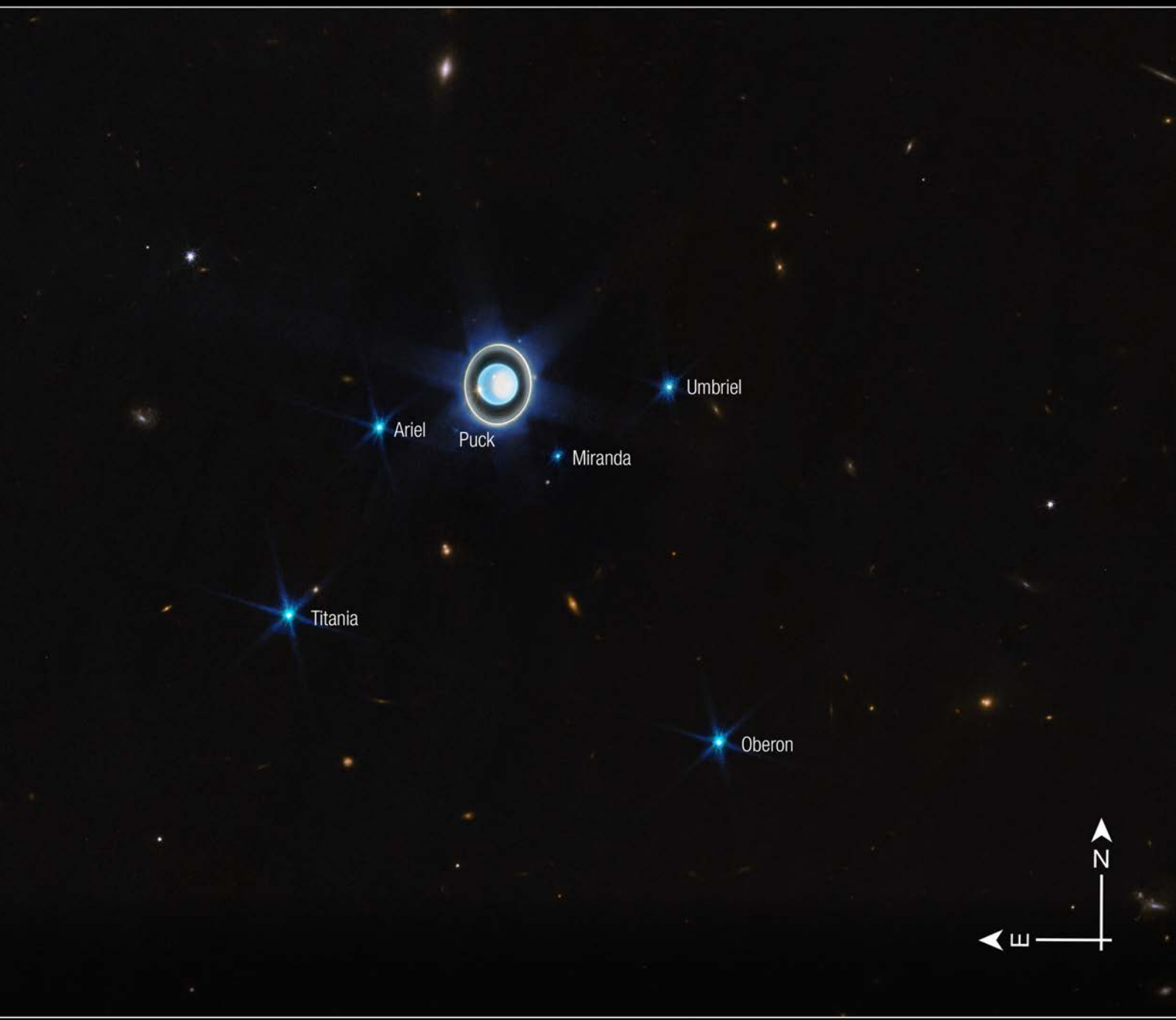
PRINCIPIUM

The Initiative and Institute for Interstellar Studies | Issue 41 | May 2023

SCIENTIA AD SIDERA | KNOWLEDGE TO THE STARS

URANUS | FEBRUARY 6, 2023



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EDITORIAL

Welcome to issue 41 of Principium, the quarterly magazine of i4is, the Initiative and Institute for Interstellar Studies. Our lead feature this time is a review of a new book *Astrotopia: The Dangerous Religion of the Corporate Space Race,* a critique by Mary-Jane Rubenstein, Professor of Religion and Science in Society at Wesleyan University. The front cover image this time is the Uranus system as seen by the JWST. The rear cover image is a visualisation of the Icarus Firefly probe by one of its investigators, Michel Lamontagne. More about both covers in *Cover Images* inside the rear cover.

We have 13 pages of Interstellar News and 3 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*.

A major news item is completion of that i4is project in communications on behalf of Breakthrough Starshot, in a Principium News Feature, *i4is delivers Communications Study to Breakthrough Starshot* and another News Feature, *Rob Swinney at the Royal Aeronautical Society*, briefing aerospace professionals on the opportunities for interstellar.

We anticipate the major interstellar event of the year, the 8th Interstellar Symposium, at McGill University, Montreal (July 10 – 13) in *IRG23 Preview*.

