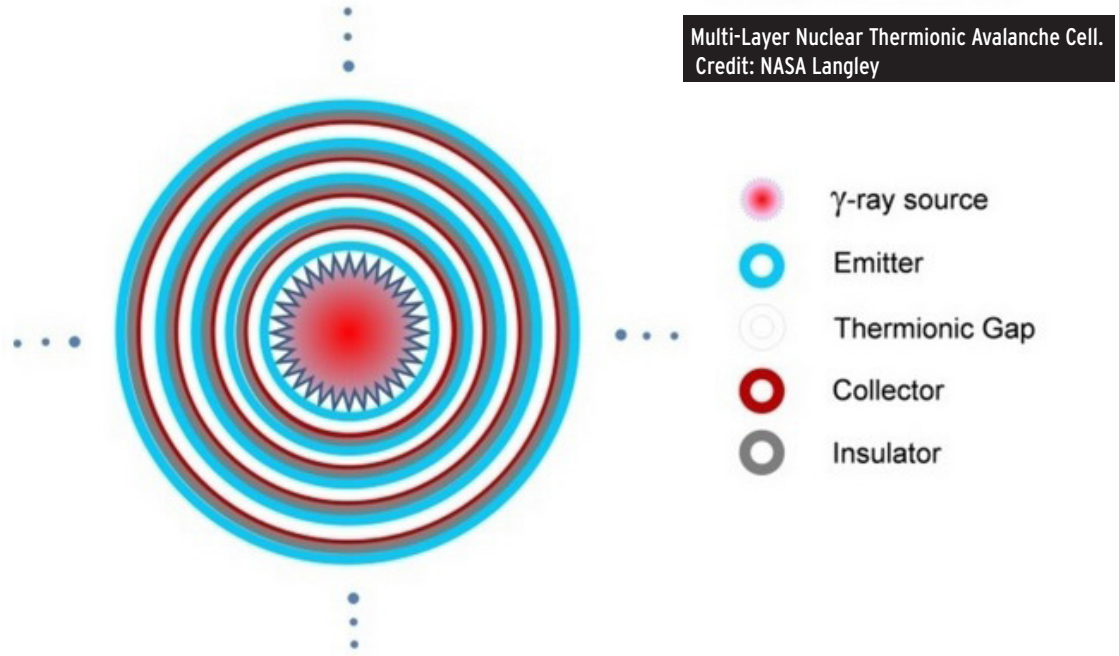
John I Davies reports on recent developments in interstellar studies

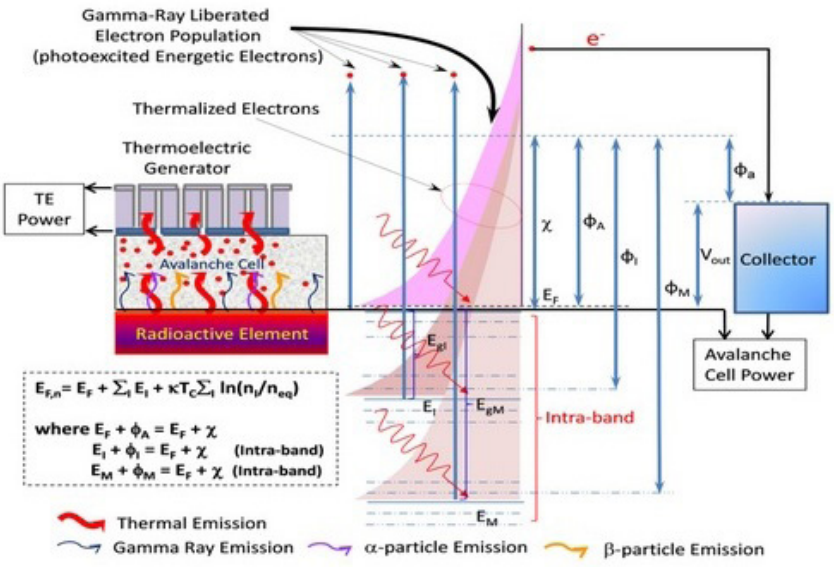
An RTG replacement?

