of building systems for 25 years.

Michel was the co-leader, with Robert Freeland III, of the Icarus Firefly design study for an interstellar probe propelled by Z-pinch fusion, see *To the Stars in a Century: Z-Pinch fusion & Firefly Icarus* by Patrick Mahon in Principium 22, August 2028 (i4is.org/principium-22/).

He is a renowned imaginer of spacecraft and space technology, including Firefly on the cover of Principium 22, a worldship fleet on the cover of Principium 30, a worldship interior on the cover of Principium 31 and an image of Firefly close to Jupiter on the back cover of Principium 41, the issue distributed at IRG23, which he reports here.

In Principium 32 February 2021 (i4is.org/principium-32/), *Worldship and self replicating systems*, Michel considers the requirements for worldships and a worldship-building society and concludes that worldships can be a relatively early part of a society beginning to occupy the solar system with little impact on its economies or ecosystems (i4is.org/wp-content/uploads/2021/06/Worldship-and-self-replicating-systems-Principium32-print-2102221659-opt.pdf).

On Lasers and Lagrange Points – 8th Interstellar Symposium

Colin Warn

Colin Warn is a Music Producer, Coder and Rocket Propulsion Engineering Student. Having been recommended by Professor Andrew Higgins, the IRG23 host at McGill University, we asked him to report on the Symposium. Unfortunately transport problems meant he only joined on the second full day of the symposium but Michel Lamontagne (see previous report) is a Montreal local. This report adapted from medium.com/@DJVeaux. All images are credited to Colin.

Introduction

A few weeks ago I had the honor and privilege to attend and present at the 8th Annual Interstellar Symposium: This year held at the incredibly beautiful campus of McGill University, based in Montreal, Canada. This was my second time attending this conference, the first time being in Tuscon, Arizona. As it was when I last attended, this conference gathered a group of academics, artists, and engineers to answer the great existential question: How (and should) humanity travel to the stars?

To capture the discussions for future me and others to reminisce on, much like my writeup at the last conference [1]. This conference report will be written from the perspective that I feel the most natural writing in: My own. In the two years since my first Interstellar Symposium, I've had the fortune to take a job at Maxar as a propulsion engineer, working primarily on plasma thrusters for NASA's Lunar Gateway as well as a mix of other government defense programs. This job has been an incredibly invaluable experience, as it not only has helped me fill in the gaps of much of my self-taught propulsion knowledge, but also has really crystalized what knowledge isn't taught in textbooks that is crucial to making theoretical advanced propulsion systems a practical reality. This knowledge, acquired in the last couple of years, helped me be "less impressed, more involved" at this conference. I'm forever thankful to the Maxar propulsion team I work with for giving, and continuing to nurture, that skillset.

[1] medium.com/@DJVeaux/warp-drives-and-wormholes-the-2021-interstellar-research-group-symposium-865071f5abf4.

Day 1 — Monday

My conference started off a bit rocky: My flight from New York was delayed one day, so I ended up not flying in until Monday night. While disappointed that I missed most of the first day's worth of talks, was great to talk to some of the presenters from the day in the late afternoon happy hour.
I particularly enjoyed my conversation with Setthivoine You of Helicity Space. Discussing the technical development roadmap and promise of his magnetic-reconnection fusion drive (arc.aiaa.org/doi/10.2514/6.2020-3835) was incredibly insightful and taught me a lot: Everything from the thermal problems they're experiencing, to the lifetime problems due to channel erosion are all very analogous to problems we see on the plasma thrusters at Maxar. Also thankful for him in reminding me of one of the big benefits of a fusion drive: That once fusion ignition is achieved, there is a net positive energy gain from the actual fusion reaction. This means that their thruster wouldn't require an external power source to continue the reaction, unlike current electric propulsion which requires separate power sources such as solar arrays/nuclear fission plants.


Incredible turnout for "Interstellar Travel: Are We Ready?"
Cameo from Mathias Larrouturou from my first conference on the right, now enhanced with facial hair.

I was also excited to make it into Montreal in time for the major public talk of the symposium: "Interstellar Travel: Are We Ready?" It ended up being a great discussion between the principal investigator of the mission that went to explore Pluto (Alan Stern), an incredibly knowledgeable space lawyer AJ Link, amongst the cast of other very knowledgeable panelists from NASA and the University of Santa Barbara who we'll revisit later. Trevor Kjorlien, the moderator, was an absolute natural and did an incredible job fielding a list of interesting questions on topics ranging from space accessibility to the practical limitations of interstellar travel (an analogy from Trevor: If the distance from Earth to Alpha Centauri was a football field, our furthest spacecraft has travelled the distance of one index card).

Day 2 – Tuesday

The following day began my first full day at the conference. And as was the case at the last conference, the entire day was filled with some very smart people talking about some very cool ideas on well-crafted PowerPoint decks. Richard Norte, an incredibly energetic and engaging presenter, blew our minds with a counter-intuitive idea on making a solar sail reflective: Place a bunch of tiny holes roughly smaller than the wavelengths of light being reflected in the sail! Poking your own holes is definitely one way to get around the micrometeoroid problem in space.

Richard Norte, starring as himself.

His PhD-candidate student working with him on the technology, Lucas Norder, also quickly became a great post-conference friend to tour Montreal with as we found out he and myself were sharing the same hostel. Kid knows a lot about machine learning optimization, also has that great Dutch perspective on life. Very charismatic and hilarious, can't wait to hang out with him again. post-conference.


A crippled Lucas Norder, being carried to safety by a touring American on our journey around Montreal

The indelible Phil Lubin, very much the mastermind of the beamed energy technology upon which much of the conference wa built on, then gave a great update on the status of the first beamed energy module prototypes his lab has been working on. Though I keep in touch with him via yearly phone-calls/road-trips down Highway One to Santa Barbara, it was great to interact with him at the conference with a ton of other like minds. The Technology Readiness Level of his beamed energy system, the path forward to development, and its adaptation to industry for spacecraft mission-enabling profiles continue to be talking points that I revisit with him every year (and upon which I based my talk at this conference).

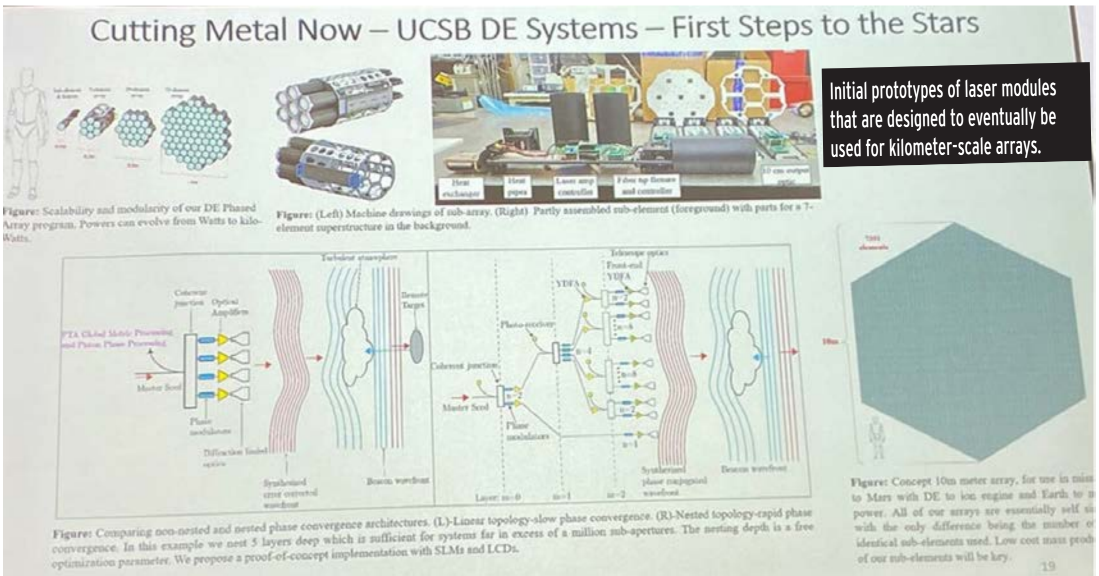
Phil Lubin et al at the public seminar: Interstellar Travel, Are We Ready?

Day 3 — Wednesday

Sonny White, fornerly of NASA's EagleWorks and now Director, Advanced Research & Development at Limitless Space Institute, moderating the morning series of lectures on Wednesday

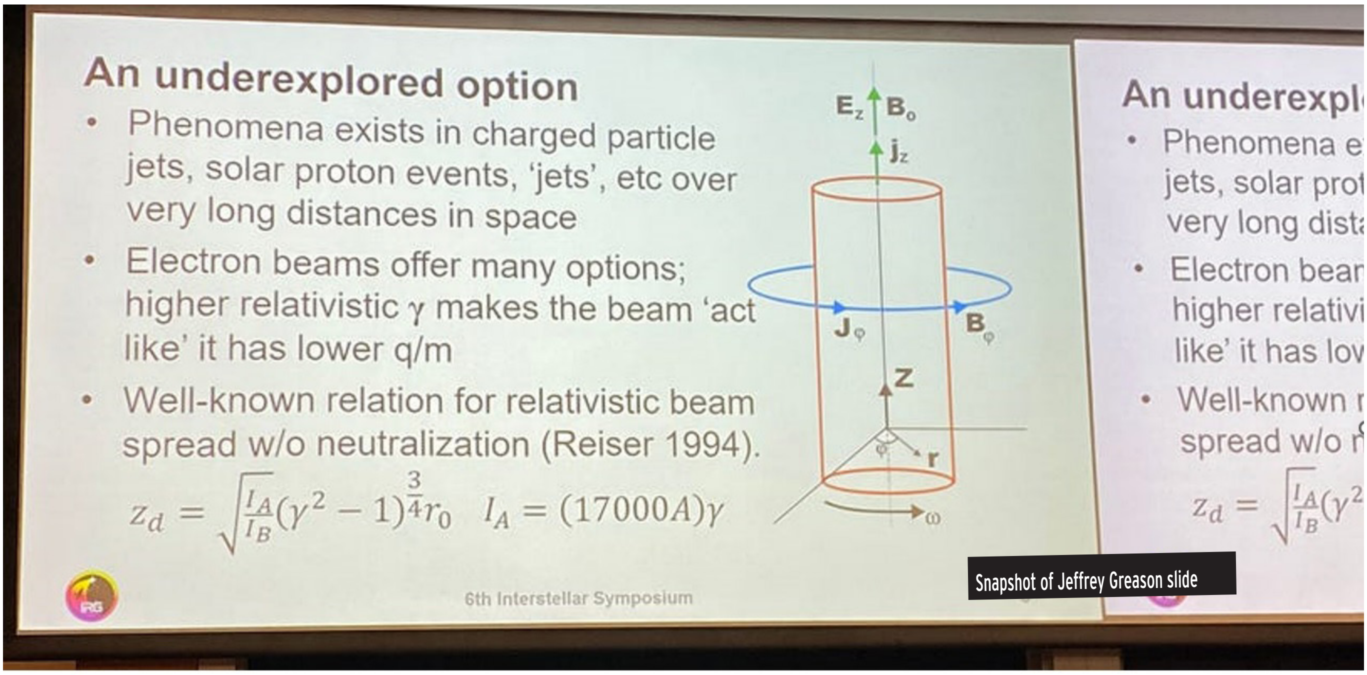
More than halfway through the symposium, the talks continued to be as strong as the previous days. Dr Rene Heller of the Max Planck Institute for Solar System Research, University of Göttingen, presented some interesting analysis on an interstellar sail mission profile that could explore all three stars of the Alpha Centauri system. Was interesting learning in his analysis that a sphere/hemisphere may be an ideal shape for such a sail such that any incident photon flux is uniformly distributed. It sounded like, talking with him afterwards, his group needed more work to determine the effects of such a sail interacting with the local magnetic fields in their mission profile (ie Eddy Current-induced forces on the spacecraft).

On the same day, Gerrit Bruhaug's presentation on interstellar communication via X-ray and Gamma-rays proved to be one that stimulated a lot of conversation and references in future talks. Could it be that other galactic systems are using these communication technologies, and we just don't have the equipment set up to listen to them? He also had a great poster on using electrostatic fields to solve the fissioning plasma core containment problem in nuclear gas core rockets that I want to shout out here as well. Also had a ton of great questions for the presenters throughout the entire conference, by far one of the more impressive attendees to engage with.



Initial prototypes of laser modules that are designed to eventually be used for kilometer-scale arrays.

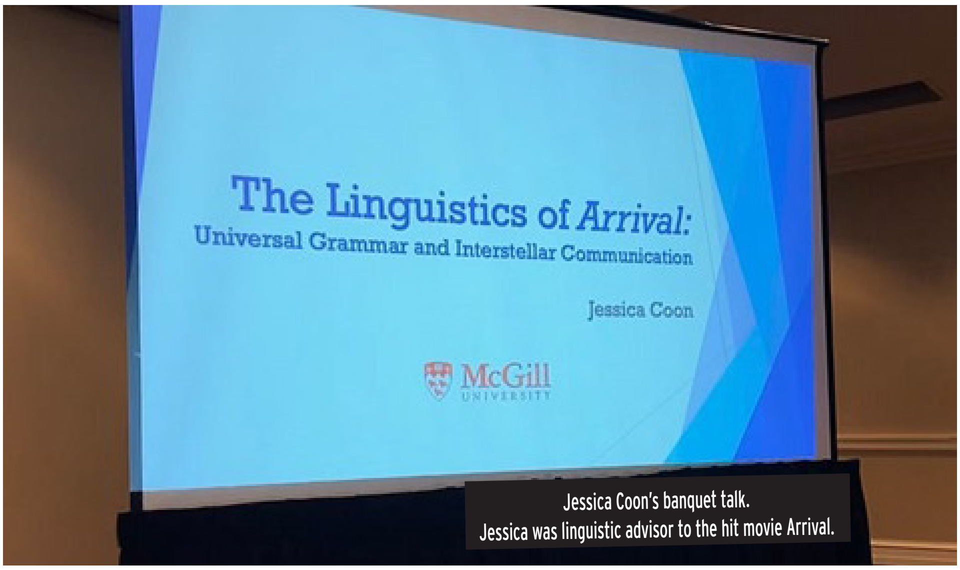
Tom Bone presented an interesting talk on using thermionic emission to harness the power of Bremsstrahlung-generated radiation (his first presentation as a master's student!). Additionally, Jeffrey Greason presented an interesting talk on revisiting the concept of using electron beams for beamed energy applications. Jeff per usual was as interesting of a speaker off the stage as he was on it.



Snapshot of Jeffrey Greason slide

Towards the end of the day it was exciting hearing about a mission concept Joseph Cassady and his team at Aerojet Rocketdyne put together to travel to interstellar objects using technologies readily available today. I'll be honest in that as I write this, I'm completely forgetting all the details of his talk, but it was great to see commercial industry proposing ideas at the conference. The forthcoming whitepaper from them is one to read when it comes out.

However, the highlight of the entire day was the banquet talk given by Jessica Coon, linguistic advisor for the hit box-office movie Arrival. In one hour, she gave a great high-level overview on everything linguistics: How all languages share a "Universal Grammar," that language's effect on thought is at best extremely subtle, and most importantly dispelling the myth that being a linguist is synonymous with being a polyglot. Topping that off with formally meeting NASA's Dr Les Johnson in person at dinner, through his wife as everyone does, Wednesday proved to be as eventful as the previous day.



Jessica Coon's banquet talk.
Jessica was linguistic advisor to the hit movie Arrival.

Day 4 – Thursday

The final day of talks, and the day in which I gave my own! The morning kicked off with a great overview from the Breakthrough Initiatives on the current state of work that's been dedicated to the widely acclaimed Breakthrough Starshot project. Was great to see the current state of sail stability analysis, laser array engineering schematics, and future work to continue to develop the technology that is currently humanity's best engineering solution to the problem that is interstellar travel.

After Breakthrough, I presented my talk on the coupling of beamed energy to potential future commercial interests: More specifically the coupling of beamed energy to electric propulsion, with its ability to scale better than other nuclear/solar power sources for certain mission profiles.

Subjectively I think the first half of my talk ended up being less-polished than I would've liked as I worked through the verbal tics born from cumulative nights of drinking and sub-optimal sleep to enable the engaging late discussions with fellow attendees at the top of the hotel. That said, from the conversations and comments at the end of the conference I think the talk went fine: My impression was that the key points were communicated to those who took an interest, and sedative to those who needed to catch up on sleep.

Rounded out the day with a great talk from Stephen Fleming on the promise of quantum computing-enabled optics to circumvent the Rayleigh limit: Potentially enabling up to a couple of orders of magnitude increase in imaging resolution.

A quick visit to the Canadian Space Agency and a Montreal-sponsored "water tornado" on our bus ride back rounded out the conference. To tie up the final loose ends that I missed from the Monday portion of the conference, I ended up talking to Emmanuel Duplay about his initial prototype for a laser-thermal propulsion system. Incredibly interesting to learn how he and his team are using lasers to ignite and sustain a plasma that heats the propellant gas (something that hasn't been explored for rocket propulsion in decades). They had problems igniting plasma with a spark plug, so they ended up transitioning to a tungsten rod to get a more consistent/efficient ignition. Excited to see the forthcoming whitepaper from him towards the end of the year formally presenting what we informally discussed.

View of downtown Montreal from the top of the conference hotel.

Presentation from yours truly.

Canada Arm: Much bigger in person than on TV.

Conclusion

Re-reading my writeup of the 2021 Interstellar Symposium, I find it surreal that many of the novel conversations I found unreal back then are now just a part of my daily life. During my day job I'm discussing the thruster-life implications of a plasma thruster whose confining magnetic field isn't optimized for its propellant, the next week I'm discussing with one of the top researchers of the Max Planck Institute whether the effects of stellar magnetic fields compromise his as-presented interstellar mission profile. To think these sorts of conversations are habitual for me now is a bit surreal: Especially given I didn't know basic trigonometry six years ago when I decided to make the transition from music production to rocket science.

A huge thank you to all the fellow attendees, but most importantly Andrew Higgins and his army of McGill volunteers who flawlessly organized and executed a conference to remember. Going to be hard for Texas to top this when the 9th Interstellar Symposium comes to town in 2025, will be exciting to revisit and do this all again in two years.