We have two articles from our chief astrodynamicist, Adam Hibberd-

- *Cost-Optimal System Performance Maps for Laser-Accelerated Sailcraft*, examining in greater detail Dr Kevin Parkin's paper to the 2022 International Astronautical Congress 2022 and
- *Project Lyra: What SpaceX could do*, an analysis of the potential of the two SpaceX "heavyweights", the Falcon Heavy Expendable and the Super-Heavy Starship combination.

The next issue, in July, will include -

- a review of *Conflicting Models for the Origin of Life* a new collection of papers discussing our own origins and those of non-humans, sentient and otherwise.
- A first report on IRG23, as previewed in this issue
- a review of Current faster than light (FTL) thinking (postponed from this issue)
- A new way of finding out what's happening in interstellar studies (to be announced to members first)

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

And if you would like to help in any part of ***Working towards the real Final Frontier*** then please take a look at our poster, full-size on page 18. There's lots to do!

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!

John I Davies, Editor, john.davies@i4is.org	**Patrick Mahon, Deputy Editor,** patrick.mahon@i4is.org

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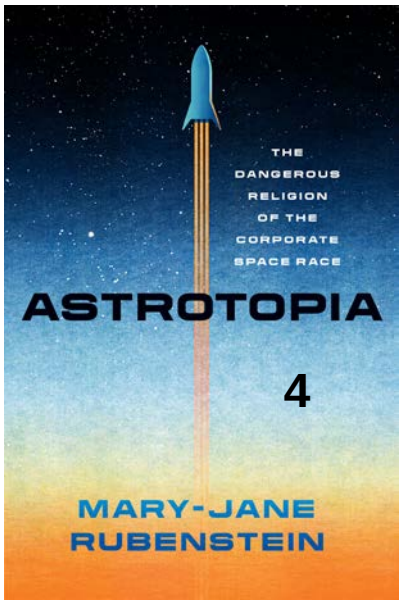

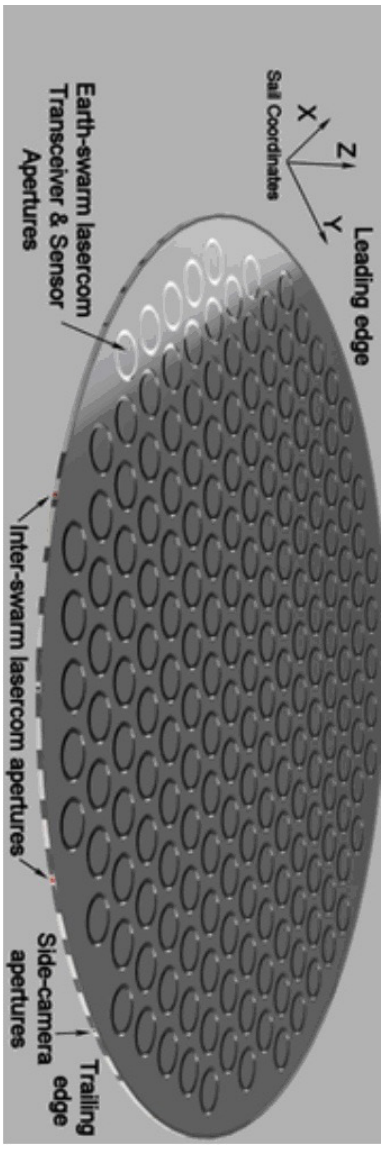

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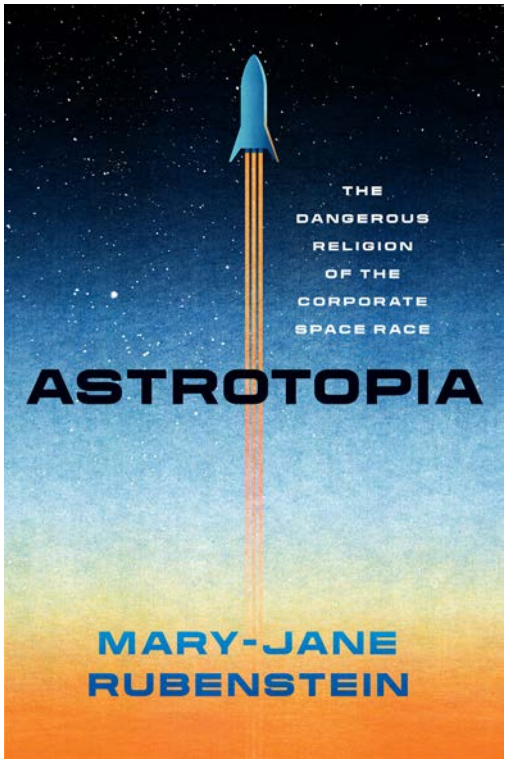
BOOK REVIEW: Astrotopia: The Dangerous Religion of the Corporate Space Race

Patrick Mahon

In *Astrotopia: The Dangerous Religion of the Corporate Space Race*, (The University of Chicago Press, 2022) Mary-Jane Rubenstein, Professor of Religion and Science in Society at Wesleyan University (mrubenstein.faculty.wesleyan.edu/), examines the corporate space race and its implications for our future. Do we want to "colonise the Solar System"? Can we put cosmic caretaking ahead of imperialism and profiteering?

Here our deputy editor Patrick Mahon reviews the book.