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



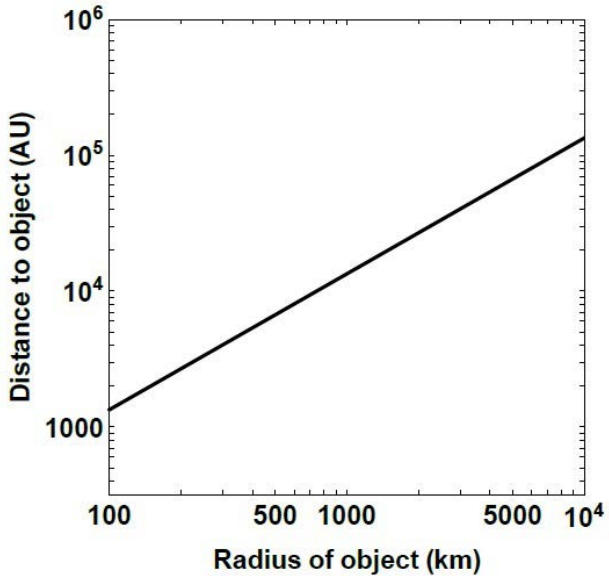
Multi-Layer Nuclear Thermionic Avalanche Cell. Credit: NASA Langley



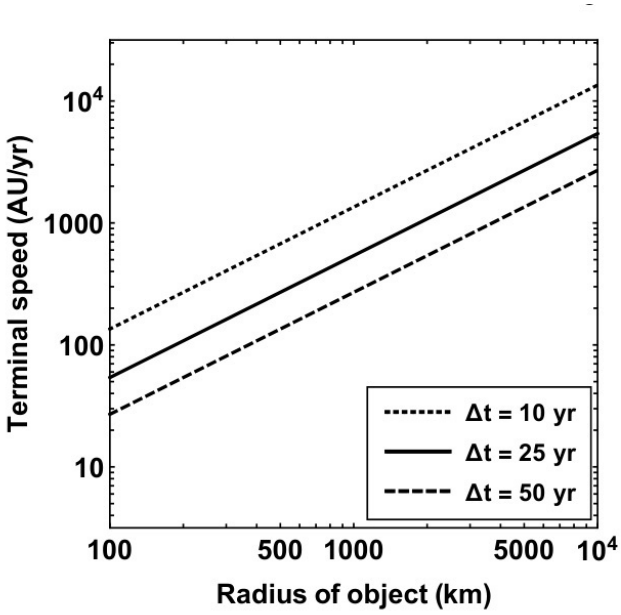
[1] en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator#Space

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

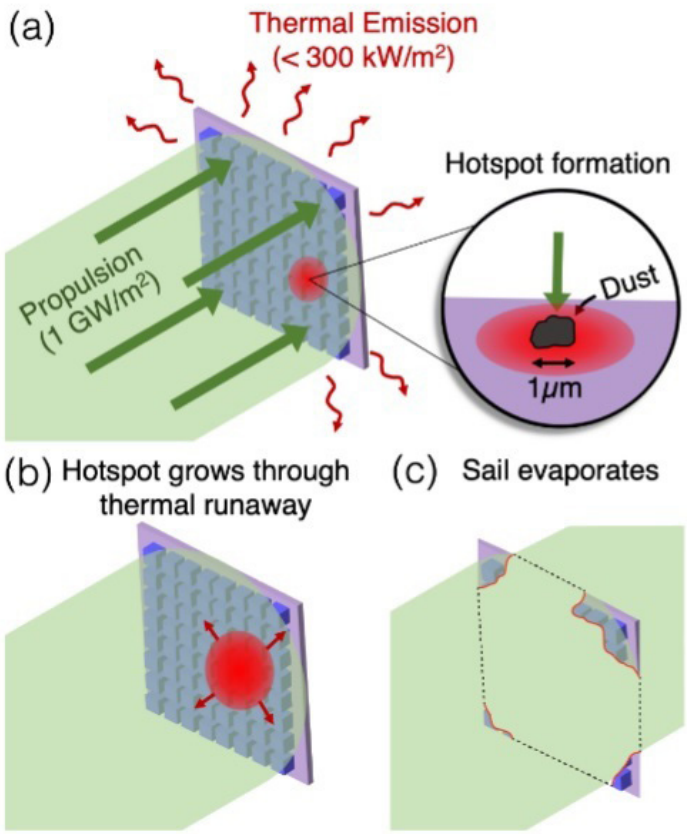
Solar cells from lunar regolith

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.