Texas A&M University, College Station, Texas. Venue of the 9th Interstellar Symposium in 2025

The Initiative & Institute for Interstellar Studies

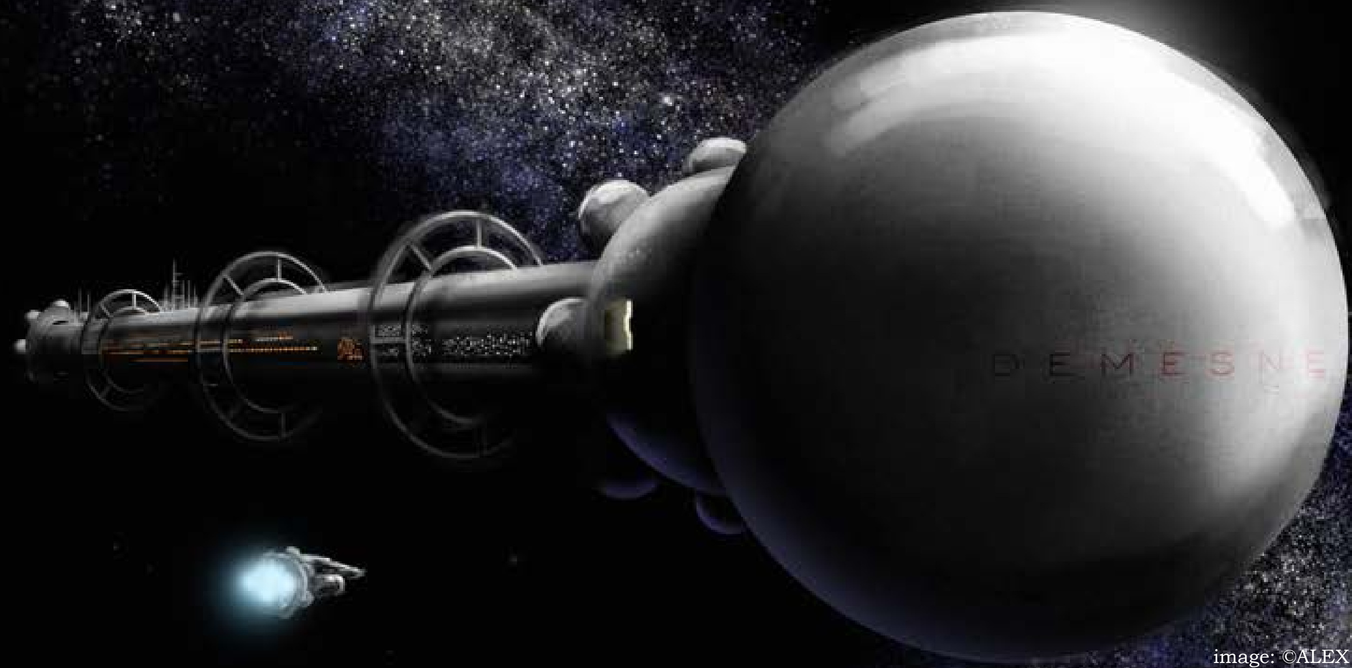


image: ©ALEX STORER

JOIN US

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 engineering of course! ...and much more....
Some of us have PhDs, some masters and first degrees and others simply have talents! What we all share is enthusiasm for the interstellar future of humanity. We have about 20 active team members, led by -

- **Dr Andreas Hein: Executive Director/Technical Director -** andreas.hein@i4is.org
- **Robert G Kennedy III: President i4is USA -** robert.kennedy@i4is.org
- **Rob Swinney: Education Director -** rob.swinney@i4is.org
- **John I Davies: Editor Principium -** john.davies@i4is.org
- **Tam O'Neill: Manager Membership/Website team -** tam.oneill@i4is.org

Join the team if you can help - become a member if you simply want to support our work.

Contact: info@i4is.org

Principium: tinyurl.com/principium

Web: i4is.org

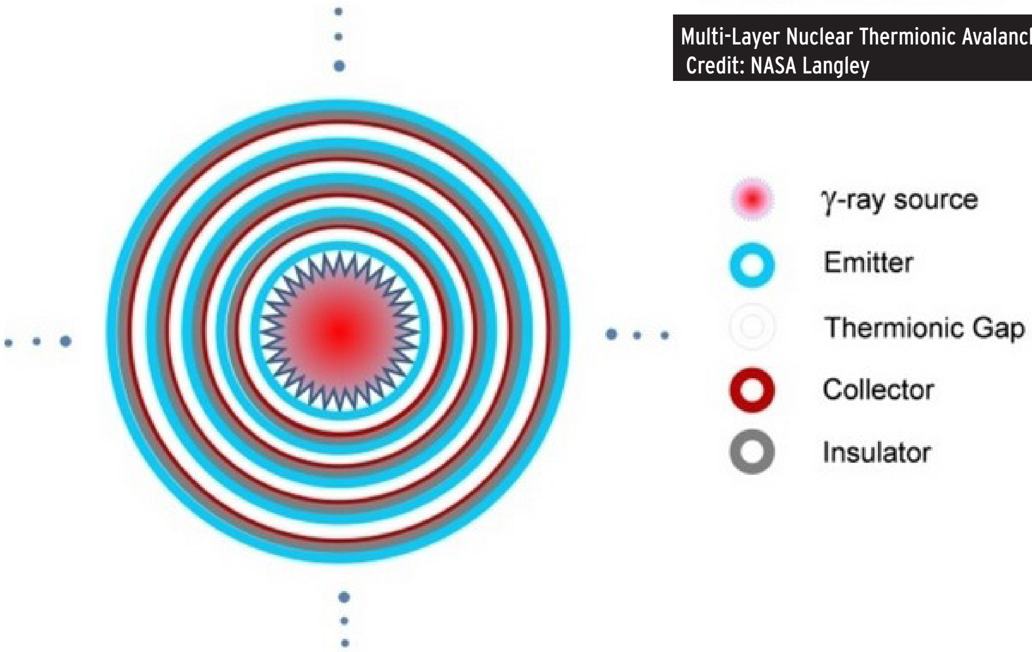
@I4Interstellar

John I Davies reports on recent developments in interstellar studies

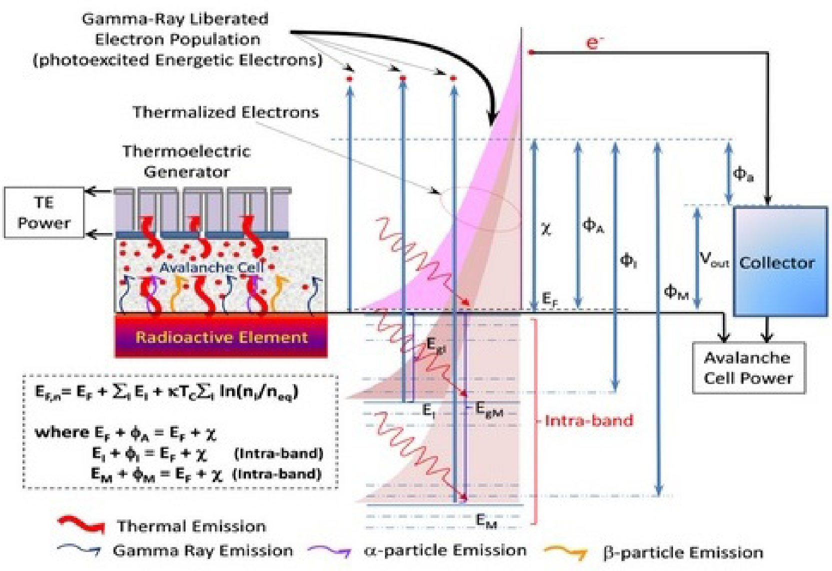
An RTG replacement?

A radioisotope thermoelectric generator (RTG) has been an essential component of deep space missions for many decades [1] since solar power is subject to the inevitable inverse square law (the energy we get near Earth, one AU from the Sun, is reduced at the distance of Saturn, ten AU from the Sun, by $10^2 = 100$ times less). A patent from NASA Langley Research Center offers an alternative, the Multi-Layer Nuclear Thermionic Avalanche Cell (technology.nasa.gov/patent/LAR-TOPS-335). It converts gamma rays (γ) directly into electrical energy with claimed benefits over an RTG -

- More simple and efficient
- Ease of manufacturing using well-established semiconductor manufacturing techniques
- Scalable to very small sizes "as small as a button cell"
- Can use isotope sources with a half-life of nearly a century



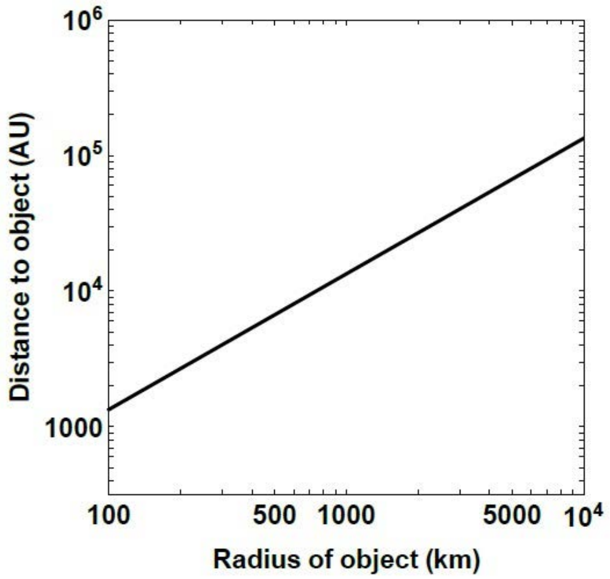
Multi-Layer Nuclear Thermionic Avalanche Cell.
Credit: NASA Langley



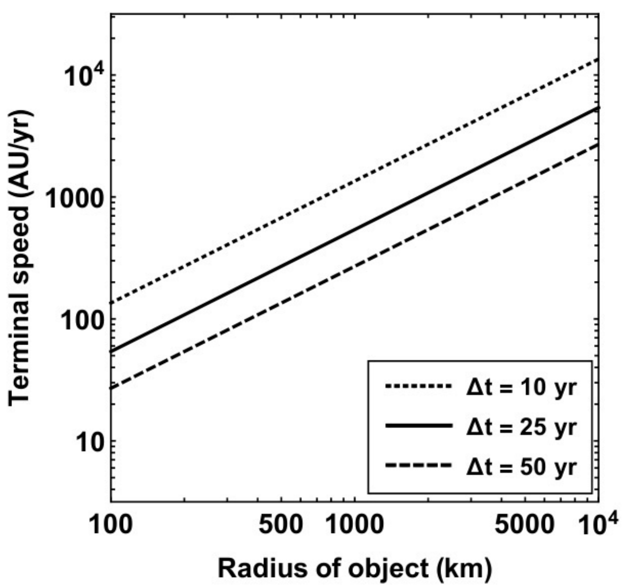
[1] en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator#Space

Chasing Nomadic Worlds

In *Chasing Nomadic Worlds: A New Class of Deep Space Missions* (arxiv.org/abs/2307.12411), three of the most active i4is experts, Manasvi Lingam, Andreas M Hein and T Marshall Eubanks [1], discuss nomadic worlds, ie objects not gravitationally bound to any star or star system. The team report they are of great interest to planetary science and astrobiology. Notably they have attracted attention recently due to constraints derived from microlensing surveys and the recent discovery of interstellar planetesimals. In this paper, Lingam et al roughly estimate the prevalence of nomadic worlds with radii of 100 km≤R≤10,000 km. The cumulative number density $n_>(>R)$ appears to follow a heuristic power law given by $n_> \propto R^{-3}$. Therefore, smaller objects are probably much more numerous than larger rocky nomadic planets, and statistically more likely to have members relatively close to the inner Solar system. Results suggest that tens to hundreds of planet-sized nomadic worlds might populate the spherical volume centered on Earth and circumscribed by Proxima Centauri, and may thus comprise closer interstellar targets than any planets bound to stars. The team provide the first systematic analysis of the feasibility of exploring these unbounded objects via deep space missions. They investigate what near-future propulsion systems could allow us to reach nomadic worlds of radius >R in a 50-year flight timescale. They conclude that objects with R~100 km are within the purview of multiple propulsion methods such as electric sails, laser electric propulsion, and solar sails. In contrast, nomadic worlds with R~1000 km are accessible by laser sails (and perhaps nuclear fusion), thereby underscoring their vast potential for deep space exploration.



The characteristic distance to a nomadic world (y-axis) with radius > R (x-axis) based on Lingam et al equation 3.
Credit: Lingam et al, Figure 1 (caption adapted)



The desired terminal speed associated with a propulsion system (y-axis) to reach a nomadic world with radius > R (x-axis) for three different choices of the flight duration: Δt = 10 yr, Δt = 25 yr, and Δt = 50 yr; this plot is generated by invoking Lingam et al equation 21.
Credit: Lingam et al Figure 2 (caption adapted)

[1] Lingam is Assistant Professor in the Department of Aerospace, Physics and Space Sciences at the Florida Institute of Technology. Hein is Associate Professor of Space Systems Engineering at SnT, University of Luxembourg and Eubanks is Chief Scientist at Space Initiatives Inc

Did Oumuamua leave us a memento?

i4is astrodynamicist Adam Hibberd has again been exploring trajectories and asks the question - *Could a Bolide Listed in the CNEOS Database have Originated from 1I/'Oumuamua?* (https://arxiv.org/abs/2307.09085). He expects to publish a peer-reviewed version soon.

His calculations show that only a relatively small amount of extra push, deltaV, would have been required for a fragment from the enigmatic ISO, the first and only of its kind so far observed, to impact Earth and that at least one object which "fits the bill" has been observed.

It's worth recalling that `Oumuamua came within 0.16 astronomical units of Earth as it headed back out of the Solar System. That's 24 million km. Since the Moon orbits at about 400,000 km Oumuamua was just 60 times further away and we imagined an astronaut on its surface looking homewards at the Earth and Moon on the cover of Principium 20, in February 2018 (i4is.org/principium-20/).

1I/`Oumuamua may be boring

In *Acceleration of 1I/`Oumuamua from radiolytically produced H^2 in H^2O ice* (arxiv.org/abs/2303.13698), Jennifer Bergner (UC Berkeley) and Darryl Seligman (Cornell University), seem to have found a plausible (and for those of us who love a mystery, boring!) explanation for the non-gravitational acceleration of our first observed interstellar object (ISO). In fact 1I was slowing as it left the vicinity of the Sun, as the Sun's gravity was pulling it back. But it wasn't slowing as much as it should have done, there must have been a non-gravitational force of some sort and comets experience this normally - it's just that you see lots of outgassing in the form of the tail and a halo around the comet itself. But nothing was seen around 1I.

They point out that a body containing large quantities of H_2O irradiated by galactic cosmic rays (GCRs) will be gradually converted to a mixture of water and its component elements hydrogen and oxygen, also in molecular form. It will still be extremely cold out there, around three degrees above absolute zero, and the GCRs won't warm things up much. So what happens when this icy mixture gets close enough to the sun for melting? The most easily liberated element, the hydrogen, starts to be released and you get outgassing - but it remains invisible. Bergner and Seligman work out that this outgassing is more than sufficient to explain the non-gravitational acceleration. They also discuss isotropic (ie in all directions) outflow versus collimated (in one direction) outflow. If isotropic then the forces would balance out so there must be some collimation and they say "In reality, the outflow geometry is likely in between these cases".

Hydrogen is hard to spot - hence the mystery. And maybe it is now solved if we assume there is a good explanation for collimation of the outflow towards the Sun, as there seems to be in conventional comets. Let's see how the next such body behaves? But it's now been a long time - 2017-2023=6 years.

Nuclear rocket by 2027?

Lockheed Martin has been announced as prime contractor to NASA and DARPA to deliver a nuclear thermal rocket, the Demonstration Rocket for Agile Cislunar Operations (DRACO) to be in orbit in 2027. Lockheed Martin will have overall accountability for spacecraft design, integration, and testing - working with other industry partners. The nuclear fission reactor (en.wikipedia.org/wiki/Nuclear_thermal_rocket) powering the DRACO engine is being designed and built by BWX Technologies [1].
Nuclear thermal rockets offer a more efficient means of propulsion for regular and long distance inter-orbit than chemical rockets together with greater propulsive power than electric systems such as ion thrusters.

Lockheed Martin visualisation of spacecraft driven by BWX Technologies DRACO engine

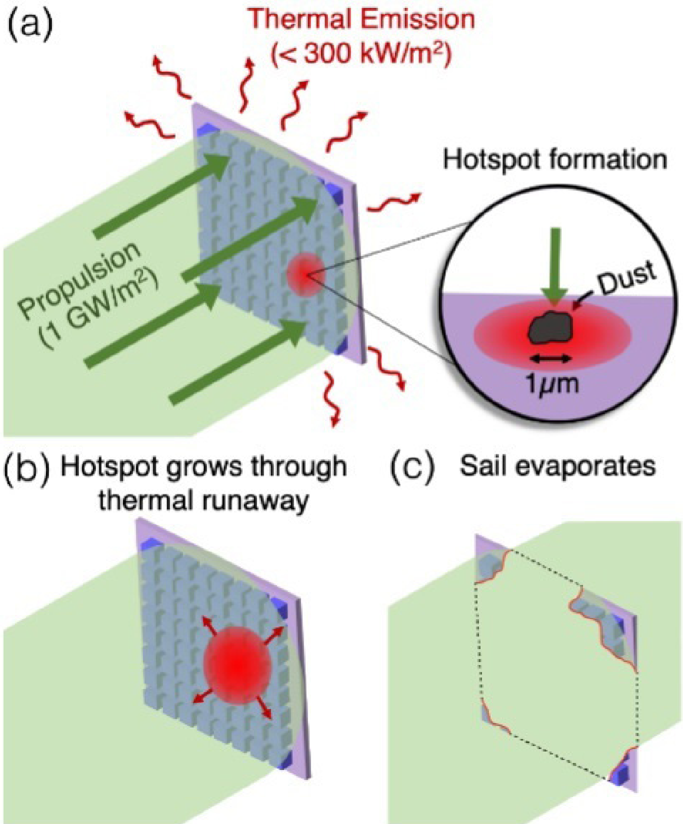
Solar cells from lunar regolith

Blue Origin has manufactured a working solar cell prototype from lunar regolith simulants (www.blueorigin.com/news/blue-alchemist-powers-our-lunar-future). If this surmounts the hurdles between laboratory and full scale production on the moon then this could be an important step towards a solar system economy - a vital early step on the interstellar path for humanity [2].

The complexities of existence

In *Life in the Cosmos: Paradox of Silence and Self-Awareness* (arxiv.org/abs/2307.05507), Jonathan H Jiang et al suggest that artificial intelligence has the potential to challenge traditional definitions of life, They suggest we have a profound responsibility as the only known life forms, that we suffer from cosmic loneliness arising from our "magnificent" self-awareness.
We have a verdant, biologically diverse Earth but an austere, seemingly lifeless backdrop of our solar system, cosmic solitude, yet intriguing mysteries. They call this a 'Proximity Paradox'. Can exoplanets give us hope to relieve our loneliness? If AI can achieve self-awareness then is SETI looking for our cousins or their non-biological descendants?

[1] BWXT to Provide Nuclear Reactor Engine and Fuel for DARPA Space Project
www.bwxt.com/news/2023/07/26/BWXT-to-Provide-Nuclear-Reactor-Engine-and-Fuel-for-DARPA-Space-Project
www.bwxt.com/what-we-do/advanced-technologies/space-nuclear-propulsion
[2] One important further step might be to transport massive quantities of these cells and their infrastructure into space where scaling is not restricted by gravity and the Sun always shines. But how can we do this economically at the scale required?



a) A 10 square metre laser sail (purple square) made of a Si/SiO2 [silicon / silicon dioxide] metasurface is accelerated through space by the radiation pressure from a 10 GW 1.55 μm laser (green arrows). A 1 μm zodiacal dust particle on the sail absorbs the impinging laser light and creates a hotspot on the sail. b) The hot area of the sail grows through a thermal runaway process wherein the Si absorbs more laser energy than can be locally thermally emitted by the sail. c) The sail is ultimately vaporized.
Credit: Jaffe et al Figure 1

Dust spots can destroy laser sails

In *The Effect of Dust and Hotspots on the Thermal Stability of Laser Sails* (arxiv.org/abs/2303.14165), Gabriel R Jaffe (University of Wisconsin-Madison) et al [1] look at the danger that interplanetary dust poses to the survival of a laser sail during its acceleration phase. They show how localised heating from a single optically absorbing dust particle on the sail can initiate a thermal-runaway process that rapidly spreads and destroys the entire sail.
They explore two potential mitigation strategies -
• increasing the in-plane thermal conductivity of the sail to reduce the peak temperature at hotspots - thus causing the hot spot to be larger but therefore cooler
• isolating the absorptive regions of the sail which can burn away individually - "quarantining" hot spot regions
For the first strategy they suggest heat propagation measured in microseconds from a spot initially at 300 K with a 1 GW per square metre incident laser light at wavelength at 1.55 μm. For the second they suggest a laser sail composed of an array of small reflective segments of silicon resonators on a silicon dioxide substrate so that each segment is surrounded by a continuous strip of silicon that serves as a “thermal runaway fuse”.
They warn that the zodiacal dust cloud [2] presents a direct danger to the thermal stability of laser sails under illumination.
Either absorptive dust particles can embed themselves in the sail after probes are lifted into space but before laser acceleration or they can heat regions of the sail through high velocity impacts during laser acceleration. Both of these can be the source of hot spots.
They model the processes and the effects of their proposed mitigation strategies, concluding that their results pave the way for laser sail designs that are thermally stable during acceleration despite the "dusty vacuum" of the interplanetary space from which they would be launched.