1 Introduction

I imagine that most readers of Principium count themselves as members of the space advocacy community, and are therefore likely to think that the acceleration in the number of space missions over the last decade or so, not least because of the growth of the commercial space sector, is a good thing. If space exploration is a valuable activity, it follows that the more of it there is, the better.

Professor Mary-Jane Rubenstein. Credit: /mrubenstein.faculty.wesleyan.edu/

Of course, just like any other activity, not everything about space exploration is wholly positive. Rocket launches create atmospheric pollution, and most of them add to the ever-growing problem of orbiting space junk.

The increasing militarisation of space – as highlighted by the creation by President Trump, in early 2020, of the US Space Force – would seem to run contrary to the declaration in the UN Outer Space Treaty of 1967 that space must only be used 'for peaceful purposes'. And the money spent on space exploration is not available to be spent on other activities, such as improving living standards or protecting the environment, which some people may see as a higher priority – particularly if the money in question ultimately comes from taxpayers.

Although some space advocates (including Elon Musk, if his public pronouncements are anything to go by) have little time for such criticisms, I think that many would acknowledge that activities in space do have some downsides – just like everything else. On balance though, they probably believe – as I certainly do – that activities in space do more good than harm, and are a valuable use of the money spent on them.

Professor Mary-Jane Rubenstein is *not* an advocate of space exploration – at least, not in its current guise. She likes space as a topic to inspire her children, and she seems to like the astronomy students that sometimes attend her classes. But when it comes to the *exploration* of space, she is particularly critical of the rapid recent growth in private space companies in the USA – the so-called *NewSpace* sector – and its two most well-known examples: Elon Musk, owner of SpaceX, and Jeff Bezos, owner of Blue Origin. *Astrotopia* explains her concerns, through the lens of her academic specialism, the study of religion.

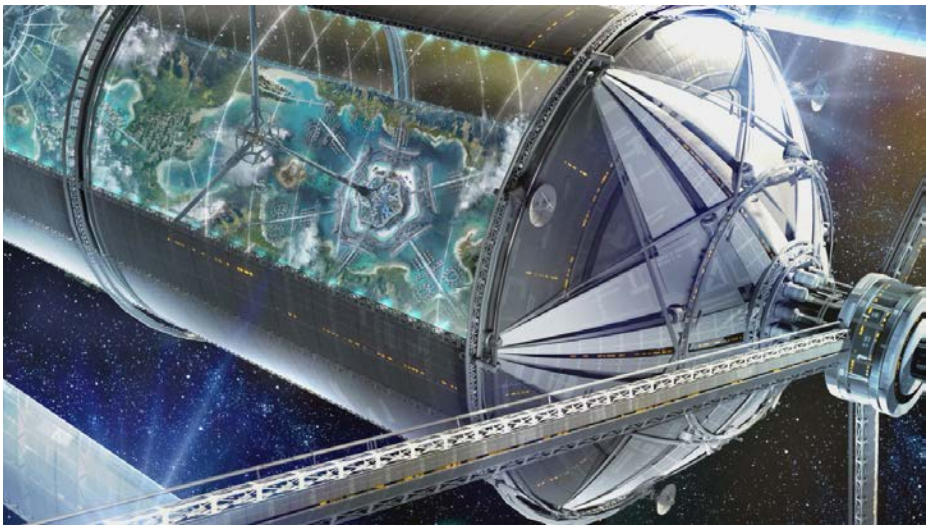
You might well ask what religion has to do with space – and thus, what reason Professor Rubenstein has for thinking that she is qualified to critique the activities of the space sector. Rubenstein anticipates this question in the Preface and Introduction to the book. Her argument, in summary, is that much, if not most, of the current and planned activity of the *NewSpace* sector, as exemplified by Musk and Bezos, represents an off-planet repeat of capitalist projects of the past, tainted by the same colonialist attitudes that led Europeans to claim Africa, America and Australia for themselves, regardless of the views of those who already lived in those lands.

SpaceX vision of a Mars city. Note two SpaceX "Starship" vehicles on landing/ launch pads on the left

Rubenstein's view is that, in an attempt to sidestep these criticisms, the vision and mission of *NewSpace* advocates – including NASA and the US Government – is stated in the same mythological and religious terms as were used for those previous projects. Space is America's 'manifest destiny', according to US Presidents from Kennedy to Trump, in just the same way that the settlement of North America was previously stated to be. And both Musk and Bezos insist that humanity has to move off Earth to avoid possible future catastrophes, which Rubenstein sees as a mythological justification as the probability of the disasters in question taking place is highly uncertain. As a result, Rubenstein sees a religious lens as precisely the one to use when critiquing what she believes many *NewSpace* advocates intend for our future in space. Professor Rubenstein doesn't only criticise others though. She also makes clear in the early pages that she plans to propose an alternate future for space exploration, based on ecological, humanist and decolonial principles. We'll look at her proposals later. The bulk of the book is structured into seven chapters. I will briefly summarise and discuss each of them in turn below.