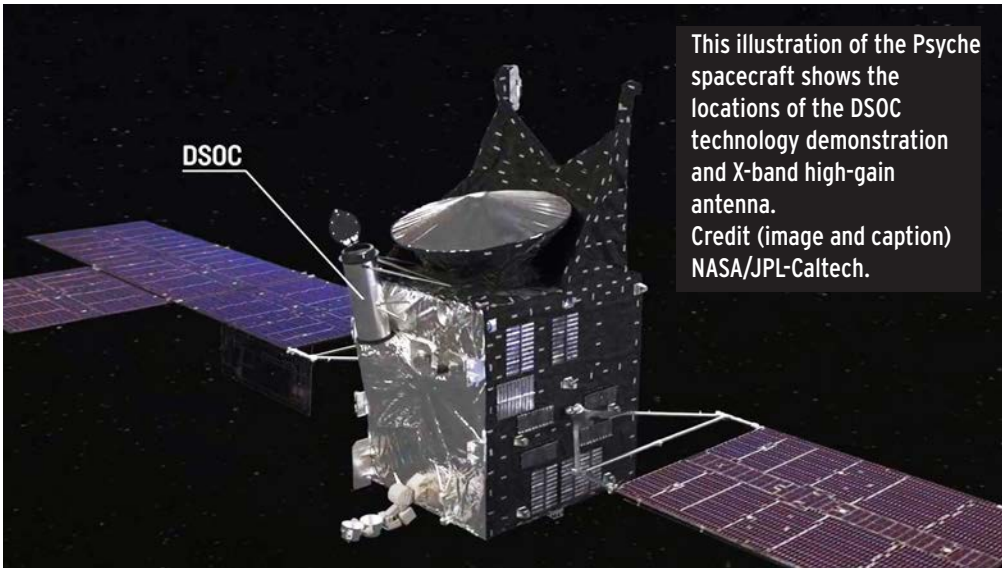
[1] P F McManamon and W Thompson (both US Air Force Research Laboratory) *Phased array of phased arrays (PAPA) laser systems architecture*, Proceedings, IEEE Aerospace Conference, Big Sky, MT, USA, 2002, www.researchgate.net/profile/Paul-Mcmanamon-2/publication/3968609_Phased_Array_of_Phased_Arrays_PAPA_Laser_Systems_Architecture/links/00b7d53c6a42f3342d000000/P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