[1] Contributors from University of Wisconsin-Madison and Korea Advanced Institute of Science and Technology
[2] This interplanetary dust cloud is the source of the zodiacal light. en.wikipedia.org/wiki/Interplanetary_dust_cloud

Turning into a plant?

In *To Create Plant-Like Astronauts Who Can Adapt to Eternal Interstellar Expeditions*, Tianxi Sun suggests humans need to adapt to live permanently in space (www.preprints.org/manuscript/202306.1302/v1). The paper suggests transforming human astronauts into plant-like astronauts with green skin and blue blood, capable of undergoing photosynthesis to produce oxygen and carbohydrates using the abundant light energy from stars. It would also protect against cosmic ray radiation and extremely low interstellar temperatures. All are hazards that "the human race will always face in its eternal interstellar expedition." Tsiolkovsky suggested this sort of development long ago!

Phased array of phased arrays for scalable laser systems

In *Phased array of phased arrays (PAPA) laser systems architecture,* [1] by Paul F McManamon and William Thompson, US Air Force Research Laboratory (AFRL), an architecture including three major subsystems is proposed -

- a phased array of laser sources (diode-pumped fiber lasers or waveguide lasers)
- wavefront con sub-aperture trol and electronic beam steering
- subaperture receiver technology.

The paper claims that combining these three technologies results in a system that has graceful degradation, can steer to as wide an angle as individual optical phased array sub-apertures, and can be scaled to high power and large apertures through phasing of a number of sub-apertures. [1].

Dystopia and Astrotopia

In our last issue Patrick Mahon reviewed Mary-Jane Robinson's *Astrotopia: The Dangerous Religion of the Corporate Space Race*. A more recent piece in the Guardian newspaper by Philip Ball, *Should we colonise other planets?* (19/8/23), takes a similar view to Professor Robinson but seems to make a weaker case. Philip Ball is a veteran (20 year) science writer and an editor at Nature so he is worth taking seriously. But Ball's piece is a patchwork of good insights and doubtful assumptions. Early on, he makes an unsupported statement "currently a crewed mission to Mars would be prohibited by the permitted radiation limits for astronauts. We don't have any solutions for that problem". This is indeed one of the hazards of all human travel outside Earth's Van Allen belts (see www.nasa.gov/feature/human-spaceflight-hazards) but much research and development is already under way to shield against the regular effect of solar particles and galactic cosmic rays and the intermittent threat of solar storms. He suggests that the Martian atmosphere makes it more attractive to humans than the Moon but does not support his assertion.

He seems to hold the common view no human problems can be solved off-Earth - but power from space is very possible within a couple of decades, satellite communications delivers ubiquitous broadband bringing us closer together and Earth observation in many forms is already helping us.

He's right that colonising Mars will be too late to solve our climate issues and that moving off-Earth is a fantasy substitute for good asteroid defence (but see Neil Stephenson's *Seven Eves* for a plausible though gloomy counter-scenario - reviewed in *The Orbits of Seveneves*, Principium 20, Feb 2018).

He's also right about the libertarian fantasy element (again see Patrick Mahon's review of M-J Robinson's *Astrotopia*). But Twitter and Amazon are, as employers, not good models for space "colonists" social position. Cheap labour will not be feasible in space for a very long time. A better example in support of his argument would be Neil Blomkamp's film *Elysium*. The rich vs poor roles are reversed in a very different technological dystopia.

Space is hostile as he says but it also has big advantages such as unlimited solar power, low energy travel outside planetary gravity wells and lots of useful materials available. He also makes a rather silly parallel between possible cities in the Amazon and space settlements. There is no "natural" environment out there to destroy.

This is a topic well worthy of debate but Ball makes a poor advocate of the "solve our problems down here first" case.

[1] P F McManamon and W Thompson (both US Air Force Research Laboratory) *Phased array of phased arrays (PAPA) laser systems architecture*, Proceedings, IEEE Aerospace Conference, Big Sky, MT, USA, 2002, www.researchgate.net/profile/Paul-Mcmanamon-2/publication/3968609_Phased_Array_of_Phased_Arrays_PAPA_Laser_Systems_Architecture/links/00b7d53c6a42f3342d000000/Phased-Array-of-Phased-Arrays-PAPA-Laser-Systems-Architecture

◀ Deep Space Optical Communications (DSOC)

A recent NASA announcement observes that "radio frequency communications from deep space are approaching their bandwidth limit, raising the need for upgraded communications systems. Future space missions, meanwhile, are expected to transmit huge volumes of science data, including high-definition images and video, significantly increasing the bandwidth required" [1] and "NASA's Deep Space Optical Communications (DSOC) experiment is the agency's first demonstration of optical communications beyond the Earth-Moon system. DSOC is a system that consists of a flight laser transceiver, a ground laser transmitter, and a ground laser receiver. " The transceiver will be an addition to the NASA Psyche spacecraft, with primary mission to the metal-rich asteroid of the same name.
DSOC will operate from shortly after launch to a gravity-assist flyby of Mars.

DSOC's flight transceiver can be identified by its large tube-like sunshade on the Psyche spacecraft, as seen here inside a clean room at JPL
Credit (image and caption) NASA/JPL-Caltech.

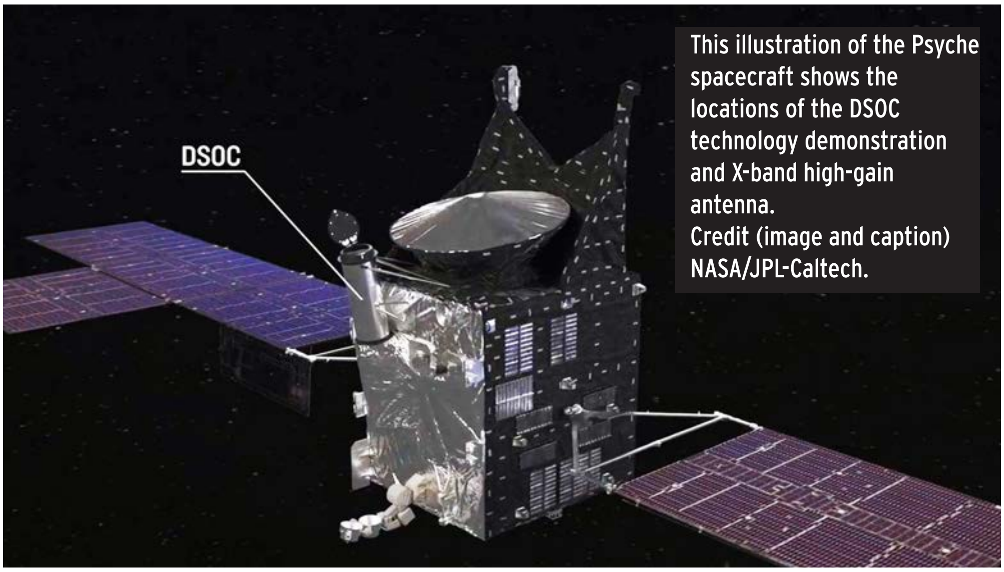
DSOC goals will demonstrate -

• flight laser transceiver and ground systems "lock" onto each other's laser signals during DSOC's calibration and commissioning phase.

• Specified downlink data rates as the Psyche spacecraft travels farther away from Earth, decreasing with increasing distance from Earth.

• Data uplink up to a distance of 1 astronomical unit.

Operations for two years from the Psyche mission launch, one to two contacts per week for the duration of the technology demonstration.



This illustration of the Psyche spacecraft shows the locations of the DSOC technology demonstration and X-band high-gain antenna.
Credit (image and caption) NASA/JPL-Caltech.

[1] Deep Space Optical Communications (DSOC), www.nasa.gov/mission_pages/tdm/dsoc/index.html

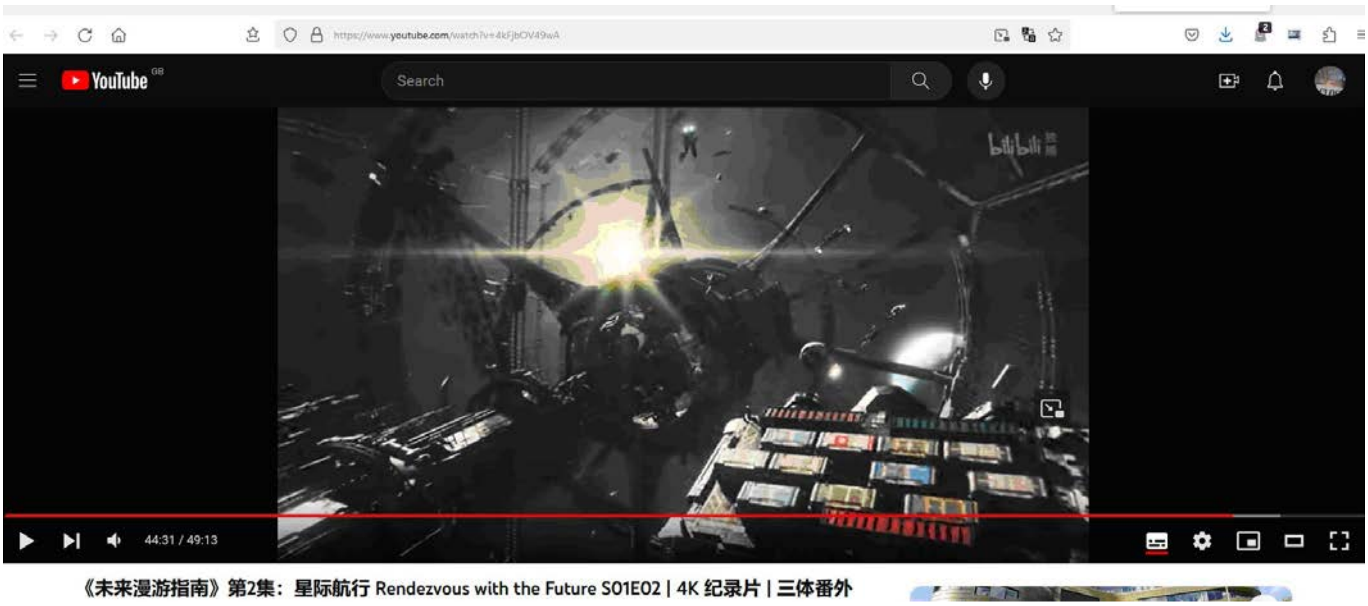
▶

Rendezvous with the Future

i4is Executive Director Andreas Hein has assisted a number of media organisations over the years. A recent major project to which he contributed is, *Rendezvous with the Future*, a BBC/Bilibili co-production [1]. It's based on the thinking of that most prominent of Chinese writers of science fiction, Liu Cixin [2]. The three episodes have been available on Youtube -
Episode 1 First Contact www.youtube.com/watch?v=hKWqdM_FQxA
Episode 2 Voyage to the Stars www.youtube.com/watch?v=4kFjbOV49wA
Episode 3 www.youtube.com/watch?v=4oDhA09bX9Q
- but are not accessible right now. We will let i4is members and readers know if and when access again becomes available.

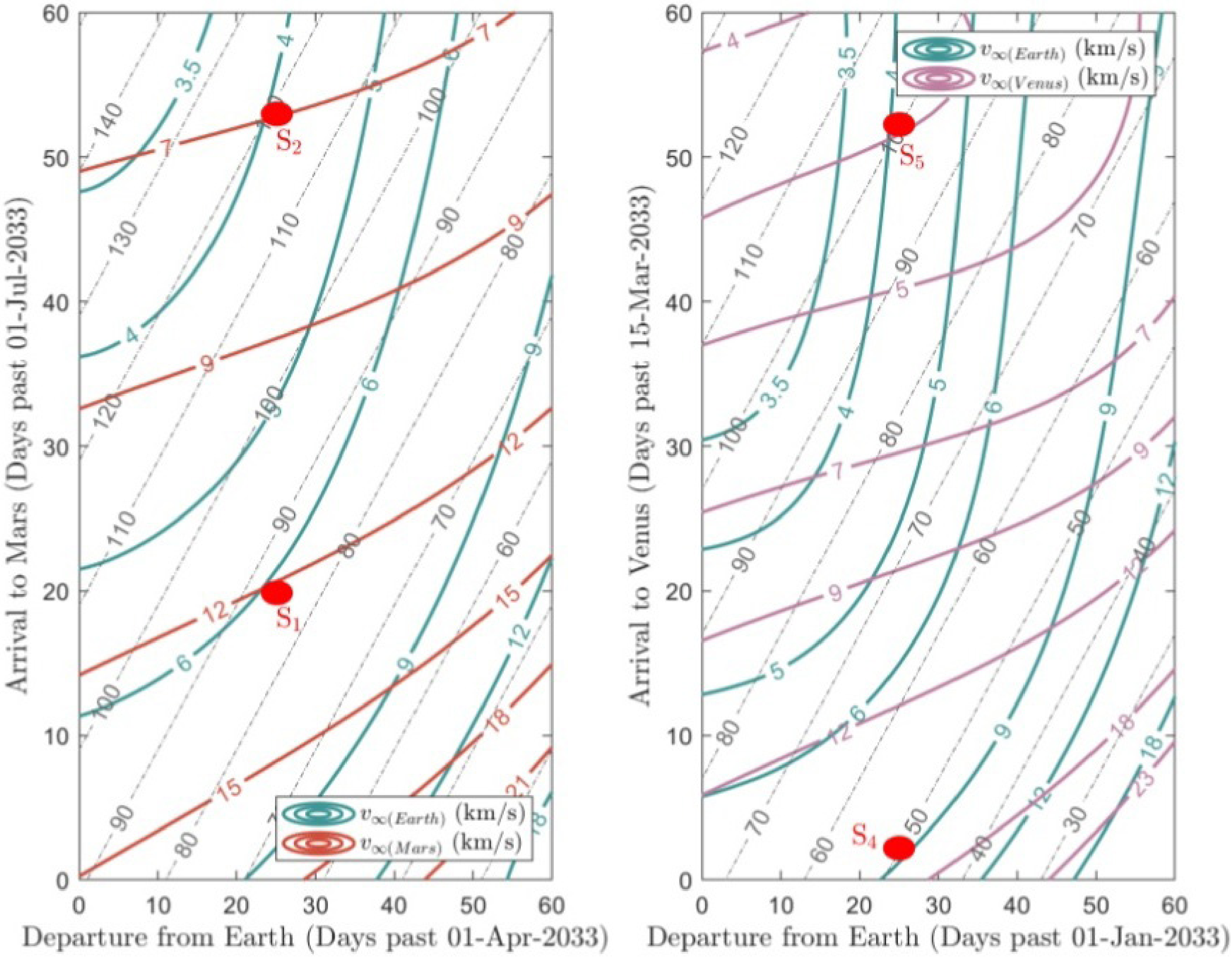
Andreas contributed especially to Episode 2, Voyage to the Stars but i4is' ideas for a worldship appear in other episodes too. They use visualisations based on the one we developed for Project Hyperion about 10 years ago and which Maciej Rebisz illustrated. It appears on multiple occasions, for example, at the end of Episode 2, where an exoplanet is settled via drop ships released from a generation ship. It also appears briefly in episode 1 and 3.

As Liu Cixin observes in the series "I think if humans want to survive, our only choice is to expand our living space in the universe. Like HG Wells once said: Human beings will either fill the universe or perish completely. There is no other choice."
We have a continuing interest in worldship thinking - see the work of i4is artist/engineer Michel Lamontagne on the front cover image to this issue and numerous contributions to Principium over the intervening years. It will also be a major part of our presence at the 2024 SF Worldcon - glasgow2024.org.



Worldship from Episode 2 Voyage to the Stars www.youtube.com/watch?v=4kFjbOV49wA at 44:24

[1] More details at en.wikipedia.org/wiki/Rendezvous_with_the_Future
[2] en.wikipedia.org/wiki/Liu_Cixin



Porkchop plots of hyperbolic excess velocities v∞ in the case of Earth departure in a 2033 launch window for Mars (left) and Venus (right). The curves of TOF [Time of Flight] reported are given in steps of ten days and highlighted by the dashed grey lines.
Credit: Giovanni Santi et al. FIG. 4

Laser sails to explore the Solar System

In *Swarm of lightsail nanosatellites for Solar System exploration* (arxiv.org/abs/2208.10980) Giovanni Santi, Universita di Padova, et al present a study of a space mission which employs nanosatellites driven by an external laser source impinging on an optimized lightsail - advocating this as a technology to launch swarms of spacecraft into the Solar System. Applications include heliosphere exploration and planetary observation. By varying the ratio between the sail area and the payload weight and the laser power, they suggest inserting nanosatellites into different hyperbolic orbits with respect to Earth, reaching targets in a relatively short time. Nanosatellites of the order of 1 kg mass are described with particular attention to the telecommunication subsystem and fabrication of the lightsails - verifying the sail thermal stability during the thrust phase and the mechanical stability of the lightsail. Potential applications of the proposed technology are discussed, including mapping of the heliospheric environment.

Statistical deltaV for fast ISO intercepts

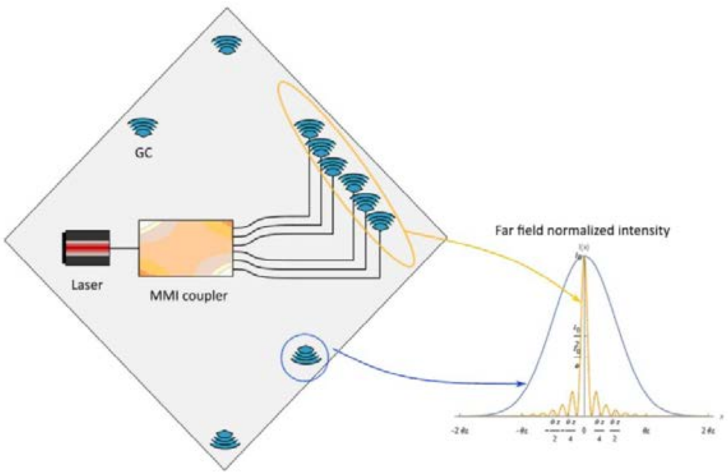
In *Interstellar Object Uncertainty Evolution and Effect on Fast Flyby Delivery and Required Delta-V* (arxiv.org/abs/2307.11887) Declan M Mages, Davide Farnocchia, Benjamin Donitz (all JPL/Caltech) consider (relatively) prompt missions to intercept new ISOs. They assume "With current propulsion technology, rendezvous with these objects is likely infeasible, and thus the maximum science return results from a rapid response flyby and impactor" and even for this restricted class of missions they "present significant challenges to navigation". They "derive the final delivery accuracy of fast flyby spacecraft to the ISO and required statistical delta-v for navigation" but "...find that these two challenges can lead to hundreds of meters-per-second or even kilometers-per-second of required statistical delta-v for navigation, reduce delivery accuracy to hundreds of kilometers, and make autonomous navigation a requirement." They find "a counter-intuitive result is that for a rapid response mission, rather than launching to the target as soon as possible, it can instead be more optimal to launch as late as possible."
Thus, if a mission launches late, the arguments against a chase mission may, to some extent, fall away. And since 1I/'Oumumua is the sole reprentative of its object class it might be the best subject for such a mission - but maybe this extrapolation becomes invalid for an object now very distant from us.

Traversable wormholes

In *Traversable wormholes with double layer thin shells in quadratic gravity* (arxiv.org/abs/2305.06829) Joao Luís Rosa et al suggest that, in quadratic gravity [1], the junction conditions permit the appearance of double layer thin shells. They explore this property of the existence of double layers in quadratic gravity to find and study traversable wormholes in which the two domains of the wormhole interior region, where the throat is located, are matched to two vacuum domains of the exterior region via the use of two double layer thin shells. Single layer thin shells are also admitted within their theory, and they present thin shell traversable wormholes.