1 Two Visions

Chapter One is titled 'Our Infinite Future in Infinite Space'. In it, Rubenstein uses Elon Musk and Jeff Bezos as her two key examples of what *NewSpace* is all about, and compares the approach of the two men. Using an analogy with science fiction on TV and in films, she sees Musk as *Star Wars* – flashy, loud, and showy – and Bezos as *Star Trek* – quieter, more thoughtful, and interested in the detail. She also contrasts their visions for the future: Musk wants to settle Mars, in order to make humanity a multi-planet species and reduce the risk of total annihilation of humankind if a planetary disaster afflicts the Earth. Bezos, on the other hand, has little interest in Mars, and is more focused on building the sorts of orbiting space habitats envisaged by Professor Gerard K O'Neill at Princeton in the 1970s, when Bezos was a student there. His rationale for getting off-planet is to move heavy industry away from Earth, both to reduce the pollution of our 'pale blue dot' and to take advantage of the potentially almost infinite supply of the materials and energy needed by an industrial society, once we're able to mine the asteroids.



The O'Neill colony as envisaged by Gerard K O'Neill and favoured by Bezos

Having established her view of what *NewSpace* is about, she suggests that this new industry is not well regulated, and indeed has been massively supported in recent years by the US Government, with NASA essentially privatising many of their more routine space launch activities, while Congress legislated in 2015 to improve the competitive position of commercial space launch operators. She finishes the chapter by noting that not only has there been economic and legislative support for *NewSpace* in the US, but also political support filtered through a theological lens, particularly from Mike Pence, Donald Trump's Vice-President between 2017 and 2021. Pence, an evangelical Christian, gave speeches asserting that it was America's 'manifest destiny' to conquer the stars in God's name, and quoting the Bible to support his point. This first chapter provides a useful introduction to some of Professor Rubenstein's key concerns. Her characterisations of Elon Musk's and Jeff Bezos's contrasting approaches to space exploration appear to be accurate. My only real concern is that she seems to believe that there is nothing more to the commercial space sector than the operations of these two men. While it is undoubtedly true that they dominate the headlines, there are hundreds, if not thousands of other companies in this sector, not just in the USA but around the world, that are using space for very different purposes, including many – such as environmental monitoring – that she would seem likely to be supportive of. It's a pity that the book fails to acknowledge this broader picture of what the *NewSpace* sector does.

2 Creation and Conquest

In Chapter Two ('Creation and Conquest'), Professor Rubenstein reviews the influence of Christianity on the modern western worldview. Her contention is that the tenets of the Old Testament underpin much of our approach to politics, ethics and science, despite many western societies having become much more secular over recent decades. I took away two main points.

The first is that we have moved away from the worldview of many pre-Christian societies, which included animist beliefs in their religions, valuing and respecting other species and the natural world in which we live, and ascribing inherent value to them. These views have been replaced by one based on the first book of the Old Testament, Genesis, which states that

God created the entire Earth for mankind's benefit, that only humans have eternal souls, and that it is therefore right and proper for us to have dominion over everything else on the planet, whether animal, vegetable or mineral. It all exists entirely for our benefit, and has no inherent value of its own. This viewpoint underpins our subsequent relationship with the world around us, from the invention of farming to the industrial revolution and beyond, where exploitation of the planet's resources is the default position, and scientific research is not just about enabling us to *understand* nature, but supports the development of new technologies that allow us to *exploit* it more effectively.

The second point that Professor Rubenstein makes follows from the above, and from reading further into the Old Testament. At various points through the first six books, God tells his chosen people, the Israelites, that he has set aside Canaan – the 'promised land' – for them, and that he wants them to take it away from those currently living there, since they believe in different gods, not Him. Non-believers do not count, and should either be converted to the one true religion, or eliminated. This biblical story has been appropriated by others to justify colonialism, and is now being used by the US Government to justify America's right to expand into space.

Given that religion is Professor Rubenstein's area of expertise, it's unsurprising that this chapter provides a clear and insightful statement of her position. As someone whose first degree was in physics, and who is broadly secular, I expected there to be little overlap between religion and our modern Western worldview. So it was a surprise to recognise the validity of the points she makes here, particularly in relation to the way that Old Testament teachings on the primacy of humans over the rest of nature feed through to the ethical worldview that underpins much of science, technology and our approach to exploiting the world around us.

3 Promised Land - or Colonialism?

Chapter Three is titled 'The American Promised Land', and explains in more detail how the USA, from the founding fathers onwards, has seen itself as the inheritor of many of those Old Testament stories. Seemingly as an aside, she notes the activities of Dennis M Hope, a Californian who has made himself rich by setting up a business selling small plots on the Moon, Mars and elsewhere in the solar system to anyone who is silly enough to pay him $25 for a certificate asserting that they now own a certain area. Obviously Mr Hope has no legal right to do this, and his customers don't actually 'own' the plots in question. But Rubenstein's point is that, although what Mr Hope is doing is clearly a scam, it's no more ridiculous than the fact that, in 1455, the then-Pope granted most of Africa to Portugal, and then in 1492, a later Pope gave Spain dominion over North America. In both cases this was done regardless of the views of the indigenous people. In the view of the 15th century Catholic Church, they didn't count because they weren't Christians. And this viewpoint came directly from the statements in the early books of the Old Testament, granting God's followers dominion over the entire Earth. Rubenstein notes that a direct consequence of this theological argument, explicitly recognised by the church, was that all the resources found in those lands – gold, precious stones, and

anything else of value – was also the property of the church, or the country they'd gifted it to. Unsurprisingly, this same argument was recycled in the mid-19th century by American settlers when they were debating whether to annex Texas, Oregon and California. The phrase 'manifest destiny' was coined at this time, and it became a shorthand for the American borrowing of the biblical argument: Christian Americans were claiming the land – and its plentiful resources – for God. The indigenous people, as non-Christians, had no say in the matter.