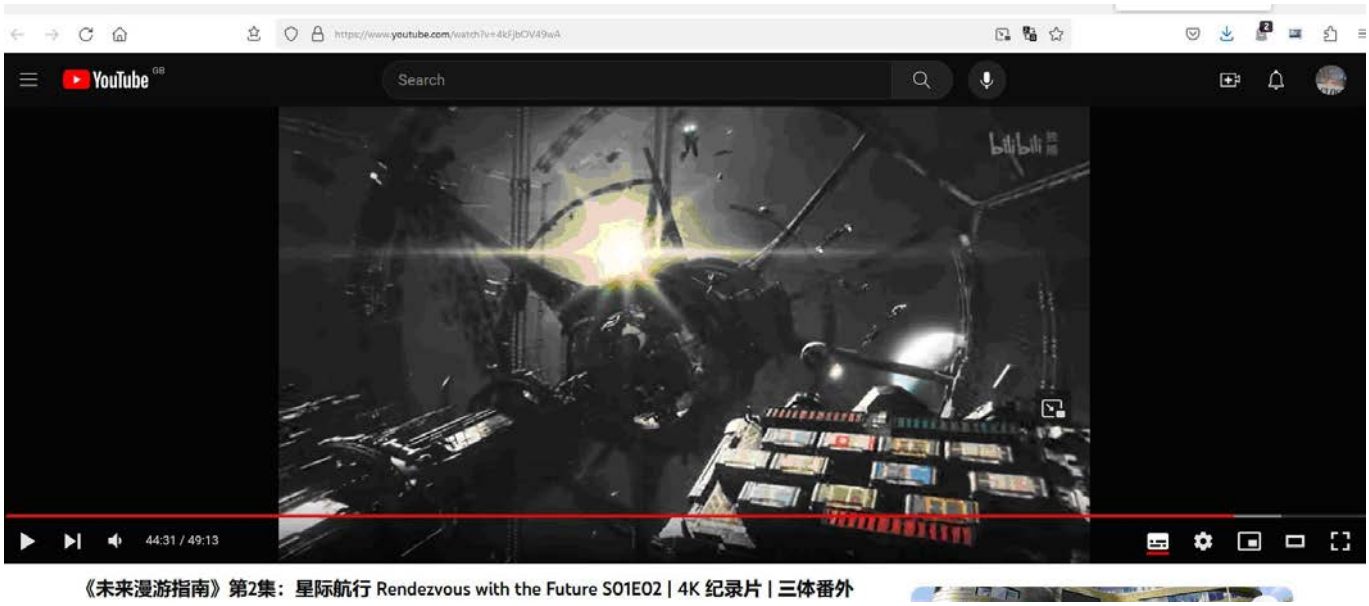
Episode 3 www.youtube.com/watch?v=4oDhA09bX9Q

- 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.

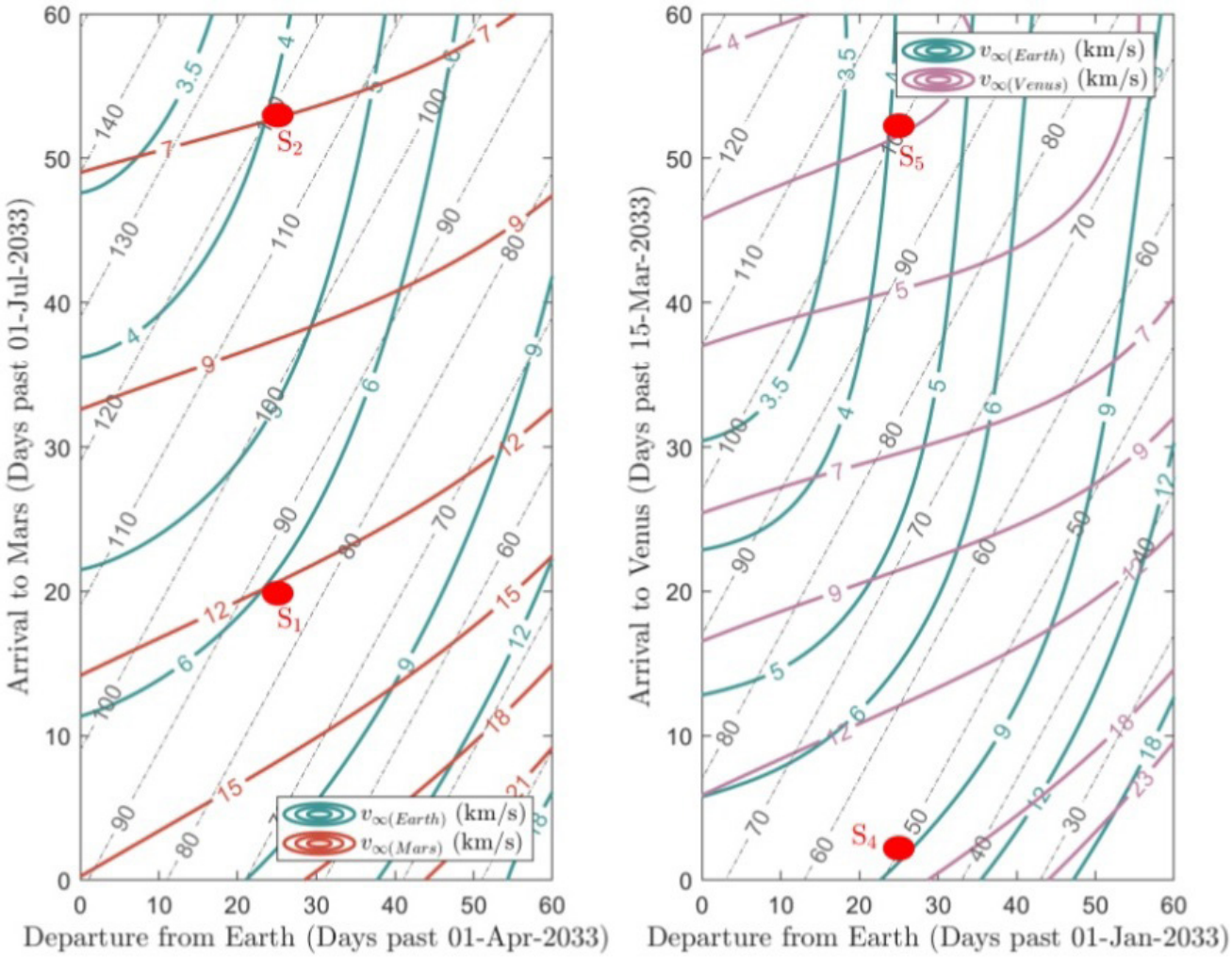
As Liu Cixin observes in the series "I think if humans want to survive, our only choice is to expand our living space in the universe. Like HG Wells once said: Human beings will either fill the universe or perish completely. There is no other choice."