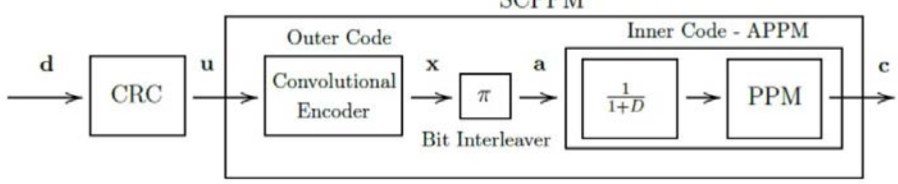
The Tree of Light

In a new paper *The Tree of Light as interstellar optical transmitter system*, Elisa Bazzani et al, University of Padova, Italy (arxiv.org/abs/2308.01900), suggest an architecture for an interstellar downlink transmitter on lightsail probe. The optical signal would be distributed to several optically coherent emitters on the sail from a central laser via a Multi-mode interference (MMI) coupler to multiple grating couplers (GCs). The emitters collectively form an Optical Phased Array (OPA) which produces a more powerful main emission lobe (and possibly steers the main emission lobe to the desired pointing angle). The downlink receiver would distinguish individual probes using the differential Doppler shift resulting from the slight variations in cruise velocity in a large swarm of probes. Channel coding would use serially-concatenated PPM (SCPPM).



Tree-of-Light working principle: the seed laser power, coming from the tree trunk, is divided into branches by means of a Multi-mode interference (MMI) coupler, which delivers the signals to N leafs, that are grating couplers, not to scale. The individual GC couples the fundamental Gaussian mode (blue), while the array, by exploiting the GCs interferences, gives rise to a narrower main lobe (yellow). Credit (image and caption) Bazzani et al Figure 1

Conceptual scheme of the SCPPM encoder. Credit(image and caption) Bazzani et al Figure 18

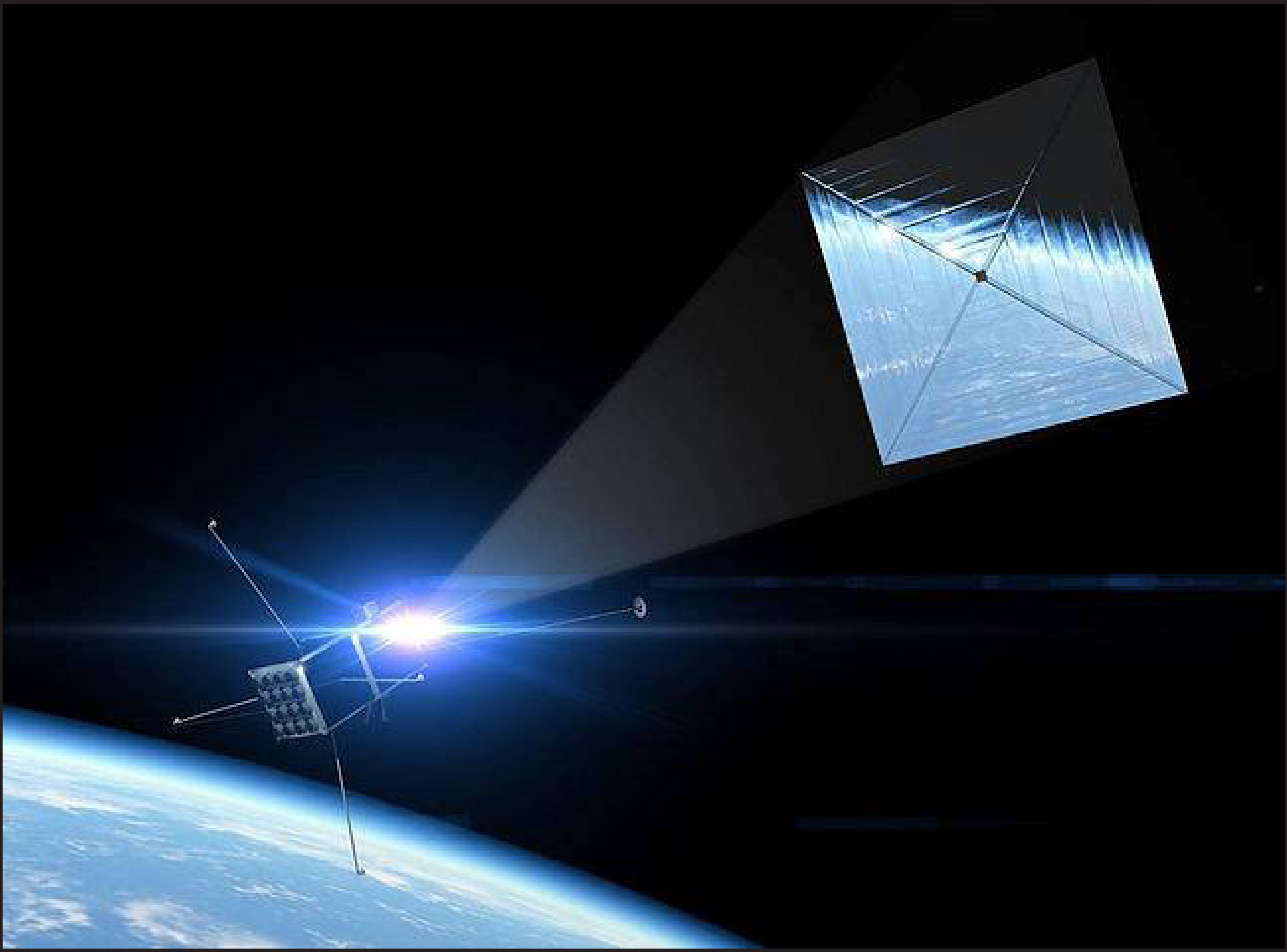


[1] See *On Quadratic Gravity*, Donoghue and Menezes 2021 arxiv.org/abs/2112.01974

JOIN I4IS ON A JOURNEY TO THE STARS!

Do you think humanity should aim for the stars?

Would you like to help drive the research needed for an interstellar future...
... and get the interstellar message to all humanity?



The membership scheme of the Initiative & Institute for Interstellar Studies (i4is) is building an active community of enthusiasts whose sights are set firmly on the stars.
We are an interstellar advocacy organisation which:

- conducts theoretical and experimental research and development projects; and
- supports interstellar education and research in schools and universities.

Join us to support our work and also get:

- members newsletters throughout the year
- member exclusive posts, videos and advice;
- advanced booking for special events; and
- opportunities to contribute directly to our work.

To find out more, see www.i4is.org/membership
Discounts for BIS members, seniors & full time students!

Interstellar flyby scientific data downlink design

John I Davies

As earlier articles in Principium have illustrated, the interstellar downlink is a very substantial technical challenge. Most recently we reported on work by an i4is team, *i4is delivers Communications Study to Breakthrough Starshot*, in our last issue, P41 [1]. Here John Davies summarises a recent tutorial paper by three major contributors to the interstellar endeavour.

Introduction

In this new paper, *Interstellar flyby scientific data downlink design* (arxiv.org/abs/2306.13550) David Messerschmitt, Philip Lubin and Ian Morrison [2] provide a tutorial review of the interstellar downlink challenge [3].

Messerschmitt et al assume -

- acceleration by directed-energy beam
- the probe is ballistic (unpowered after initial acceleration)
- cruise at 10-20% c and flyby with no deceleration
- probe mass 1 to 1,000 grams
- optical communication using pulse-position modulation (PPM) with error-correction coding (ECC)
- data is downloaded during a period following encounter with the target star and any exoplanets
- very large receiver collection area on or near Earth is composed of individual incoherently-combined diffraction-limited apertures

They provide performance indices of interest to scientific investigators including -

- total launch-to-completion data latency
- total volume of data reliably recovered

And address issues including the interaction between the speed and mass of the probe and the duration of downlink transmission, transmit and receive pointing accuracy, beam size and receiver field of view.

The paper contains many parameters which requires the reader to hunt for their definition until memorised so this article has an Appendix with an index of them.

[1] i4is.org/wp-content/uploads/2023/05/News-Feature-i4is-delivers-Communications-Study-to-Breakthrough-Starshot-Principium41-23052291003-1.pdf

[2] David Messerschmitt is Professor Emeritus of Electrical Engineering and Computer Sciences at UC Berkeley, Philip Lubin is Professor of Physics at UC Santa Barbara, Ian Morrison is at the Curtin Institute for Radio Astronomy, Curtin University, Western Australia.

[3] See also *The Interstellar Downlink*, Principium 31 November 2020 (i4is.org/wp-content/uploads/2021/08/The-Interstellar-Downlink-Principium31-print-2011291231-opt.pdf) for an introduction to the subject and *The Icarus Firefly Downlink*, Principium 36, February 2022 (i4is.org/wp-content/uploads/2022/02/The-Icarus-Firefly-Downlink-Principium36-AW-2202191002opt.pdf) for the specific case of a large fusion powered probe.

Interstellar distances

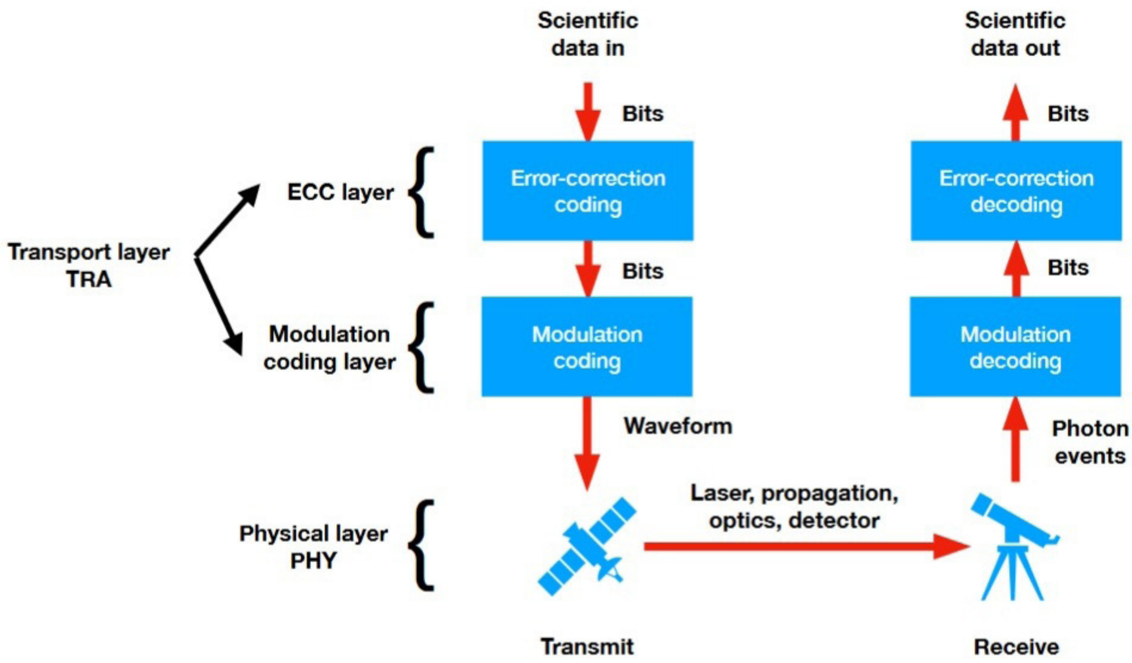
The numerical examples in the paper assume a mission to Proxima Centauri (the nearest star to our Sun) initially launched by directed-energy propulsion from the vicinity of Earth.
The paper assumes an idealised downlink equation [1] -

$$\frac{P_R}{P_T} = \frac{1}{\lambda^2 D_{star}^2} \cdot A_T A_C$$

- to give the relationship between transmit power and received power. To maximise beam collimation they assume the downlink will use the shortest wavelength that penetrates Earth atmosphere efficiently, 350—400 nm also taking into consideration interfering radiation from the target star Proxima Centauri [2].

Protocols

They present a protocol layering of the downlink [3].



Coordinated transmit-receive communications architecture.

Functionality is divided into three layers, each layer with a transmit and receive component. Logically each layer in the transmitter is coordinated with its counterpart in the receiver. The physical layer (PHY) includes everything from transmit laser to optical detection in the receiver. The transport layer (TRA), comprised of the modulation coding and ECC (error correction coding) layers, provides an intensity-vs-time waveform in the transmitter and recovers scientific data from the sequence of photon detection events in the receiver.
Credit (Image and caption): Messerschmitt et al, Figure 2 [4]

[1] Citing S Schelkunoff, H Friis, *Antennas: theory and practice*, Vol. 639, Wiley, 1952
[2] The received signal will be at a longer wavelength (redshifted) due to Doppler at 20%c. For example a transmit wavelength of 292 nm will produce a received signal at 350 nm. There will also be a relativistic effect at this significant fraction of the speed of light, see en.wikipedia.org/wiki/Relativistic_Doppler_effect and en.wikipedia.org/wiki/Relativistic_beaming.
[3] Protocol layering is fundamental to data communications design, see en.wikipedia.org/wiki/Communication_protocol#Protocol_layering
[4] Source: Fig 25 of D G Messerschmitt, P Lubin, I Morrison, *Challenges in scientific data communication from low-mass interstellar probes,* The Astrophysical Journal Supplement Series 249 (2) (2020) 36. iopscience.iop.org/article/10.3847/1538-4365/aba126/meta

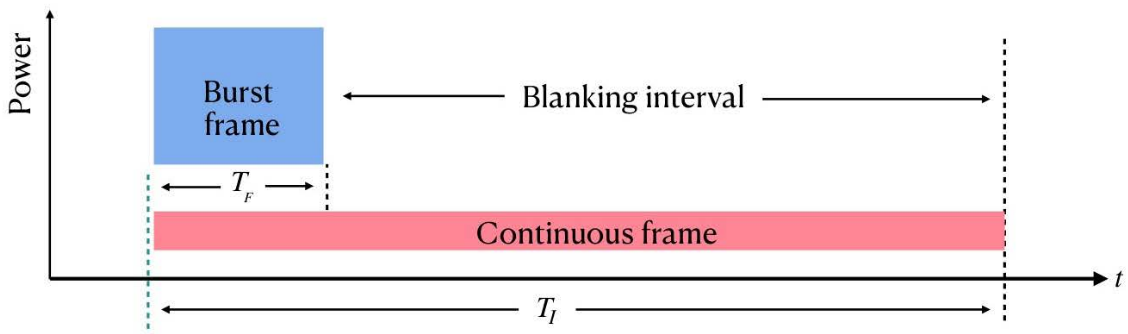
Background radiation

The paper categorises all unwanted data at the receiver as background radiation. It divides this into -

- Noise is radiation that accompanies, but cannot be separated from the data signal because of its overlap in time, wavelength, and direction with sources including cosmic background radiation, the deep star field, zodiacal radiation (due to solar-system dust emissions and scattering) and sunlight and moonlight scattered in the earth's atmosphere. Sunlight is an absolute block for a terrestrial optical receiver so only half of each day, on average, is available to the receiver.
- Dark counts are spurious signals originating in the receiver optics or in the optical detectors. Cooling optics and detectors helps here as does optical bandpass filtering (ie blocking unwanted parts of the spectrum). The remaining unwanted signals tend to appear for all detectors so this problem grows if there are many detectors for one signal.
- Interference can be distinguished from the wanted signal by its time, wavelength, or direction. The major source in this case is the target star itself. But a swarm of probes can produce mutual interference and multiplexing is required. Options are time division multiplexing (TDM probes wait their turn to transmit), frequency division multiplexing (FDM probes transmit at different wavelengths) and space division (SDM probe signals appear from differing directions and/or receivers are widely dispersed).

The paper considers the option of a space-based receiver, which would eliminate atmospheric interference, outages from weather and Earth rotation and wider choice of transmit wavelengths to avoid target star interference [1]. But it rapidly concludes that "given the likely necessity for a massive receive collector, this may not be affordable" [2].

The paper proposes burst-mode transmission, so that a higher power signal occupies just a fraction of possible transmit time, exchanging baseband bandwidth for improved signal to noise ratio.



An illustration of burst-mode transmission, in which a section of transmitted signal of duration T_I is compressed into a shorter duration $T_F < T_I$ at higher power, so that the total energy is not affected. This creates a blanking interval known to the receiver, during which there can be no signal photon detections and any background photons can be ignored. Credit (image and caption): Messerschmitt et al Figure 3

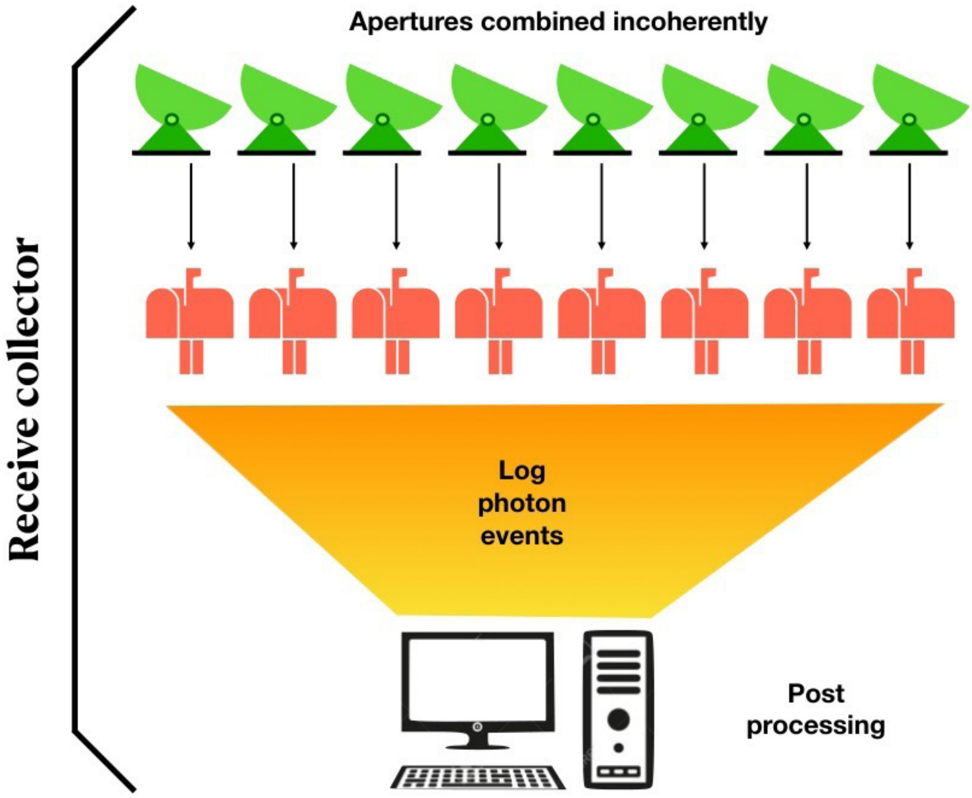
[1] It would also allow cooling of the receiver by radiation (as in the James Webb telescope) and, long term, allow scaling of the optical receivers unconstrained by Earth gravity.
[2] It would have been interesting to see a comparison with a space based downlink receiver which would allow a freer choice of wavelength and no outages either regular, due to rotation of the Earth, or intermittent, due to weather. Will the additional challenges of deploying in space have been overcome by the time probes are launched?

Transmitter and Receiver

The paper states "A single diffraction-limited aperture is the canonical building block of optical electromagnetic transmission and reception." and "Issues related to pointing accuracy are quite distinctive for space vs terrestrial platforms, and for transmit beam vs receive FOV [Field of view (of the receiver)]".