The chapter closes by noting that many *NewSpace* proponents, including the Trump administration, have adopted this same rhetoric of 'manifest destiny' when talking about America's role in space over the coming decades. And although space may not have indigenous people to worry about, it certainly has lots of resources to claim.

I found the historical detail of the Catholic church's direct involvement in colonialism fascinating here, even if it was deeply disturbing at the same time. However, this chapter also raised one of my key concerns about this book. There is a lot of focus, here and in later chapters, on the damage caused by historic colonialism to the peoples who were subjugated. That is, of course, an extremely valid topic for discussion. However, this discussion is then transplanted wholesale to the issue of the future exploration of our solar system, without any proper acknowledgement of the massive difference between the two situations.

Rather obviously, there are no advanced, intelligent lifeforms – whether human or extra-terrestrial – on the Moon, Mars or, as far as we can tell, elsewhere in the solar system. It is possible that primitive life existed on Mars a long time ago, since it appears that liquid water once flowed on its surface. It is even possible that bacteria are still alive today in the sub-surface permafrost on Mars, just as this may also be true of the sub-surface oceans

A humourous but pessimistic view of the US space programme in October 1958 - complete with LGM labour driving Soviet tractors. The Vanguard launchers orbited just 3 satellites out of 11 launch attempts. The Juno I launchers were more successful.
Credit: Carl Giles/Daily Express

of Jupiter's moon Europa and Saturn's moon Enceladus, or even in the clouds of Venus. But in all cases, we're talking microscopic bacteria. Not macroscopic intelligent beings who could be subjugated. The point is briefly alluded to, but almost immediately dismissed as a minor detail. And yet it seems to me to weaken the parallels between historical colonialism and the future exploration of the solar system very significantly indeed.

4 The Final Frontier?

In Chapter Four ('The Final Frontier'), Professor Rubenstein examines the USA's activities over the early decades of the space race, from Sputnik to Apollo. She notes the evident contradiction between the repeated demands of US politicians, in the aftermath of Sputnik-1, that America must 'win' the space race and 'control' outer space, and the many speeches from US Presidents which insisted that the US was acting 'for all mankind'.

Rubenstein then fast-forwards to Apollo 8's circumnavigation of the Moon in late 1968, and focuses on the fact that the crew chose, during their live broadcast back to Earth on Christmas Eve, to read the creation story from the first book of Genesis. She questions why they chose to read this, rather than a secular text, and concludes that it was part of the US mission to claim the Moon on behalf of Christianity – not least in opposition to a Soviet Union which was officially atheist.

The last part of this chapter notes that national defence has always been part of the rationale for the space programme, going right back to President Eisenhower's public pronouncements in 1958, shortly after Sputnik. However, the emphasis on defence has recently been brought to centre stage by President Trump's creation in the last year of his administration, of the hilariously-titled 'Space Force'. But how does this increased focus on military activities in space square with the requirements of the 1967 UN Outer Space Treaty?

My main comment on Chapter Four is that I felt Professor Rubenstein might be at risk of the same fault here that is true of any of us with a particular specialism: that of having a hammer, and therefore seeing everything as a nail. It seems to me much more reasonable to explain how NASA and the US Government acted during the space race as a direct response to the global geopolitics of the Cold War and the reality that America was self-evidently the most powerful member of the Western Alliance – and the only one with the capability to launch humans into space – rather than to see it as some kind of imperialist plot to win space for Christianity.

"Earthrise" perhaps the most influential image from the entire Appllo prgramme. Credit: NASA/Bill Anders

In a related vein, I was unconvinced by her assertion that the Apollo 8 crew read out the first lines from the Book of Genesis, in their public broadcast on Christmas Eve 1968, as part of a US plan to claim the Moon for God, in opposition to the atheists in the USSR.

The Command Module pilot on the Apollo 8 mission, Jim Lovell, subsequently co-wrote with Jeffrey Kluger the book, 'Lost Moon: the Perilous Voyage of Apollo 13' (1994) about his ill-fated, but much more famous, second journey to the Moon as the Commander of the Apollo 13 mission. Near the end of chapter 2 in that book, he recounts the circumstances of the Genesis reading, and makes it clear that the choice of reading material was the crew's, not NASA management's. And their rationale for choosing that text was simple: they were reading it 'on the eve of the holiest day in the Christian calendar'. Reading out some biblical text about the creation of the world on that date, when you're the first three humans in history *ever* to be able to see the whole globe of the Earth from a quarter of a million miles away, seems to me an entirely reasonable personal choice for the crew to have made themselves.

5 Who owns space?

Chapter Five is titled 'Whose Space Is It' and begins with a discussion which will, I imagine, be familiar to most readers of Principium. It concerns both the purpose and the value of space travel, with Rubenstein referencing the many critics who argue that space travel is a waste of time and a huge waste of money which 'could be better spent back on Earth'. This criticism came to the fore during the Apollo programme, perhaps most famously epitomised by Gil Scott-Heron's spoken poem 'Whitey on the Moon' [1]. It is now rearing its head again, prompted particularly by the recent wave of space tourism missions.