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

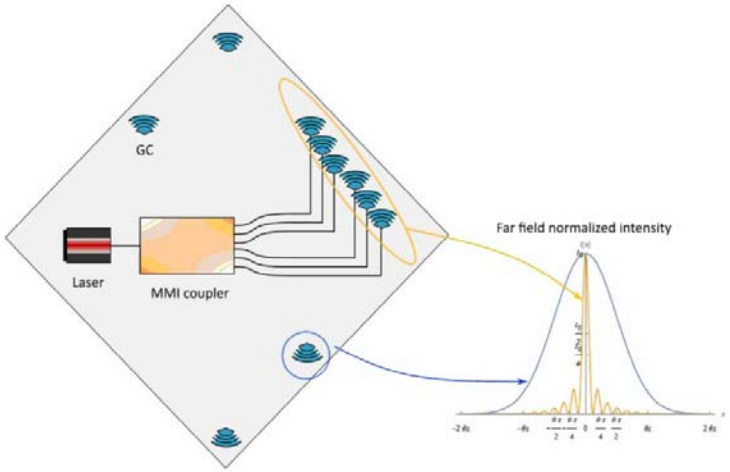
In *Interstellar Object Uncertainty Evolution and Effect on Fast Flyby Delivery and Required Delta-V* (arxiv.org/abs/2307.11887) Declan M Mages, Davide Farnocchia, Benjamin Donitz (all JPL/Caltech) consider (relatively) prompt missions to intercept new ISOs. They assume "With current propulsion technology, 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.

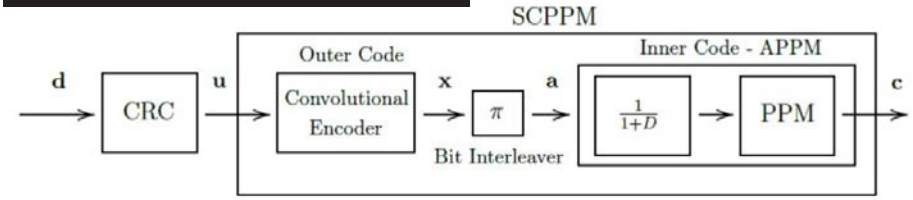
The Tree of Light

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