At the transmit end the downlink transmission is likely to be the only function following target encounter so transmit beam pointing is the only issue for spacecraft attitude control and the paper takes the view that the transmitter may be simply part of the spacecraft structure. This also eliminates the moving parts, always a reliability challenge, typical for the transmit antenna of deep space probes. At the receive end the challenge for either a ground-based or a space-based receiver has much less onerous requirements given that scaling to quite large apertures and more sophisticated processing are possible. The paper considers a range of aperture and pointing accuracy issues [1].

The target star and planet will be in motion ("proper motion") for the whole downlink period, assumed to be two years. The paper assumes that the probes will follow this motion but it is not clear to what extent this will happen given the very high velocity of the probes [2].



A receive collector composed of multiple apertures. This achieves simultaneously a FOV controlled by the aperture size together with a larger total collection area to achieve a signal photon counting rate. Λ_S commensurate with data rate $\mathcal{R}$ through the relation $\mathcal{R} = \Lambda_S \bullet$ BPP. For simplicity and without affecting the FOV, the apertures are combined incoherently by simply locating a photon-counting optical detector (shown as a mailbox icon) at each aperture and accumulating their photon counts. The resulting collector is not diffraction-limited, but this is fortunately unnecessary at the receiver.
Credit (image and caption): Messerschmitt et al Figure 5 (citing *Challenges in Scientific Data Communication from Low-mass Interstellar Probes*, Messerschmitt et al 2020, iopscience.iop.org/article/10.3847/1538-4365/aba126/meta Figure 3.)

[1] An additional issue is the fate of the downlink photons encountering the protons of the interstellar medium (ISM) constituting a "bow wind" for such long distance communications.

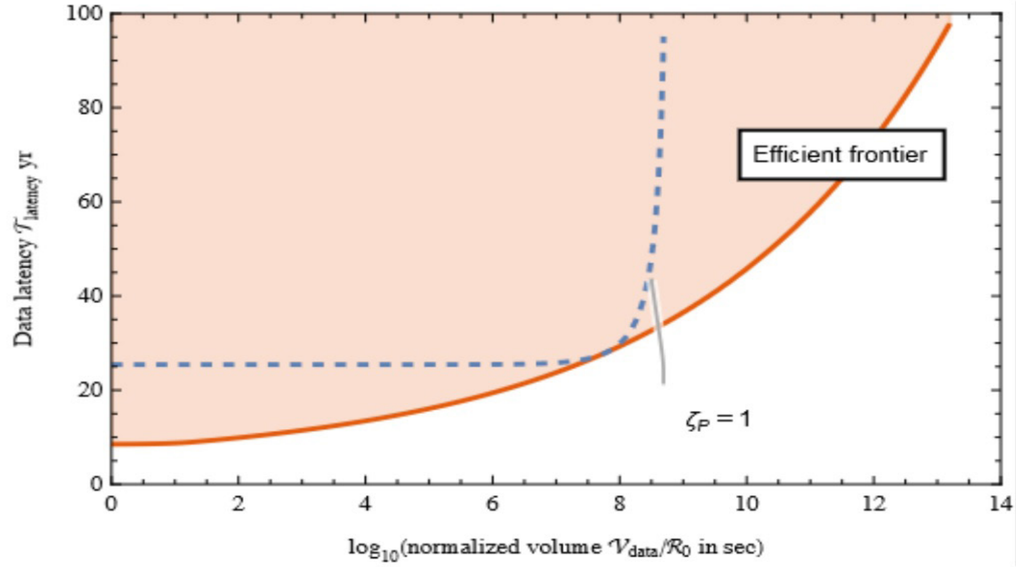
[2] See also the issue of space division multiplexing (SDM) under Background Radiation above.

The data rate $\mathcal{R}$ is proportional to frequency and thus the reciprocal of wavelength, λ, and the paper states that "Depending on area and the chosen technology, maintaining a transmit aperture close to the diffraction limit at shorter wavelengths will necessitate tighter fabrication tolerances proportional to the wavelength." and "With a large number of apertures and associated optical detectors, the average interval between signal photon detections is large. This is another indicator of the aggressive requirements on detector dark counts."
The choice of a terrestrial receiver imposes a number of outage challenges. These are similar to those of a terrestrial optical telescope including inability to receive during daylight hours, instability of light transmission through the atmosphere and cloud cover. More about this in Interstellar Distance and Background Radiation above - and in Error Correction below.

Downlink operation time

The paper assumes that the downlink will take place over several years and identifies a tradeoff between data volume and latency. It sees the consumers of the data, science stakeholders, as asking - how much data do we get back reliably, and how long do we have to wait for that data? This is the data volume V_{data} (total number of data bits returned), and the data latency $T_{latency}$ (elapsed time from probe launch to return of the data in its entirety). The mass ratio ζ_P, the ratio of the actual probe mass to some baseline value, is significant in that if the launch beam and power remain fixed across multiple probe launches, the speed of the probe is directly affected by the probe mass, and hence by ζ_P. In particular the speed decreases as $\zeta_P^{1/4}$ with increasing mass, and the total launch energy increases as $\zeta_P^{3/4}$. The mission design parameters- $\{\zeta_P , T_{down}\}$ can be varied to manipulate the mission performance metrics $\{V_{data} , T_{latency}\}$ to achieve the best $\{V_{data}, T_{latency}\}$ tradeoff. For example, if the launch beam remains fixed (except possibly for the time duration of probe acceleration), a larger ζ_P results in a lower cruise speed for the probe u_P and a longer $T_{latency}$. Overall travel-time increase is "deleterious" but all the other impacts are beneficial. The paper defines a normalised volume of data against data rate $V_{data} / \mathcal{R}_0$ as a performance metric to guide the choice of the mass ratio ζ_P and duration of the operation of the downlink data transmission T_{down} characterised as $\{\zeta_P , T_{down}\}$. $\mathcal{R}_0$ is the data rate (in bits per second) at the beginning of downlink transmission [1].
The paper states that choice of a mission operation point somewhere on the efficient frontier (lower boundary of feasible region of operation) provides flexibility in setting mission priorities. There are several compelling reasons to consciously select different operating points along the efficient frontier for different missions sharing a common launch infrastructure. Considerations include -

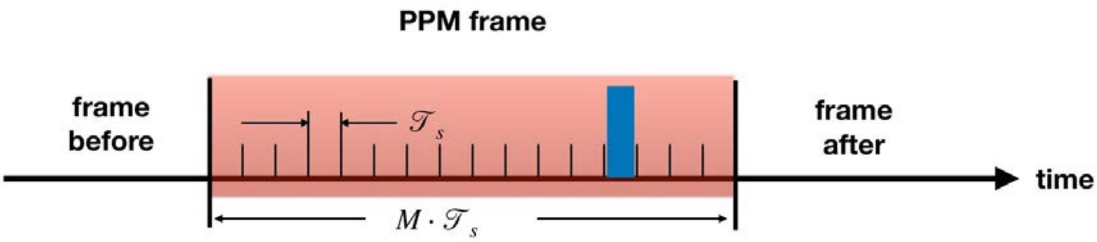
- Priority of large V_{data} versus small $\mathcal{R}_0$ / $T_{latency}$ (initial data link rate/elapsed time from probe launch to return of the data in its entirety).
- Different probes may carry different types of instrumentation entailing different mass and data volume requirements.
- Evolution of probe technology over time with technology validation first and greater scientific data return later.
- Missions to different targets at different distances.



Plots of data latency Tlatency (in years) vs the log of the normalized data volume Vdata/$\mathcal{R}_0$ (in seconds) where $\mathcal{R}_0$ is the data rate (in bits per second) at the beginning of downlink transmission (data rate declines from there as the square of propagation distance) for mass ratio $\zeta_P = 1$. V_{data} (in bits) is found by multiplying by the assumed value for $\mathcal{R}_0$. Any volume- latency mission operating point within the shaded region is feasible. The lower boundary of this region, called the efficient frontier, is an efficient operating point in the sense of maximizing the volume for a given latency, or minimizing latency for a given volume. The set of operation points obtained by fixing $\zeta_P = 1$ and varying downlink operation duration T_{down} are shown as a dashed curve.
Caption (image and caption): Messerschmitt et al Figure 6

Modulation

The paper chooses pulse-position modulation (PPM) which exploits the advantages of burst-mode in combating noise in the highly demanding environment of tiny probes transmitting over interstellar distances, as explained in section *Background radiation* above [1].
The paper states that PPM combined with an appropriate error correcting code (ECC) protocol layer "can achieve close to theoretical constraints on photon efficiency, subject to assumptions about peak and average power".



Pulse-position modulation divides the received signal power at the optical detector into frames, where each frame is further subdivided into M slots each of duration Ts. The convention is that the received signal power is all within a single slot within the frame, which communicates $\log_2 M$ bits of "raw" information (if the slots are equally likely to be so-energized). The average number of photons detected for each energized slot is K_s, and this is also the average number of photons detected for the whole frame. The peak-to-average power ratio is thus PAR = M.
Credit (image and caption): Messerschmitt et al Figure 7

[1] See also - Report of the paper *The Starshot Communication Downlink* in Principium 27, November 2019, page 28; News item *Challenges in Scientific Data Communication from Low Mass Interstellar Probe* in Principium 28, February 2020, page 17; Survey article *The Interstellar Downlink*, section 4.4.2 Burst pulse-position modulation (BPPM) in Principium 31, November 2020, page 38; *The Icarus Firefly Downlink*, section 5 Possible Laser downlink in Principium 36, February 2022, page 8.

The paper states that the peak power for a PPM transmitter on these tiny spacecraft is limited by the capabilities of semiconductor lasers [1] leading to the need for optical detectors at the receive end which exhibit the lowest possible dark counts and the use of pulse compression.

Error Correction

The example given for transmit error correction suggests an 83.4% overhead for error correction emphasising the considerable challenge of delivering error-free scientific data in this challenging environment [2]. The paper deals in detail with these challenges. One key factor is distribution of the ECC job over substantial amounts of the science data since the ECC performance tradeoff against overhead favours protecting longer blocks of data [3]. There is a big difference between encoding to include the ECC bits at the transmit end and decoding to perform the correction at the receive end. The former must be done with the minimum computing resources (storage and computation) while the latter has the enormous resources available on Earth (or in near Earth space).

The problem of outages, especially for a terrestrial receiver including prolonged weather events, means that even a single image must be transmitted over many times the longest expected outage. The paper gives the example of a one week maximum outage requiring that the image data must be spread over a whole year.

Conclusion

This article has only given a simplified overview of this valuable paper. As the paper remarks -

> *This tutorial has attempted to capture these dependencies as well as the local considerations coming into play within each subsystem. A required scope of core principles is large, spanning quantum mechanics, optics, and device physics on the one hand to information theory and finite field algebra [4] on the other. Such an undertaking is best conducted as collaboration among different types of expertise. In setting requirements and making concrete tradeoffs, that collaboration should include the ultimate stakeholders, which includes funding sources and domain scientists.*

The interstellar downlink is at least as big a challenge as propulsion for a near term interstellar mission. There is much to be done in both theoretical and practical work to achieve that first close-up image of an exoplanet and all the other data we will need to achieve a step forward in our knowledge as large as that between telescope observation of Pluto and the flyby by the New Horizons probe.

This article has benefited from comments kindly provided by Peter Milne and T Marshall Eubanks. Any remaining errors and ommissions are, of course, the responsiblity of the author.

[1] The limits appear to be at around 1 watt, see Song et al, *Processes of the Reliability and Degradation Mechanism of High-Power Semiconductor Lasers*, 2022, www.mdpi.com/2073-4352/12/6/765

[2] Contrast, for example, this with typical Forward Error Correction for mobile phones of 14-25% www.nokia.com/blog/what-the-fec/

[3] For example see en.wikipedia.org/wiki/Hamming_distance and note that to correct an error in one bit of information requires two additional bits, an overhead of 66%, while seven information bits require only three additional bits, an overhead of only 30%.
Error correction techniques have advanced enormously since Claude Shannon first defined the fundamentals of communications theory in the 1940s and the paper simply gives an example of Reed-Solomon coding (en.wikipedia.org/wiki/Reed%E2%80%93Solomon_error_correction) but clearly expects that substantial work is still to be done in this area of design. Note that in most terrestrial communications these techniques are described as Forward Error Correction (FEC) to distinguish from the more common situation in data communications where only error detection is required since corrupted data can be re-transmitted since latency is not critical. Re-transmission with 8 years round trip latency is clearly not feasible.

[4] See math.libretexts.org/Bookshelves/Abstract_and_Geometric_Algebra/Abstract_Algebra%3A_Theory_and_Applications_(Judson)/22%3A_Finite_Fields

APPENDIX - Parameter Index

In the interest of readability of this article and the source paper here are the parameters used, in the order of their appearance in the paper, with the defining page number in the paper.

Parameter	Measure	Page ref
c	velocity of light 300,000 km/sec	1
A_C	size of the collector at the receiver (the receiver aperture area)	3
A_T	transmit aperture area (size of the downlink transmitter antenna)	3
D_{star}	distance to the target star/exoplanet	3
P_R	downlink received power	3
P_T	downlink transmit power	3
λ	wavelength of downlink signal	3
ECC	error correcting code (additional downlink data which permits the receiver to correct some data errors)	5
PHY	physical layer of the downlink protocol stack - the lower layer	5
TRA	transport layer of the downlink protocol stack - the upper layer	5
BPP	bits per photon	7
$\mathcal{R}$	data rate (bits reliably recovered per unit time)	7
Λ_S	photon detections per unit time	7
FOV	field of view (of the receiver)	8
SBR	signal-to-background power ratio	8
PPM	Pulse position modulation	12
T_F	Duration of compressed signal	12
T_I	Duration of uncompressed signal	12
W	signal bandwidth	12
δ	duty cycle factor (for burst-mode)	12
$T_{latency}$	data latency - elapsed time from probe launch to return of the data in its entirety	23
V_{data}	total number of data bits returned	23
T_{down}	duration of downlink transmission	23
u_P	cruise speed of the probe	24
$\mathcal{R}_0$	data rate (in bits per second) at the beginning of downlink transmission [1]	24
Efficient frontier	lower boundary of feasible region of operation	25
ζ_P	mass ratio - the ratio of the actual probe mass to some baseline value.	26
K_s	average number of photons detected for each energized slot (in a PPM frame)	29
M	Each transmitted data frame is subdivided into M slots each of duration T_s.	29
T_s	Each transmitted data frame is subdivided into M slots each of duration T_s.	29

News Feature

Project Icarus revisited - 30 September

John I Davies

More than 10 years ago, Project Icarus kicked off at the BIS HQ with a symposium which included key members of the 1970s BIS Daedalus study team.
Project Icarus aimed to build on the Daedalus design using some 30 years of fusion research since the '70s and design an Icarus interstellar probe – son of Daedalus. The Project Icarus team produced several Icarus variants, pre-eminently among them 'Firefly' [1] but also others such as Resolution/Endeavour that would become 'Pegasus'.

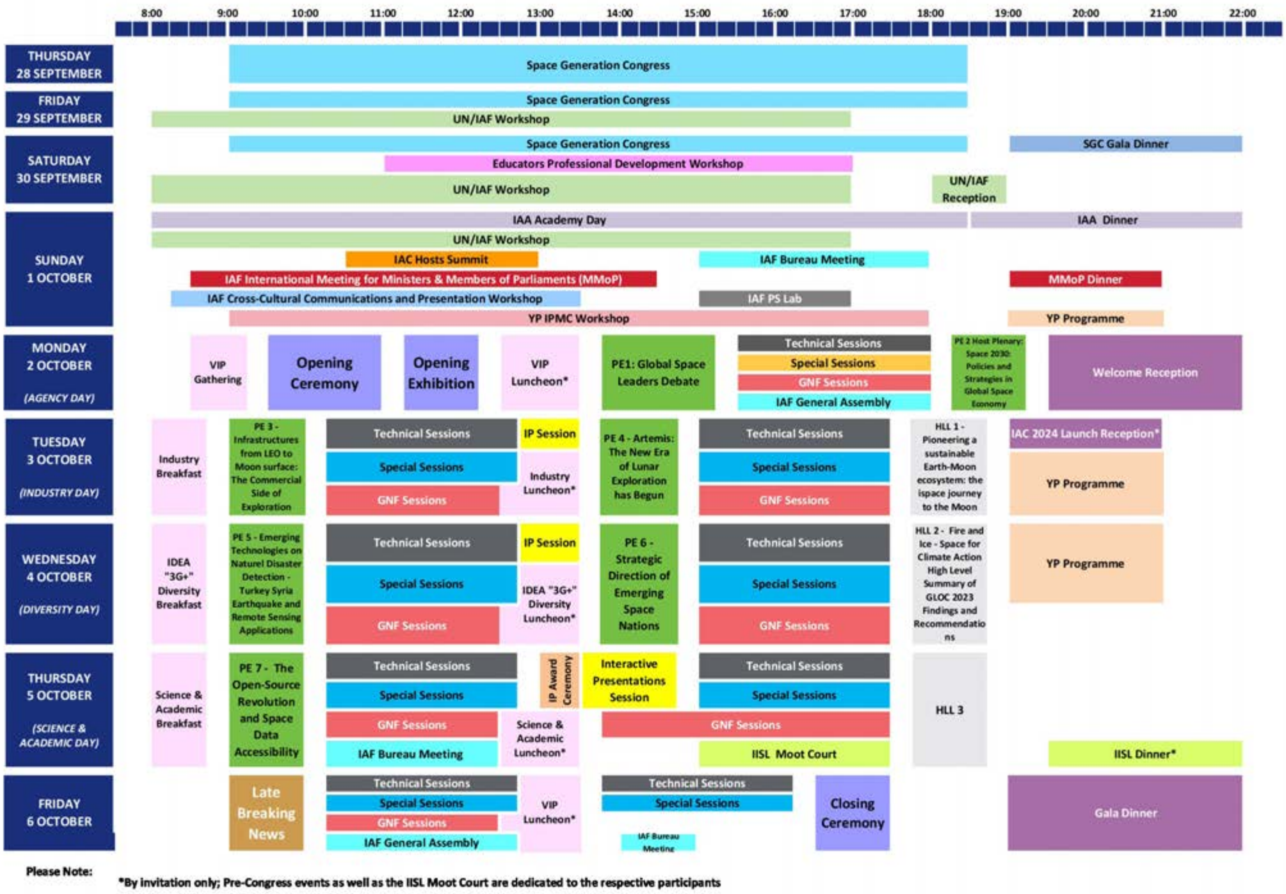
This symposium at BIS HQ London aims to provide a 'book end' to BIS Project Icarus and the designs. i4is Deputy Executive Director Rob Swinney was Project Director of Icarus in its latter years and is the host and organiser of the event. Come along to find out how far we have come since the legendary Daedalus project - and meet Rob and members of the Icarus teams, core i4is team members and others who have contributed over the years.
Tickets at -
bis-space.com/shop/product/project-icarus-symposium-2023/

[1] See *Reaching the Stars in a Century using Fusion Propulsion* i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/, First published in Issue 22 | August 2018 i4is.org/principium-22/

IAC 2023
The Interstellar Presentations

John I Davies

This feature identifies items related to interstellar studies which are listed to appear at this year's International Astronautical Congress, IAC23.
If you spot anything we miss then contact principium@i4is.org and we will endeavour to cover it in our news feature following the congress, for the November edition P43. All of the programme items listed here are visible via iafastro.directory/iac/browse/IAC-23/.



The Programme

Here is the programme with IAF identifying codes for the symposium sessions.