Rubenstein goes on to talk about the geopolitical response to the space race. The United Nations set up its Committee on the Peaceful Uses of Outer Space (COPUOS) in 1959, and this committee has subsequently produced several pieces of international law, most notably the 1967 Outer Space Treaty. This legislation initially appears to be very helpful to Rubenstein's argument, for three reasons. It insists that space 'is not subject to national appropriation', is to be used 'for the benefit of all peoples', and must only be used 'for peaceful purposes'. Unfortunately, as the author acknowledges, there are caveats within the Treaty wording on all these points, watering them down and providing loopholes, such as the one which allows the US Government to create a 'Space Force'. Following the Apollo landings on the Moon, COPUOS drafted a Moon Treaty which, amongst other things, said that the Moon is 'the common heritage of mankind', and as a result, any resources extracted from the Moon would be subject to 'equitable sharing' by all State Parties. Although this Treaty has been signed by several countries, none have their own space programmes. The main countries that *do* have a space programme all refused to ratify the Treaty, so its provisions have no real-world effect. As a consequence, it was legally permissible for Congress to pass the 2015 Commercial Space Launch Competitiveness Act, which allows any US citizen or corporation to claim any space resources they manage to extract, whether on the Moon or anywhere else. Many people contest the ethical validity of this legislation, but it does seem to be legally watertight.

[1] Gil Scott-Heron's poem is very audible in the sound track of the Neil Armstrong biopic *First Man* (2018).

This brings us to the heart of Rubenstein's argument: *NewSpace* is all about the capitalist exploitation of space resources, not about ensuring that space remains the common heritage of all humanity. But to what end? She would prefer that the money be spent down here on Earth, solving social problems. But she also doesn't see what the point is of mining space for resources, if all you do with those resources is use them to expand your mining activities. To Rubenstein, the whole argument appears circular – go to space to mine resources, so that you can go further out to mine more resources, so that … And in the meantime, every launch creates more space junk in orbit around our planet. What's the point?

Unsurprisingly, as a keen advocate of space exploration, I don't agree with the argument that space exploration is pointless and the money should instead be spent down on Earth. The counter-arguments are many, and will be familiar to Principium readers, so I'll limit myself to the most obvious point: that the investment in space exploration *is* spent down on Earth, since the money goes into the wages of those working in the space industry, or perhaps into the dividends of shareholders in private space companies. But in both cases, it's undeniable that these people live 'down on Earth', and that's where they spend their money.

The middle part of this chapter is about the

'The New World Order' imposed from the air in Alexander Korda's film *Things to Come* (1936) based on H G Wells' novel, *The Shape of Things to Come* (1933).

limitations of the UN's activities through COPUOS. The criticisms are factually valid, but seem to me a little naïve. I've had a very minor level of involvement with a couple of UN Treaties over the last three decades, as part of my day job as a policy wonk on sustainability issues, and the reality is that, in practice, no UN Treaty delivers anywhere close to 100% of what's written on the page. Why? Because the UN is not a single World Government of the sort that HG Wells proposed in 'The New World Order' (1940). The UN can't force anything through, certainly not against the views of larger countries like the USA. It operates on the basis of consensus, and that means that almost everything the UN does is subject to the ultimate reality of international relations: that every country acts in its own best interests. We might wish it were otherwise, but when we're in the midst of a year-long war in Eastern Europe, caused by the illegal invasion of one sovereign country by another, it surely must be clear that the UN has a limited ability to solve any problem where the strategic interests of major countries are at stake. So to say that COPUOS hasn't been able to force the USA, Russia or China to play nicely in space is true, but also entirely unsurprising.

Uluru-Kata Tjuta National Park. parksaustralia.gov.au/uluru/discover/nature/geology/

6 Rights for Rocks?

In Chapter Six ('The Rights of Rocks'), Professor Rubenstein explores the issues of the value and rights of things that aren't humans. She notes that most people, even if not religious themselves, wouldn't dream of visiting a cathedral and then jumping all over the pews or daubing graffiti on the walls. Yet if we turn to Australia, and consider Ayers' Rock, or Uluru, as it's known to the Aborigines, who consider it a sacred site, we find at least some visitors are happy to climb all over the site and carve their initials into it, despite polite requests from the indigenous population to treat it with respect. Is the difference between these two cases due to the fact that a cathedral is comprised of rocks that have been fashioned into an imposing building by human effort, whereas Uluru is a natural rock formation? Does the value of a cathedral come from the human labour that made it? In the Western worldview, the answer is probably yes. But for other people with other belief systems, rocks, rivers, landscapes and the flora and fauna that inhabit those landscapes can have an inherent value of their own, and in some cases be seen as persons or even deities. In those worldviews, rocks can indeed have rights, and aren't simply resources to be exploited by humanity.