A1.	IAF/IAA SPACE LIFE SCIENCES SYMPOSIUM
A2.	IAF MICROGRAVITY SCIENCES AND PROCESSES SYMPOSIUM
A3.	IAF SPACE EXPLORATION SYMPOSIUM
A4.	52nd IAA SYMPOSIUM ON THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI) – The Next Steps
A5.	26th IAA SYMPOSIUM ON HUMAN EXPLORATION OF THE SOLAR SYSTEM
A6.	21st IAA SYMPOSIUM ON SPACE DEBRIS
A7.	IAF SYMPOSIUM ON ONGOING AND NEAR FUTURE SPACE ASTRONOMY AND SOLAR-SYSTEM SCIENCE MISSIONS
B1.	IAF EARTH OBSERVATION SYMPOSIUM
B2.	IAF SPACE COMMUNICATIONS AND NAVIGATION SYMPOSIUM
B3.	IAF HUMAN SPACEFLIGHT SYMPOSIUM
B4.	30th IAA SYMPOSIUM ON SMALL SATELLITE MISSIONS
B5.	IAF SYMPOSIUM ON INTEGRATED APPLICATIONS
B6.	IAF SPACE OPERATIONS SYMPOSIUM
C1.	IAF ASTRODYNAMICS SYMPOSIUM
C2.	IAF MATERIALS AND STRUCTURES SYMPOSIUM
C3.	IAF SPACE POWER SYMPOSIUM
C4.	IAF SPACE PROPULSION SYMPOSIUM
D1.	IAF SPACE SYSTEMS SYMPOSIUM
D2.	IAF SPACE TRANSPORTATION SOLUTIONS AND INNOVATIONS SYMPOSIUM
D3.	21st IAA SYMPOSIUM ON BUILDING BLOCKS FOR FUTURE SPACE EXPLORATION AND DEVELOPMENT
D4.	21st IAA SYMPOSIUM ON VISIONS AND STRATEGIES FOR THE FUTURE
D5.	56th IAA SYMPOSIUM ON SAFETY, QUALITY AND KNOWLEDGE MANAGEMENT IN SPACE ACTIVITIES
D6.	IAF SYMPOSIUM ON COMMERCIAL SPACEFLIGHT SAFETY ISSUES
E1.	IAF SPACE EDUCATION AND OUTREACH SYMPOSIUM
E2.	51st IAF STUDENT CONFERENCE
E3.	36th IAA SYMPOSIUM ON SPACE POLICY, REGULATIONS AND ECONOMICS
E4.	57th IAA HISTORY OF ASTRONAUTICS SYMPOSIUM
E5.	34th IAA SYMPOSIUM ON SPACE AND SOCIETY
E6.	IAF BUSINESSES AND INNOVATION SYMPOSIUM
E7.	IISL COLLOQUIUM ON THE LAW OF OUTER SPACE
E8.	IAA MULTILINGUAL ASTRONAUTICAL TERMINOLOGY SYMPOSIUM
E9.	IAF SYMPOSIUM ON SECURITY, STABILITY AND SUSTAINABILITY OF SPACE ACTIVITIES
E10.	IAF SYMPOSIUM ON PLANETARY DEFENSE AND NEAR-EARTH OBJECTS
GTS.	GLOBAL TECHNICAL SYMPOSIUM

The Interstellar Programme Items

Shown alphabetically by IAF identifying code. Access them all via iafastro.directory/iac/browse/IAC-23/.

C4,10-C3.5,1,x80575	KEYNOTE: Nuclear Thermal Propulsion - Progress and Potential	Dr Dale Thomas	University of Alabama in Huntsville	United States

This keynote address will describe the current research and development efforts currently underway within the United States on Nuclear Thermal Propulsion (NTP), with a particular focus on the Demonstration Rocket for Agile Cislunar Operations (DRACO) project, a joint effort of the United States Defense Advanced Research Projects Agency (DARPA) and the National Aeronautics and Space Administration. The impact of NTP propulsion on both human and scientific exploration of the Solar System will also be discussed. And finally, the topic of advanced NTP propulsion will be addressed, including liquid fuel NTP engines.

C4,10-C3.5,2,x79343	Deployment of the large size solar sail	Dr Vladimir Ya Kezerashvili	New York City College of Technology	United States

A solar sail presents a large sheet of low areal density membrane and is a propellant-less propulsion system for future exploration of the Solar System and beyond. One of the important objectives of the propulsion using a solar sail is the development of the mechanism for the deployment and stretching of large membranes in space. In this work we present a comparison of two novel concepts for deploying and stretching of the large size solar sail:
i. the deployment and stretching of the thin circular membrane attached to the superconducting current loop [1,2],
ii. the deployment and stretching of the thin circular membrane attached to the inflatable toroidal shell [3].
In the framework of a strict mathematical approach based on the theory of elasticity elastic properties of a circular solar sail membrane, inflatable toroidal shell, and superconducting wire loop are analyzed. Within classical electrodynamics it is predicted the magnetic field induced by the Bi-2212 superconducting wire with today achievable engineering current densities can deploy and stretch the large membrane. The formulas for the superconducting wire and sail membrane stresses and strains caused by the current in the superconducting wire are derived. It is predicted that by introducing the gas into the inflatable toroidal shell one can deploy and stretch a large size circular solar sail membrane. The formulas for the toroidal shell and sail membrane stresses and strains caused by the gas pressure in the toroidal shell are derived. The analytical expressions obtained for both type of the deployment mechanism can be applied to a wide range of solar sail sizes. Numerical calculations for the sail of radii up to 100 m (10,000 m^2) made of CP1 membrane are presented. We demonstrate the feasibility of deployment and stretching of a solar sail with a large size circular membrane attached to superconducting wire loop or the inflatable toroidal shell.

References

1. V Ya Kezerashvili and R Ya Kezerashvili, *On deployment of solar sail with superconducting current-carrying wire*, Acta Astronautica 189, 196–198 (2021).
2. V Ya Kezerashvili and R Ya Kezerashvili, *Solar sail with superconducting circular current-carrying wire*, Advances in Space Research 69, 664-676 (2022).
3. V Ya Kezerashvili, R Ya Kezerashvili, and O L Starinova, *Solar sail with inflatable toroidal shell*, Acta Astronautica 202, 17–25 (2023).

C3,5-C4.10,4,x75360	Application of Nuclear Power and Propulsion Systems of High Power Level for Space Transportation	Dr Vladimir Koshlakov	Keldych Research Centre	Russian Federation

Realization of new research and exploration space missions requires a qualitative increase of spacecraft (SC) power and propulsion capabilities. Because of that high power space tug [1,2] based on nuclear power system (with power level up to hundreds of kW – MW) and electric propulsion system, is mainly considered as a new transport vehicle for near-Earth and deep space missions realization. Nuclear power systems are characterized by significantly greater compactness than solar panels, independence of the generated power from the distance to the Sun, light conditions, and increased radiation resistance. The use of electric propulsion (EP) thrusters for such tasks as inserting a spacecraft into orbit, keeping a spacecraft in orbit, interplanetary flights and missions in deep space provides significant savings in the used propellant mass in comparison with traditional chemical propellant thrusters due to the high specific impulse of EP thrusters. Projects aimed at development and application of space vehicles based on nuclear power propulsion system (PPS) of high power level have been conducted since the very beginning of the space exploration Era. Interest in such projects [1] arises as human activity in space grows, for example: project Prometheus (NASA, USA), project Transport Power Module (Russia) and European-Russian projects DEMOCRITOS and MEGAHIT [2]. New projects of SC with nuclear PPS continue to appear due to the development of new designs and technological solutions for the main parts and subsystems of high power level nuclear PPS. One of the promising options is a nuclear power and propulsion consisting of a gas-cooled reactor, a closed Brayton cycle Power Conversion Unit (PCU) and an Electric Propulsion (EP) thrusters [1]. Efficiency of nuclear power and propulsion systems application for transport missions to Moon, to Mars and to Europa (Jupiter's satellite) is analyzed in comparison with conventional chemical propulsion systems. It is shown that high power level power and propulsion systems can have significant advantage in comparison with conventional chemical propulsion, so their application is actual for realization of near-Earth and deep space transport missions.

References

1. A S Koroteev, et al, *The Nuclear Power Propulsion System for the Spacecraft*, Izvestiya RAS, Energetica, 5, 2015, Moscow, Akademkniga Publ., pp. 45-59, (in Russian).
2. Jansen, F et al, '*NPPS Flagship: Cluster of Electric Thrusters*, IAC-19,C4,4,12,x52152, 70th International Astronautical Congress, Washington DC, United States, 2019, 21-25 October.

C4,10-C3.5,8,x77652	Development of a high power Nuclear Electric Propulsion System for interplanetary missions	Mr Vlad-George Tirila	University of Southampton	UK

There is a renewed interest in the development of nuclear fission power sources for space applications. With the large growth in the space sector, missions requiring nuclear fission reactors are again being considered, as demonstrated by NASA planning to fly a prototype nuclear thermal propulsion system 2025. Example missions include: to the Moon, as part of human's return to the lunar environment, space tugs for heavy cargo transport, and missions exploring the far solar system where solar power is unfeasible. Many of these missions require a nuclear fission power system for operating a high power electric propulsion system (ie an ion thruster) that drives the spacecraft towards these distant endeavours. As part of a UK Space Agency funded consortium, through its enabling space exploration call, this paper presents our work to develop a cohesive and concurrently designed nuclear electric propulsion system, with the electric propulsion system designed from outset for integration of a space suitable nuclear fission reactor, and vice versa. Within the minimum year-long project, a Hall ion thruster has been developed for operation at high power, with a power requirement of at least 10 kW. The Hall ion thruster is designed for operation with a variety of different propellants, including both standard gaseous propellants and also condensable propellants such as magnesium. These propellants require heating into a vapour phase, which can be completed using excess heat available from the nuclear fission reactor system. This thruster has been designed, and will be manufactured for testing to be completed within the University of Southampton facilities in the summer of 2023. From the nuclear reactor perspective, we will develop a nuclear reactor concept within the 10 – 100 kW range that can be integrated with the electric propulsion system. We will make use of Low Enriched Uranium (LEU) Tri-structural Isotropic (TRISO) fuel particles, and through partners expertise previously developed components wherever possible. Two power conversion system options will be considered: Stirling Engines and static Thermo-Electric (TE) methods. Using our broad computational tools for the analysis of the proposed reactor type and associated power conversion systems, core physics, including both neutronic and thermal, will be assessed with tools that are computationally efficient, allowing the use of global optimisation methods. This enables the effective exploration of the many trade-offs that exist to find fission power systems that have minimal mass and volume whilst meeting mission requirements.

C4,10-C3.5,9,x76895	Research Progress toward Engineering Feasibility of the Centrifugal Nuclear Thermal Rocket	Dr Dale Thomas	University of Alabama in Huntsville	United States

The Centrifugal Nuclear Thermal Rocket (CNTR) is a Nuclear Thermal Propulsion (NTP) concept designed to heat propellant directly by the reactor fuel. The primary difference between the CNTR concept and traditional NTP systems is that rather than using traditional solid fuel elements, the CNTR uses liquid fuel with the liquid contained in rotating cylinders by centrifugal force. If the concept can be successfully realized, the CNTR would have a high specific impulse (1,800 s) at high thrust, which may enable (i) viable near-term human Mars exploration by reducing round-trip times to 420 days and (ii) direct injection orbits for scientific missions to the Solar System outer planets and Kuiper Belt objects. The CNTR could also use storable propellants such as ammonia, methane, or hydrazine at an Isp of 900 s, enabling long-term in-space storage of a dormant system. Research is presently underway to determine resolutions for the significant engineering challenges that the CNTR concept presents. Papers were presented at the 2021 and 2022 IACs which described these challenges, the study plan to address them, and progress to date. In particular, the 2022 paper highlighted the challenge of neutronics driving the heat generation gradient in the liquid uranium annulus, which results in the greatest heat generation on the outer wall of the annulus, where the maximum temperature of the containment wall is constrained to maintain structural integrity. This constraint was resulting in performance projections well below the theoretical projection. This paper provides a follow-on update which summarizes progress of the overall research effort, including strategies and key results to date on leveling the heat generation gradient in the liquid uranium annulus. The paper will also summarize the 3D modelling of the gaseous hydrogen bubbles in the liquid uranium and experimental results on gaseous and liquid analogs to validate the analytical models. Finally, estimates of engine key performance parameters including specific impulse, thrust and thrust to weight ratio will be given, and mission analyses of scientific missions to various solar systems destinations including Kuiper belt objects.

C4,10-C3.5,10,x76665	System Design Optimization for a Centrifugal Nuclear Thermal Rocket	Mr Mitchell Schroll	Propulsion Research Center	University of Alabama in Huntsville	United States

A Centrifugal Nuclear Thermal Rocket (CNTR) is a high-performance engine concept utilizing a liquid uranium fuel to achieve a theoretical specific impulse of 1,800 seconds. The design is a modification of traditional Nuclear Thermal Propulsion (NTP) in that it utilizes a high energy density uranium reactor to heat a propellant gas, eliminating the need for mass hungry oxidizers. While the concept of a CNTR dates back to the early 60's and 70's in work conducted by Nelson, Grey, and Williams, no significant advancement has been made in the modelling of the system since then. Research conducted in the interim based the system design around the work by Nelson, utilizing the same geometry and system performance assumptions since deemed the baseline design. Recently, efforts by Keese et al have shown that this initial baseline design had erroneous assumptions and the newly calculated values show a significantly reduced performance of the engine than previously thought, giving rise to the need to determine the optimum design configuration for future work. A comprehensive systems model was developed incorporating the propellent tanks, turbomachinery, regenerative cooling systems, centrifugal fuel element turbines, core fluid dynamics, nucleonics, and nozzle dynamics. The systems model was then overlain with a thermodynamics module allowing for various propellent and materials properties to be considered. Finally, a multidisciplinary design optimization framework was implemented within the code to iteratively solve the optimum geometry and operating conditions for various use cases, such as: long duration loiter, deep space scientific missions, and manned planetary missions. The results from the optimization study found that each use case has similar geometries but differing operating conditions. This result was expected since the main difference between the cases is the propellent used and therefore a function of their thermodynamic properties as they relate to the gas dynamics and turbomachinery and less so their nucleonic heating profiles. The new optimized designs improve upon the existing work done by Nelson et al by using higher fidelity models and more modern techniques, reducing the need for high level assumptions previous models used as well as increased confidence in the design configuration. These new configurations can now serve as a baseline for future work into further design improvements and mission trade studies with significantly improved fidelity.

C4,IP,5,x78557	Fusion-Enabled Plasma Propulsion for Enabling Interstellar Missions	Mr Ravinder Singh	Concordia University	Canada

This proposal introduces a disruptive propulsion technology concept that utilizes fusion-enabled plasma propulsion to enable interstellar missions. Fusion-enabled plasma propulsion is a type of advanced propulsion technology that combines the principles of nuclear fusion and plasma thrusters to generate propulsion. The proposed system would use magnetic fields to confine and compress hydrogen isotopes to induce fusion reactions, generating high-energy plasma that is expelled out of a nozzle to provide thrust. This technology has the potential to enable interstellar missions by providing significantly higher specific impulse than conventional chemical propulsion, enabling higher velocities and shorter travel times. Additionally, the fusion fuel used in this system is abundant and readily available in space, reducing the need for costly and complex refueling operations. The proposed fusion-enabled plasma propulsion system also has potential applications for in-space propulsion, including high-power electric propulsion for manned and robotic missions to Mars and other destinations in the solar system. This paper will provide a detailed description of the proposed fusion-enabled plasma propulsion system, including its key components, performance characteristics, and potential applications. The paper will also discuss the technical and engineering challenges associated with developing and implementing this technology, and will explore potential pathways for technology maturation and integration into future space missions.

D4,4,1,x80088	Communications receiver designs for interstellar probe missions	Prof Philip Mauskopf	Arizona State University	United States

We describe the designs of the ground station communications receiver system for the Breakthrough Starshot mission and other interstellar probes. Past interplanetary missions within the solar system such as the New Horizons mission to Pluto and the Kuiper belt use the NASA deep space network (DSN), a system of large radio dishes distributed around the world, to downlink data obtained during flybys. The next generation NASA probes such as the Psyche mission will test higher capacity optical communications systems. Future interstellar probes will require larger collecting areas and use of optical communications to overcome the signal loss over interstellar distances. We describe four concepts for large area ground receivers: i) an array of 1 meter diameter low cost incoherently combined reflecting apertures, ii) an array of 1 meter diameter low cost reflecting apertures coherently combined into 50 meter diameter optical receivers, iii) a space-based collecting aperture based on low mass nanophotonic reflectors similar to the Breakthrough Starshot lightsail design and iv) a crowd sourced citizen science initiative to produce small receivers for "backyard" collection of communications signals. We also describe astronomy projects which can be carried out using these receivers.

D4,4,2,x75652	High Temperature-superconductor material (HTSM) used for electronics in Radio-isotropic Thermal heat generator(RTG) where Thorium rods are being used as cells for source.	Mr Abhishek Singh	National Space Society (USA) -Mumbai chapter	India

Since launch of Voyager 1 we have that the exploration of deep space has become one of the primary aspect of space missions, but sending a satellite that far often cause an issue with the power management which is caused in traditional electronics being made on silicon board. The idea in this paper is to use a high temperature superconducting material with RTGs which will help in conserving the power since we know that the decay in power of the system will be much less than the traditional system as the power output of any superconducting material is to be given by the V=IR but since we have that the net power output of any supercomputer is zero the net resistance will also be zero in theoretical sense but on practical ground can be assured that this power decay will be far less on a logarithmic scale. Also we have that the RTGs choice for fuel rods can be thorium as we have that the thorium being least radioactive we won't be looking too seriously with the fact that all the electronics on board will be affected by the radioactivity.

D4,4,3,x79329	High-Speed Scientific Spacecraft Launches with Commercial Launch Vehicles	Dr Ralph L McNutt, Jr	Johns Hopkins University	United States

Reaching the outer solar system and interstellar space beyond has always been challenging due to the long distances and long travel times. Initial work on planetary gravity assists in the early 1960s by Minovitch and Flandro laid the basis for expanding reachable space with then-existing launch vehicles. Such gravity assists have been key enablers for orbital exploration missions to Mercury (MESSENGER), Jupiter (Galileo, Juno), and Saturn (Cassini-Huygens) by trading higher mass for lower launch energy from Earth (C3). They have also enabled close passes to the Sun (Parker Solar Probe) and moderately rapid solar system escape, coupled with fast flybys of various planetary-sized bodies: Mariner 10 (Mercury via Venus), Pioneer 10 (escape via Jupiter), Pioneer 11 and Voyager 1 (escape via Jupiter and Saturn), Voyager 2 (escape via Jupiter, Saturn, Uranus, and Neptune: the "Grand Tour"), and New Horizons (escape via Jupiter and Pluto). Two of these missions hold the first and second places for the most energetic launches (New Horizons: C3 = 157.7502 km^2/s^2; Parker Solar Probe: C3 = 152.222 km^2/s^2). Disadvantages in using Earth and Venus gravity assists to increase spacecraft injected mass to Jupiter and beyond include the time penalty and the need for a customized propulsion system to provide a deep-space maneuver (DSM). For "timely" transits to Neptune with a large orbiter or rapid solar system escape with an Interstellar Probe, more capable launch vehicles can be enabling by pushing the injected mass versus C3 curves "to the right." While the most extreme speeds asymptotically away from the Sun (7 to 8 au/yr) can be achieved with fast Jupiter gravity assists and super-heavy lift launch vehicles (SHLLV) such as the Space Launch System (SLS) surmounted by multiple upper stages, solar system escape speeds larger than those achieved by Voyager 1 are possible with existing and upcoming large commercial launch vehicles. Such vehicles include the Falcon-Heavy, New Glenn, and Vulcan Centaur. Better performance accrues with the fully expendable versions of these vehicles and/or with "refueling" in a low-Earth orbit, with performance versus launch cost as a central trade. Even better performance can be projected with SHLLVs in development, such as the Starship Super Heavy and Long March 9. We discuss some of the possibilities and trades such newer vehicles can enable in the near term for continued – and more distant – exploration of the solar system and beyond.

D4,4,5,x79852	The Next Ten Years: 100 Year Starship's Second Decade	Mr Jason Batt	100 Year Starship	United States

The next ten years of the 100 Year Starship (100YSS) are poised to be transformative, driven by ongoing advancements in space propulsion technology, public-private partnerships, and the development of life support systems for long-duration space missions. However, 100YSS is not just about technological advancements; culture, purpose, and the human experience are increasingly important areas of focus. At the recent Nexus Nairobi 2023 event, leaders from various fields came together to explore the intersection of culture, purpose, and space. The event emphasized the ways in which space exploration can inspire new approaches to cultural and societal challenges. The tagline for Nexus Nairobi 2023, "Space. Radical. Vital. Down to Earth," reflects the idea that developments in space technology have the potential to improve our lives here on Earth. Health technologies developed for long-duration space travel could have applications for improving healthcare in remote or underserved communities on Earth. Remote imaging and sensing technologies developed for space exploration can be used to address environmental issues on Earth, such as deforestation, water scarcity, and climate change. Education programs developed for space missions can inspire and engage students around the world in STEM fields. Moreover, the cultural impact of space exploration cannot be overstated. Art, music, and literature inspired by space exploration can promote a sense of wonder, curiosity, and imagination, which can inspire innovation and creativity in other fields. The next ten years of 100YSS will be a time of rapid change and innovation, driven by advancements in technology and the intersection of culture, purpose, and space. By fostering collaboration and dialogue across disciplines and cultures, we can build a more inclusive and holistic vision of the future of space exploration, one that recognizes the potential of these developments to improve our lives here on Earth. Ultimately, 100YSS can inspire a new approach to space exploration, one that recognizes the importance of culture, purpose, and the human experience. As we look ahead to the next ten years of 100YSS, it is clear that the intersection of culture, purpose, and space will be increasingly important. By working together across disciplines and across borders, we can build a brighter future for all of humanity, one that is rooted in a deep sense of wonder, curiosity, and imagination.

D4,4,6,x77432	Interstellar Exploration Using "EXPLORER" Spacecraft - Building The Foundation	Mr Aditya Prakash	Indian Institute of Technology Kanpur	India

Humanity's quest for exploration and discovery has driven our progress for thousands of years. Our ancestors, who ventured out on boats in search of new lands, continue to inspire us to pursue this legacy. In this spirit, we propose the development of a self-sustaining ecosystem spacecraft (EXPLORER) capable of interstellar exploration and human settlement. This research paper lays the foundation for the development of EXPLORER and identifies the areas of research required to make this vision a reality. The proposed spacecraft is designed to travel millions of light-years in search of habitable zones, containing a nuclear energy-based ecosystem that gets its energy from a nuclear reactor (or artificial sun). This miniaturized version of Earth will contain only the necessary resources, recycling mass to ensure sustainability. The EXPLORER will be protected by a shield to protect it from interstellar dust, debris, and radiations, and will use gravitational pull and advanced propulsion technology with the least mass consumption to reach its destination. One of the biggest challenges in interstellar exploration is to find the most dense place in the universe with habitable zones and the least energy path to it. A large part of the universe remains unknown and the journey will be purely based on exploration. Hence, the transportation technology must be advanced enough to handle these challenges. Our solution is to develop technology that can map the universe ahead of us and chart a path that minimizes energy consumption while maximizing speed and efficiency. The EXPLORER will be designed as a self-sustaining ecosystem capable of supporting human life for generations. The explorers on the spacecraft will grow, develop, reproduce, and pass down their knowledge and experiences, just as our ancestors did. Our ultimate goal is to establish human settlements on habitable planets and carry on the legacy of exploration and discovery that our forefathers started. The development of EXPLORER will require substantial time, resources, and knowledge, making it a task for future generations. Nevertheless, it holds the potential to expand human presence in the universe, establish new civilizations, and bring humanity closer to a sense of brotherhood in this vast universe. This research paper highlights the technological challenges and solutions for the development of EXPLORER and sets the direction for future research. It aims to bridge the gap between reality and science fiction and is a continuation of the legacy of our ancestors.

D4,4,7,x75821	Interstellar Exploration: from Science Fiction to Actual Technology	Prof Giancarlo Genta	Politecnico di Torino	Italy

The exploration of the solar system has already started: robotic probes reached all the planets and many minor bodies, and the plans to land humans on Mars are being developed. The technology for even the most advanced missions in the solar system doesn't need advances in basic science. Traveling through the solar system can be described through what is called 'hard science fiction,' ie science fiction strictly based on scientific knowledge. Interstellar exploration is completely different. Robotic flyby missions to the nearest stars using nanoprobes can be performed using technologies based on known science, while anything beyond this requires advances which we don't know how to implement, but even we are not sure whether they are possible at all. Here the point is not only the technological aspects but even the scientific bases on which the relevant technologies may rest. The missions requiring less scientific-technological advances, are slow missions, like space arks (generation ships) or missions based on hibernation with travel times up to hundred years. To implement both, the uncertainties are more related to the advances in space medicine and biology than in propulsion and physics. The fastest travels allowed by the current interpretations of the relativity theory are relativistic missions in which the time contraction at speeds closing the speed of light is exploited to decrease the travel time for the astronauts, although the travel time seen by those who remain on Earth is close, in years, to the distance travelled expressed in light years. However, the energy required for this type of travel is large and grows drastically with the increase of time contraction. FTL travel, which seems to be possible following some interpretations of relativity involving either wormholes or warp drive, requires substantial advances in fundamental physics. A symptom of this is that the novels dealing with interstellar travels belong more to the space opera than to the hard science fiction subgendres, not following strictly scientific credibility. No novels of this kind explain in some detail how the relevant machinery works, and even less scientifically realistic are the movies and TV series of this kind. Moreover, to achieve a travel time allowing to reach distant star systems in reasonable times using warp drives, the authors of Star Trek had to resort to the Warp Factor which is essentially an exponential scale. This makes the requirements for FTL travel even more difficult to achieve.

D4,4,8,x79861	Exploring Interstellar Travel in Video Games: Shaping Public Perceptions and Support for Future Initiatives	Mr Jason Batt	100 Year Starship	United States

Interstellar travel is a subject of great interest to scientists and the public alike, and video games have become a popular medium for exploring this topic. From procedurally generated galaxies to rich storytelling, video games have the potential to both accurately represent the scientific and technological challenges of interstellar travel and inspire players to learn more and support future initiatives. This interactive presentation will explore the trends in the industry and analyze what interstellar travel video games get right and wrong. It will examine the challenges of balancing realism with creative freedom and the trade-off between scientific accuracy and storytelling. It will also analyze specific games and how they handle interstellar travel, from simulating the challenges of engineering to offering a fantastical vision of the future. The presentation will discuss how games like No Man's Sky and Elite Dangerous use procedural generation to create vast, seemingly infinite universes for players to explore, inspiring a sense of wonder and discovery, but also leading to limitations in terms of scientific accuracy. Games like Mass Effect and the Outer Worlds create rich, immersive worlds with engaging characters and compelling narratives but also take liberties with science and technology to serve the story. The presentation will also analyze specific interstellar travel video games, such as Kerbal Space Program and Space Engineers, which aim for scientific accuracy and realism, allowing players to simulate the challenges of space travel and engineering. Other games, like Star Citizen and EVE Online, offer a more fantastical vision of interstellar travel, incorporating alien races and futuristic technologies. One of the key themes of the presentation will be how video games can encourage or discourage public support for interstellar initiatives. By portraying interstellar travel in a positive light and emphasizing the potential benefits, video games can inspire interest in science and technology and encourage critical thinking and problem-solving skills. However, if video games perpetuate misconceptions or present a negative view of interstellar travel as a tool of conquest, they may discourage public support for future initiatives. The presentation will conclude by examining the potential benefits of interstellar travel video games and their role in shaping public perceptions and support for future initiatives. Overall, interstellar travel video games represent a fascinating and growing subgenre, and this presentation will provide an overview of the industry, analyze its trends and examine specific games, and consider the potential benefits and drawbacks of this genre.

D4,4,9,x79839	The Canopus Award for Excellence in Interstellar Writing: Celebrating Fiction and Nonfiction that Champions the Dream of Interstellar Travel	Mr Jason Batt	100 Year Starship	United States

The Canopus Award for Excellence in Interstellar Writing is a prestigious literary award that recognizes outstanding works of fiction and nonfiction that promote and celebrate the dream of interstellar travel. Established in 2015 by 100 Year Starship, the Award seeks to honor those who contribute to this field through their writing. A panel of experts in the fields of science, engineering, and literature evaluates each nominated work based on its scientific accuracy, literary quality, and overall contribution to the field of interstellar travel. The judges also consider the work's impact on public awareness and engagement with the concept of interstellar travel.

The Canopus Award seeks to inspire and encourage new writers to explore the themes of interstellar travel and the possibilities it holds for humanity's future. It also recognizes established authors who have made significant contributions to the field of interstellar writing. Past winners of the award include Kevin J Anderson and Rick Wilber for "The Hind," Jeff Lemire and Gabriel Hernandez Walta for Sentient, and Alex McKenzie and Punske for "Language Development During Interstellar Travel." These works represent some of the best writing in the field of interstellar travel, inspiring readers to think about the possibilities of space exploration and to imagine a future where humanity is a spacefaring species. In addition to recognizing outstanding writing, the Canopus Award also helps to broaden public awareness and support for interstellar travel initiatives. By highlighting the importance of interstellar travel in popular culture, the award encourages public engagement with space exploration and fosters a sense of excitement and wonder about what lies beyond our planet. The award also helps to bring attention to the challenges and opportunities associated with interstellar travel, inspiring researchers and innovators to pursue new technologies and solutions to the challenges of space exploration. The Canopus Award celebrates the power of imagination and creativity in our quest for knowledge and understanding of the universe. Through recognizing exceptional works of fiction and nonfiction, the award inspires us to think about the possibilities of space exploration and to imagine a future where humanity is a spacefaring species. By promoting public awareness and support for interstellar travel initiatives, the Canopus Award helps to shape a brighter future for all of us.

E7,IP,8,x80109	Interstellar Investments: A Legal Odyssey of Space Law and International Investment Law	Mr Anmol Dhawan	International Institute of Space Law (IISL)	The Netherlands

The rapid proliferation of commercial activities in Outer Space and the subsequent expansion of private investments poses a significant challenge to the traditional international space law framework. The current regime needs to adapt to the modern commercial reality and regulate the legal issues that arise from the increasing involvement of the private space sector. This paper examines the intersection between international investment law and space law to address these challenges and evaluate avenues for more robust protection to space investors. This paper firstly analyzes whether investments in space activities - particularly in the satellite industry - could fall within the purview of Bilateral Investment Treaties (BITs) and Article 25 of the International Centre for Settlement of Investment Disputes (ICSID) Convention. If so, investors may enjoy broader substantial protection by benefiting inter alia from the requirements of Most-Favoured Nation (MFN), Fair and Equitable Treatment (FET), and Full Protection and Security (FPS). Further, the current state of space law does not provide self-exercisable remedies to private actors who rather depend on their home state to obtain compensation for damage suffered, based on the concept of diplomatic protection. In this context, the authors examine how the investor-state dispute resolution (ISDS) regime could address the specificities of space-related disputes and provide further incentives for space investments. Private operators can resort to arbitration under investment treaties, which can offer more efficient and effective dispute resolution mechanisms than national courts. Indicatively, investors can benefit from awards that grant compensation for losses suffered due to state actions, such as the denial or revocation of licenses. To this end, we discuss significant cases, such as Devas, which exemplify the benefits of the potential of ISDS, if used for space disputes. In conclusion, this paper highlights the relevance of international investment law in addressing some of the practical challenges that arise from the growing involvement of the private space sector in space activities and in strengthening the global rule of law. To that end, the authors examine how the use of international investment law standards could contribute towards mitigating space debris, ensuring space safety and sustainability, and promoting the peaceful use of Outer Space. Based on the findings, this paper calls for more comprehensive and coherent policies and regulations that could accommodate the evolving nature of the space industry and encourage more investments in Outer Space. ■

The Journals

John I Davies

Here we list recent interstellar-related papers in the Journal of the British Interplanetary Society (JBIS), published since the 1930s, and Acta Astronautica (ActaA), the commercial journal published by Elsevier, with the endorsement of the International Academy of Astronautics.

JBIS

Three issues of JBIS (online) have appeared since the report in our last issue, P41. Later issues are in print but not yet online.

Title (open publication)	Author	Affiliation
Abstract/Précis/Highlights		

JBIS VOLUME VOLUME 76 NO.2 FEBRUARY 2023 PAGES 70-76		
Exploring the Feasibility of a Power-Generating Pulsed Nuclear Magnetic Nozzle	Nathan M Schilling	University of Alabama in Huntsville

Crewed missions to Mars and robotic missions to the gas giant planets are challenging because of the current lengthy trip times (2 years to Mars, ~20+ years to the gas giants) with current propulsion technology. These trips endanger astronauts due to the harmful effects of radiation and microgravity and represent a significant fraction of a PI's (Principal Investigator's) lifespan for uncrewed gas giant missions. To make these trips safer and more reliable, trip times need to be reduced dramatically. Pulsed nuclear fusion propulsion systems promise to reduce these trip times down to 1-3 months for the Mars mission and 1-4 years for gas giant missions. However, widespread use of these systems is hampered by many technical factors, including efficient conversion of directed jet power for thrust and generation of input power for fusion reactor operation. To address both challenges, the present authors propose using the novel power-generating magnetic nozzle; this nozzle uses high-strength magnetic fields for thrust generation and low-strength fields for power generation. Most approaches in the literature consider the effect of either the high-strength fields or the low-strength fields but, for this work, the authors would like to show their combined effect. To address this, we use two computational tools in tandem from prior work: the Smoothed Particle Fluid with Maxwell equation solver (SPFMax) and a plasma flux compression generator code. The former will determine the effect of the high-strength fields and the latter will determine the effect of the low-strength fields. Combined, they show the effect on thrust, efficiency, and power generation. The present authors find that the inclusion of a power-generation system reduces nozzle efficiency by 7% and thrust by the same amount, however, this is a relatively small reduction. The authors also confirm prior work regarding non-dimensional scaling parameters of the power generation system. These results reduce the technical risk associated with these nozzles, hopefully allowing for their application in current concepts/programs, make interplanetary trips safer and more reliable, and allowing humanity to venture out and explore the solar system.

JBIS VOLUME 76 NO.3 March 2023 Interstellar Issue		
Mission Concept and Development of the First Interstellar CubeSat Powered by Solar Sailing Technology	Piotr Fil et al	Imperial College London

Project Svarog is a student-led initiative aiming to reach the heliopause using a solar sail. Orbital models have proven the feasibility of the mission given the mass-to-area ratio of about 9 grams per square meter of the sail for a satellite launched on a piggyback mission to Mars. Solar sailing increases the flexibility of missions to the outer Solar System, as unique planet alignment, which was crucial for gravity assists is no longer required. Long-term missions require a better understanding of thin membrane behaviour since buckling of sail material under solar radiation pressure might cause the spacecraft to tumble unpredictably. Reduced order model of membrane deflection is thus coupled with orbital simulation, resulting in the determination of the operation regime, for which the mission escapes the Solar System. Additionally, vacuum chamber experiments designed to investigate the effects of solar radiation pressure and heating on the transient and steady-state behaviour of the sail have been devised. The system is designed to be built as a 6U CubeSat, being one of the first missions to utilise small-scale platforms for deep space missions. Granted that the first mission is successful, the Svarog system could also serve as a low-cost testbed for new technologies and research opportunities in deep space.

A Re-appraisal of the Challenges Associated with Detecting Alien Signals and Technosignatures	Gary S Robertshaw	Royal Astronomical Society

The Rare Earth Hypothesis contends that Earth's unusual formation and distinct evolutionary pathways led to the unlikely emergence of Homo sapiens. This contention is developed further by combining the universal principles of the Newtonian n-body problem and Darwinism to argue that there is also an inherent randomness in the sequence, timing, duration and nature of evolutionary outcomes on alien worlds. This has two important implications. Firstly, where alien life might emerge, evolutionary pathways must differ considerably to those on Earth. Within this, intelligence is not the goal of evolution nor is it necessarily the best adaptation for a given niche; there is no systematic, inexorable progression towards higher intelligence and technology. Secondly, the chances of an advanced alien civilisation emerging from a separate, random evolutionary pathway with matching technology, and proximate signalling in deep time are vanishingly small. This re-appraisal of the challenges associated with detecting alien signals has the advantage of using two key universal principles without relying explicitly on anthropocentric assumptions.

Application of the HeliosX ICF Advanced Propulsion Mission Analysis Code to Perturbed Interstellar Design Models	Kelvin F Long	Interstellar Research Centre, Stellar Engines Ltd,

HeliosX is a system integrated programming design tool which has the purpose of calculating spacecraft mission profile and propulsion performance for inertial confinement fusion (ICF) driven designs. This code uses the vehicle configuration input and capsule assumptions and then calculates the likely mission profile for a given destination target. The key technology is the inclusion of the fusion propulsion system and an adequate modelling of its likely energy outputs. This paper discusses calculations for perturbed design concepts from a baseline model in both series and parallel thrust mode. These new concepts are collectively known as the advanced baseline models which are presented in preliminary form under the names Resolution, Endeavour and Pegasus. These are for missions to 4.3 ly in trip times of less than 100 years for flyby and rendezvous configurations carrying a 150 tons payload. The designs utilise an ICF capsule mass of 0.288 g filled with $D^{-3}He$ fuel detonated at a pulse frequency in the range 100-150 Hz. The calculations show that the propulsion systems are characterised by thrusts 0.3-2 MNkg-1, jet powers 1.2-9.2 TW and specific powers 2.9-5.1 MWkg-1 for interstellar missions at 0.045-0.049c. In addition to the preliminary mission performance calculations we also discuss the philosophy and methodology used in the design evolution.

Acta Astronautica

Title	Number+date	Author	Affiliation
The inferred abundance of interstellar objects of technological origin	Volume 208 (July 2023)	Carson Ezell, Abraham Loeb	Harvard University

Interstellar objects discovered crossing through the solar system can either be natural objects or technological artifacts from extraterrestrial civilizations. Evidence from our own civilization suggests that early-stage technological civilizations are already able to launch artificial objects beyond their star system, and early-state to late-stage technological civilizations in the Milky Way may have an interest in exploring potentially habitable regions throughout the galaxy. Based on our rate of detection for both natural and artificial populations of interstellar objects, we can estimate their respective local number densities and the total quantity of such objects bound by the Milky Way thin disk. We propose a model for calculating the quantity of such objects based on their observed velocity and number density. We consider the relevance of our model given several detections of interstellar objects over the past decade, and we discuss the implications of the estimated quantity of both natural and artificial objects for understanding their nature and origin.

Operational performance parameter range in ICF propulsion theory	Volume 210 (September 2023)	Kelvin F Long	Interstellar Research Centre, Stellar Engines Ltd

This paper explores the operational performance parameter range for inertial confinement fusion propulsion systems under the assumption of best case and worst case mission scenarios. This includes the spacecraft thrust, jet power and specific power. We show the derivation of the key driving equations and then simplify these with approximations for ease of domain space analysis. This includes a consideration of minimum and maximum values for jet efficiency, momentum weighting factor, nozzle divergence angle, fuel burn-up fraction, capsule mass and detonation pulse frequency. It is estimated that the range of parameter values may be of order 0.001 N–100 MN thrust, 1000 W–1,000 TW jet power, 0.01 W/kg–10 GW/kg specific power. Although this range includes values that are likely outside the realistic design space of applicability and to show this data from published designs is also examined. The analysis is considered for reaction isotopes of low mass hydrogen and helium nuclei only and does not take into account the possibility of propellant expellant augmentation, vehicle staging, design optimality or enhanced fuel reactions.