So where does that leave space mining? Asteroids contain large amounts of valuable material, and mining them could be a key element of the *NewSpace* agenda for space exploration. However, the practicalities have not yet been worked out, as it's difficult to mine stuff in a low gravity environment. Similarly, there are questions about what you do with the material once you've mined it. Do you keep it in space, and if so, what for? NASA's answer to that question is 'to help us deliver our mission'. In other words, to support their plans for going back to the Moon, and then on to Mars. Focusing on the latter, Rubenstein runs through the many challenges that will face anyone who wants to live on the red planet for more than a short period, and then discusses the concept of terraforming that has been proposed as one solution. Most approaches to terraforming are challenging to implement and will take a long time, so why bother? Robert Zubrin's answer, according to Rubenstein, is that it's necessary for America to have a frontier to settle, even if it's difficult to do, because that's an inherent part of what has made the country great. Elon Musk's answer, as we've already heard, is the need for humanity to become a multiplanetary species, to reduce the risk of extinction. Rubenstein

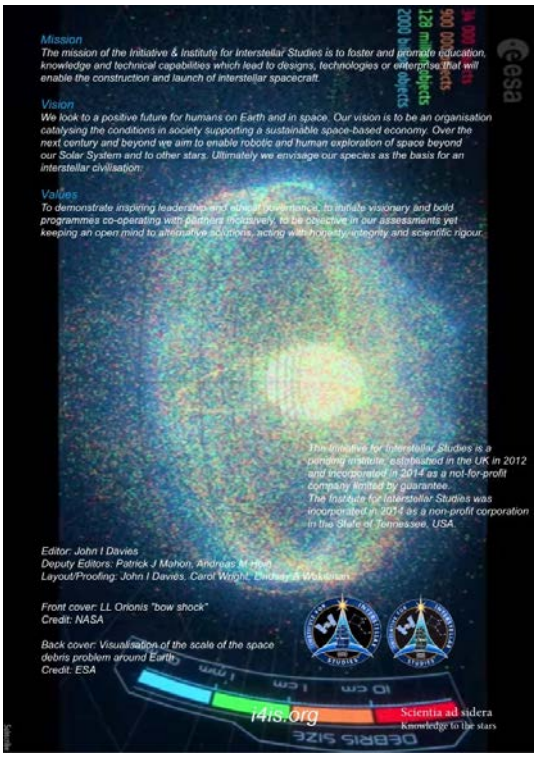
rejects these arguments, and suggests that we should focus our time and attention on dealing with the environmental problems here on Earth instead, since our 'pale blue dot' is quite clearly the most habitable place for humans to live, now and in the foreseeable future.

Would it be OK to terraform Mars if it turned out that life still exists there today, even if that life was just primitive bacteria? Carl Sagan's view was that if Mars still harboured life, it should not be destroyed. Elon Musk seems likely to disagree, presumably on the basis that improving the likelihood that living humans will continue to exist is more important than preserving the future evolutionary possibilities of some Martian bacteria. But this brings us back to the ethical question of whether things that aren't human – in this case, including Martian bacteria and rocks – should be considered as having any existence value, and potentially the right to continue to exist, or not?

If we take a historical perspective, we have to recognise that there was a time when the legal system of countries like the UK and USA split humans into those (adult male property owners, generally) who had rights, and those (including women and slaves) who had few or none. The fact that this is no longer the case indicates that legal and ethical judgements can change over time. Rubenstein invites us to consider how our approach to space exploration might change in the future if we suspended our current worldview, and adopted a less anthropocentric one.

I found myself agreeing with several of the arguments made by Professor Rubenstein here. If we are to expand out into the solar system, we need to have a serious debate about the circumstances under which it is OK to set up a permanent base on a planetary or lunar body, or to consider terraforming such a body. At the moment, the Earth is the only place in the whole universe where we have clear evidence of the existence of life. We presumably do not want to destroy any living organisms elsewhere in the solar system, given how much they could teach us about the circumstances under which life can exist beyond the Earth. But at the same time, we would presumably want to have clear evidence that living organisms *are* present, for example below the surface of Mars, before using that evidence to restrict the kinds of exploration or exploitation of that planet or moon.

As a professional environmentalist, I similarly have a lot of sympathy for the points Rubenstein makes about orbiting space junk, and the general sense that some in the *NewSpace* sector – most obviously, Elon Musk – seem to be happy to pollute space in much the same way that we've polluted our own planet.



Visualisation by the European Space Agency of the scale of the space debris problem around Earth - rear cover of P34 August 2021.

However, I think there's a straightforward solution here. Sustainability issues need to be taken more seriously when space missions are planned, and that should be a requirement imposed by the regulators, just as it is by many governments for Earth-based activities with the potential to pollute. You can then get into an evidence-based discussion about which types and levels of environmental damage are acceptable and which are not, rather than resorting to the easy binary choice of 'all pollution is fine', or 'no pollution is acceptable', neither of which is a helpful guide to sensible decision-making.

However, I think there are limits to how far you can take this argument. Is anyone seriously going to argue that any small asteroid in the middle of the asteroid belt, not previously mapped by astronomers and never seen by anyone on Earth, has such inherent value that there should be a veto on mining it? It's clear from Professor Rubenstein's argument that some people would take this position, on the basis that it's not 'our' asteroid to mine, and that the asteroid has just as much right to exist as we do. However, for as long as we continue to mine huge amounts of material down here on Earth, with all the resultant environmental pollution and human rights problems that are well-documented in the mining sector, particularly in low-income countries, then I think we should probably focus our concern there, rather than on the potential future mining of an as yet unidentified asteroid.