Project Lyra: Another possible trajectory to 1I/'Oumuamua	Volume 211 (October 2023)	Adam Hibberd	i4is

The first interstellar object to be discovered, 1I/'Oumuamua, exhibited various unusual properties as it was tracked on its passage through the inner solar system in 2017/2018. In terms of the potential scientific return, a spacecraft mission to intercept and study it in situ would be invaluable. As an extension to previous Project Lyra studies, this paper elaborates an alternative mission to 1I/'Oumuamua, this time also requiring a Jupiter Oberth Manoeuvre (JOM) to accelerate the spacecraft towards its destination. The difference is in the combination of planetary flybys exploited to get to Jupiter, which includes a Mars encounter before proceeding to Jupiter. The trajectory identified is inferior to previous finds in terms of higher deltaV requirement (15.6 km/s), longer flight duration (29 years) and less mission preparation time (launch 2026), however it benefits from a feature absent from previous JOM candidates, in that there is little or no deltaV enroute to Jupiter (ie a free ride) which means the spacecraft need not carry a liquid propellant stage. This is marginally offset by the higher deltaV needed at Jupiter, requiring either 2 or 3 staged solid rocket motors. As an example, a Falcon Heavy Expendable with a CASTOR 30B booster followed by a STAR 48B can deliver 102 kg to 1I/'Oumuamua by the year 2059. Other scenarios with shorter flight durations and higher payload masses are possible.

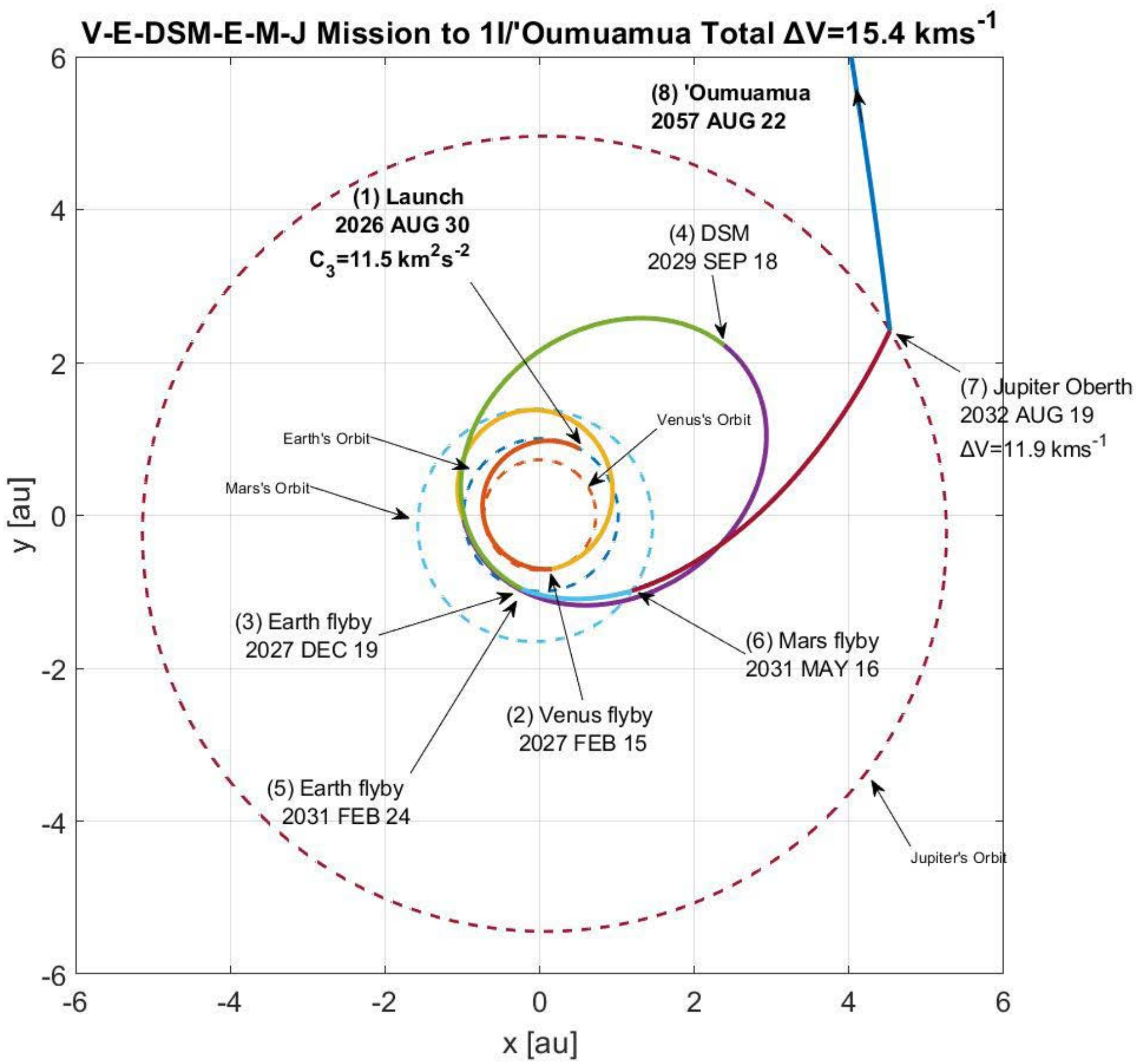


Illustration of trajectory from an earlier preprint version-
Project Lyra: There is Another Way Adam Hibberd. i4is.org/project-lyra-there-is-another-way/

BECOME AN i4is MEMBER

Let's aim for the stars!
Would you like to help drive the research needed for an interstellar future...
...and get the interstellar message to all humanity?

"The open road still softly calls, like a nearly forgotten song of childhood. We invest far-off places with a certain romance. This appeal, I suspect, has been meticulously crafted by natural selection as an essential element in our survival ... Catastrophic events have a way of sneaking up on us, of catching us unaware. Your own life, or your band's, or even your species' might be owed to a restless few - drawn, by a craving they can hardly articulate or understand, to undiscovered lands and new worlds."

Carl Sagan

If you like what you see in Principium, and want to help us do more, please consider becoming a member.

i4is was founded in 2012 and incorporated in both UK and USA in 2014. More than a decade on, we're making great strides in our technical research, education and outreach programmes. We are now recognised as a leading organisation in interstellar studies with worldwide activity and support. Try a Google Scholar search - i4is interstellar - for just a sample of our technical and scientific work.
The core team and our members are a growing community of enthusiasts who are passionate about taking the first steps beyond our solar system. Our ambitions are high, but to achieve them we need your support.
The best way you can support our mission is to become a subscribing member. If you wish, and you have the time, we would love you to get actively involved with our projects. But we appreciate that not everyone who shares our interstellar vision can do this. Becoming a member is a great way to show your support and help us expand our activities.
And it's not just about rockets and starships. Interstellar Studies raises questions about the place of our species in the universe, the nature of that universe and even fundamental questions about the nature of humanity.

Members have access to exclusive benefits, including:
• videos of i4is lectures and presentations;
• member-only talks on interstellar topics;
• early access to selected Principium articles before public release;
• regular newsletters keeping you up to date with the latest interstellar news; and
• corporate publications, including our annual report.

More details of the benefits of membership are on the i4is members' page, also in this issue of Principium. If you would like to join, please go to i4is.org/membership.

Join i4is and help us build our way to the Stars!
To find out more and join, see *i4is.org/membership*

THE i4iS MEMBERS' PAGE

Parnika Singh and John I Davies

The i4is membership scheme exists for anyone and everyone who wants to help us achieve an interstellar future. Your membership will help fund our technical research and educational outreach projects. In return, members receive many exclusive benefits, including our program of educational talks, a monthly newsletter, preprints, and access to the members-only area of the website which contains exciting tools and new material added on a regular basis. If you are passionate about an interstellar future for humanity, joining our membership scheme is the perfect way for you to get more involved while also helping us take the vital early steps towards finally reaching the stars. To find out more, visit www.i4is.org/membership.

i4is Book Club

i4is has recently launched a science fiction book club for readers and writers. We read and discuss stories that take the eyes above and beyond the horizon, that inspire minds and hearts to leap from here and now to tomorrow and elsewhere. We examine stories for their readability as well as for what we can learn from them as writers. Due to the worldwide nature of the i4is membership, this book club will be held once a month on Zoom. To join the club, please email bookclub@i4is.org for the link.

Members' Newsletter

The i4is Member's Newsletter is an exclusive newsletter that keeps you up to date with the most compelling interstellar advances, research, and news.
Since the last Principium issue, two such member newsletters have been delivered, including coverage of a variety of different developments pertaining to interstellar travel. This includes an announcement on the creation of a short story anthology by i4is members; information on the discovery of the potential remains of an interstellar meteor; summaries of exciting papers on the development of light-sail propulsion and deep space communication systems; and much more. If you are interested, be sure to become an i4is member!

New Search Facility

Using the alert database access kindly provided by our friends at the Interstellar Research Group (irg.space) we have created an enhanced search facility that searches all database fields as you type. We are working on adding additional features to this search soon, including filtering by category. This is another member's only feature, so remember to join i4is today to gain access to this exciting new tool. You can also request daily alerts from IRG directly by going to irg.space/interstellar-updates/ which is a site available to anyone interested in interstellar space – member or not.

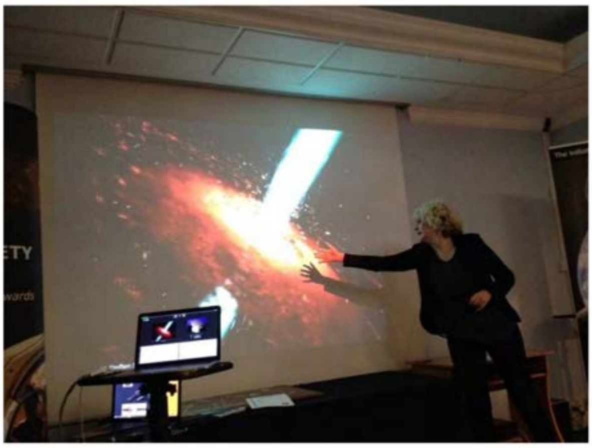
Getting More Actively Involved

i4is is always looking for volunteers to help support humanity's venture onto the interstellar stage. If taking a more active role in our work is of interest to you, we'd love to hear from you! There are many different ways you can help us take our programs forwards, whether your skills are technical, educational, administrative, or financial. The more volunteers we have, the more we can achieve! If you think you could volunteer some time, please get in touch at info@i4is.org, and one of us will get back to you as soon as possible.

The 2024 World Science Fiction Convention - Glasgow Scotland

i4is was at the last UK-based World Science Fiction Convention at Excel London in 2014. The SF world is important to us both in terms of outreach to a community which thinks about our future, our technologies and the "inner space" which we inevitably project on to the interstellar vision for our species.
We will be at the 2024 event in Glasgow (glasgow2024.org/) with both programme items and an exhibition presence. We already have both writers and thinkers interested in involvement and we will have another Big Object at a similar scale to our 4m high monolith (as in 2001: A Space Odyssey) in 2014.
If you plan to be there next year or if you might think about it then please get in touch - Glasgow24@i4is.org. Scotland is renowned for both its advanced technology and its SF connections (eg Iain M Banks, Charles Stross, Ken MacLeod, Gary Gibson).

NEXT ISSUE



Faster than light (FTL) travel
Silke Britzen and Remo Garattini at an i4is symposium from P30, *Wormholes Come to London*, in 2014

- **Current FTL thinking**: Faster than light (FTL) travel has been the subject of much serious thinking and it still engages the brains of some of the brightest on the planet but are we any nearer to achieving it other than in fiction? Parnika Singh, author of *An analysis of interstellar exploration focused on propulsion technologies* (Journal of High School Science 7.1, 2023) and Dr Dan Fries, Deputy Head of the i4is Technical Team, will review where things stand.
- 73rd International Astronautical Congress 2023, The Interstellar Papers: A first report on **IAC23**, as previewed in this issue.
- IRG 8th Interstellar Symposium 2023 - a review of papers and presentations.
- **plus** Interstellar News and interstellar papers in The Journals.

Interstellar thinking from 100 years ago

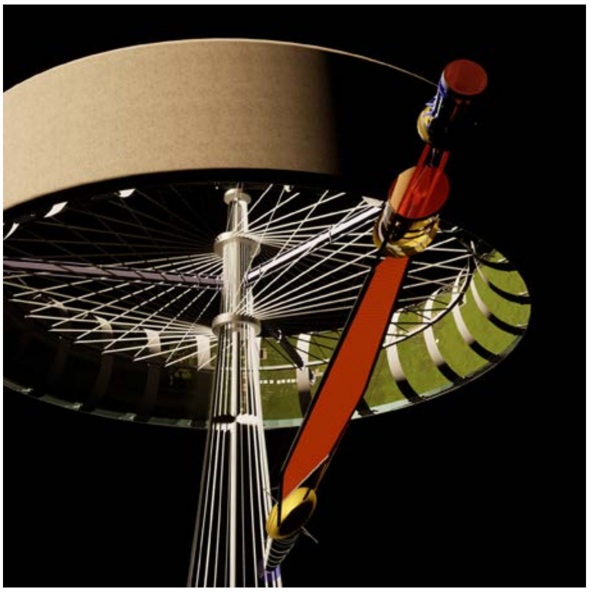
This parallel beam of electric or even light (solar) rays should exert pressure by itself (there can be no doubt that such pressure exists), such pressure can give the vehicle a sufficient speed. In that case, one would not need any supplies for ejection.
The last method would seem to be the most refined.

K E Tsiolkovsky

COVER IMAGES

Our cover images for this issue look at our own Solar System both as it is and as one small part of it might be if we build a big interstellar probe.

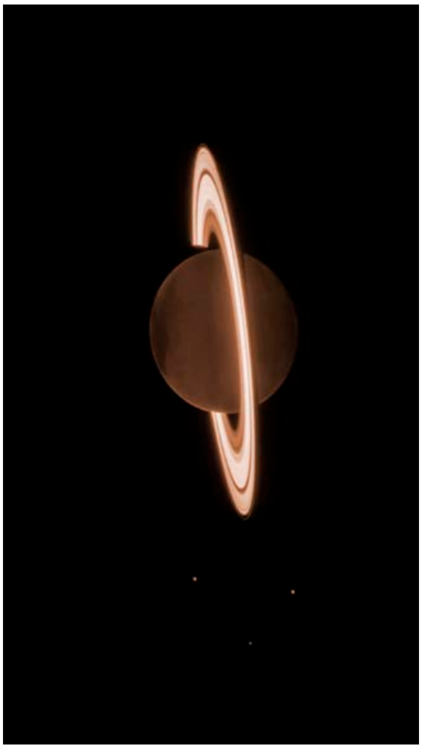
FRONT COVER



The fast and the slow bot to the stars

Description by artist and engineer Michel Lamontagne, "It shows a fast fusion starship, similar to Firefly, that is approaching a much slower generation ship sometime during its long journey to another star. The fusion ship has crossed the distance from Earth to the Worldship in a few years, while the Worldship has been on its way for centuries. The radiators and nozzle are cooling down from their bright white color after the last deceleration burn. Perhaps it is carrying critical supplies, or new crewmembers in cryosleep. It will resupply from the ample fuel stores of the generation ship and return home, or perhaps go on ahead to the target system, a different star or another generation ship on a similar trajectory.". www.deviantart.com/michel-lamontagne/art/Closing-in-975944347

BACK COVER



A strange but familiar planet from the JWST

Saturn from the James Webb Space Telescope NIRCam (Near-Infrared Camera). Image taken on 25 June 2023 - webbtelescope.org/contents/media/images/01H3X9BMPCX165ZK9RA49J2416

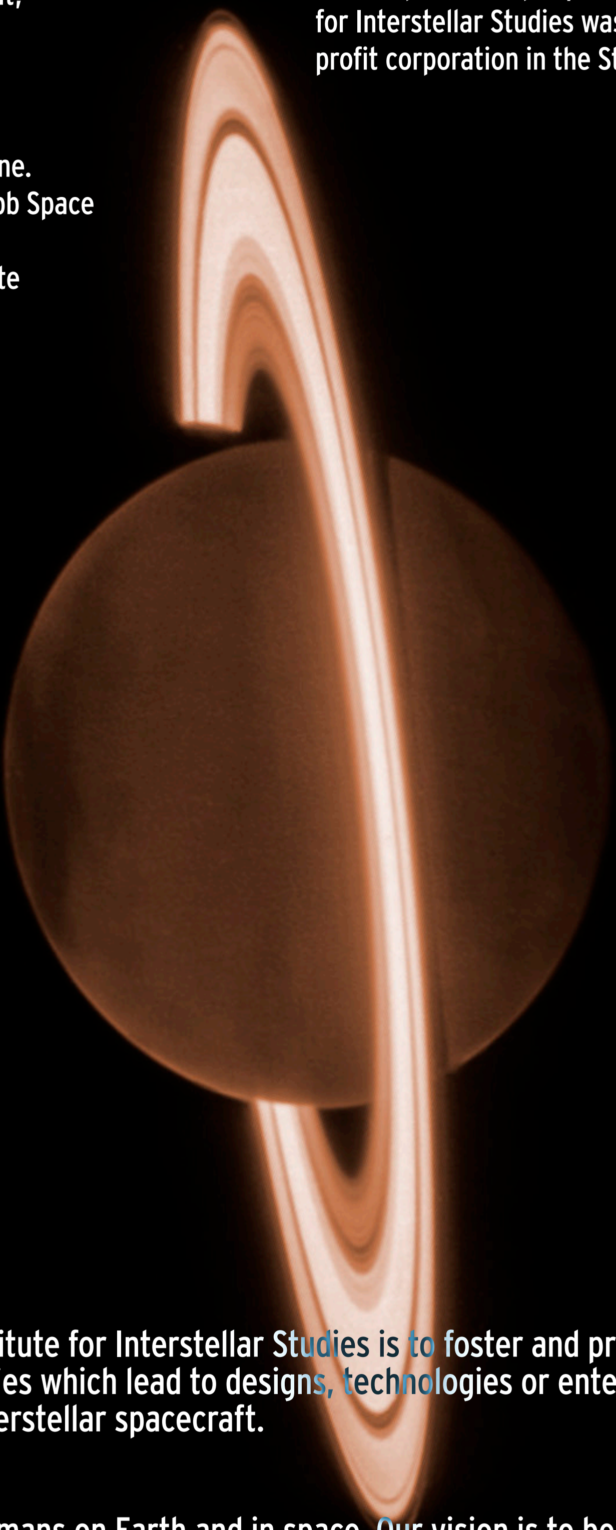
NASA comments "Saturn itself appears extremely dark at this infrared wavelength observed by the telescope, as methane gas absorbs almost all of the sunlight falling on the atmosphere. However, the icy rings stay relatively bright...". When will we see another planet as remarkable as Saturn? When will our probes visit it? If it has habitable moons then might some of our descendants live there?

Credits: NASA, ESA, CSA, STScI. See web page for full individual credits.

EDITOR: John I Davies
DEPUTY EDITORS: Patrick J Mahon, Andreas M Hein
CONTRIBUTING EDITOR: Samar AbdelFattah
LAYOUT/PROOF: John I Davies, Carol Wright, Lindsay Wakeman

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.

Front cover: The Icarus Firefly probe.
Credit {visualisation): Michel Lamontagne.
Back cover: Saturn from the James Webb Space Telescope (JWST).
Credit: Space Telescope Science Institute



SCIENTIA AD SIDERA
KNOWLEDGE TO THE STARS

Mission

The mission of the Initiative & Institute 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 look to a positive future for humans on Earth and in space. Our vision is to be an organisation catalysing the conditions in society supporting a sustainable space-based economy. Over the next century and beyond we aim to enable robotic and human exploration of space beyond our Solar System and to other stars. Ultimately we envisage our species as the basis for an interstellar civilisation.

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.

I4IS.ORG