7 A View from ET?

The final chapter is titled 'Other Spacetimes', and considers how our current approach to, and future plans for, space exploration might appear to any extra-terrestrials that visited the Earth. Professor Rubenstein doesn't think they'd be very impressed. So are there viable alternatives to our current model of space exploration? She suggests some, drawn from certain strains of science fiction. Her focus is on the work of Afrofuturist SF writers such as NK Jemisin and Octavia Butler. In their work, she sees the seeds of alternative ways to imagine the future of space exploration, which break with what she sees as a colonialist, capitalist and exploitative legacy, and replaces it with something more inclusive, peaceful and harmonious.

I read a lot of science fiction, and I certainly see it as providing interesting thought experiments when considering the future of space exploration. However, the first distinction I would make, if using written SF to back up my arguments in this debate, would be between so-called 'hard' SF, which makes an effort to be consistent with known scientific and engineering principles, so that it's at least conceivable that what happens in the story might be physically possible, and 'soft' SF, which is often more focused on social or political issues, and the use of the story as a metaphor. My impression of the stories that Rubenstein refers to in this chapter is that they fall more towards the soft SF side of the spectrum.

Musk and Bezos from BBC *Elon Musk and Jeff Bezos: The Silicon Valley space race*
www.bbc.co.uk/news/av/world-us-canada-49006786

I read a lot of soft SF, and I enjoy much of it. But I wouldn't see it as a particularly useful starting point when planning the future of the space programme. Space exploration is currently very difficult, and very expensive, not least because it has to take place within a demanding envelope of scientific and technological constraints. Once we've settled the entire solar system, soft SF stories may have much to teach us about how to live in harmony with each other in all our new and exciting environments. But as far as the next 50 years of the global space programme is concerned, I don't think soft SF is particularly relevant to the difficult challenge of designing a programme that is practically, technologically and economically viable.

8 Conclusion

Seen as a whole, 'Astrotopia' is an interesting book which contains many fascinating insights into the ways in which religion – and, in particular, the religion of the Christian Old Testament – has become bound up in the standard worldview of the Western democracies. However, I'm afraid that it failed to convince me that the *NewSpace* sector is a 'dangerous religion', as the book's sub-title asserts, or that a religious lens is the most useful one to adopt when analysing the future of space exploration. There are three main reasons why I say this.

The first is that Professor Rubenstein's main concern is ultimately not with *NewSpace*, but with the American capitalist economic model. Throughout the book she makes clear that she thinks that capitalism is wrong, particularly when it leads to the creation of highly wealthy people like Elon Musk and Jeff Bezos, who choose to spend the money they've made on activities which she doesn't like, such as SpaceX and Blue Origin. That is, of course, a view shared by many other people.

But it seems to me that the topic the book is nominally focused on – the dangers of the *NewSpace* sector – is actually just a symptom of the wider issue of the pros and cons of modern capitalism.

My second point is that she makes a persuasive argument for the way that, in the past, the Catholic church and several countries used what's written in the early part of the Old Testament to justify the colonisation of Africa and North America, with horrendous consequences for the indigenous people who were already there. However, she fails to show convincingly how that argument is relevant to the future human exploration of the rest of our solar system, where the number of indigenous, intelligent lifeforms is, to the best of our knowledge, zero. There are useful analogies that can be made between the two situations, but on the key issue, they are fundamentally different.

Finally, I am unconvinced by Professor Rubenstein's assertions of the centrality of religion to the *NewSpace* model of space exploration. It is true that American political leaders often use religious rhetoric to bolster their arguments for this or that policy choice, particularly in space. But with the exception of Trump's Vice-President, Mike Pence – who as an evangelical Christian very much does take what the Bible says literally – my view, as a big fan of political set-piece speeches, is that these days at least, most speechwriters will add in religious imagery and rhetoric to a political speech because it sounds good and gets your point across, not because they, or the person they are writing the speech for, actually believes any of it. And much more obviously, neither Elon Musk nor Jeff Bezos, the two key targets of this book, have ever shown any overt sign of using religion as part of their decision-making process in relation to their activities in space.

'Astrotopia' is an interesting book and I learned a lot from it. However, although it contains many valid criticisms of the current model of American space exploration, it did not convince me that this model is fatally flawed. Nor did it demonstrate a radically different alternative that could deliver any *actual* space exploration in a way that was technologically feasible and economically viable.

Patrick Mahon has been Deputy Editor of Principium since issue 16 in February 2017. He was born in 1969, a few months before the first Moon landing. Watching the first Space Shuttle launch live on TV in 1981 started a lifelong fascination with space exploration.

Patrick is Head of Policy at Common Seas, a UK-based NGO focused on tackling ocean plastic pollution around the world. He has worked on environmental policy for most of the last 30 years, following a BSc in Mathematics and Physics at the University of Warwick. He also has an MSc in Environmental Decision Making from the Open University.

In his spare time, Patrick is a writer and reviewer, mainly of science fiction. He has been a member of the Board of Directors of the Initiative for Interstellar Studies since 2018, and is a Fellow of the British Interplanetary Society.

The Initiative & Institute for Interstellar Studies

image: ©ALEX STORER

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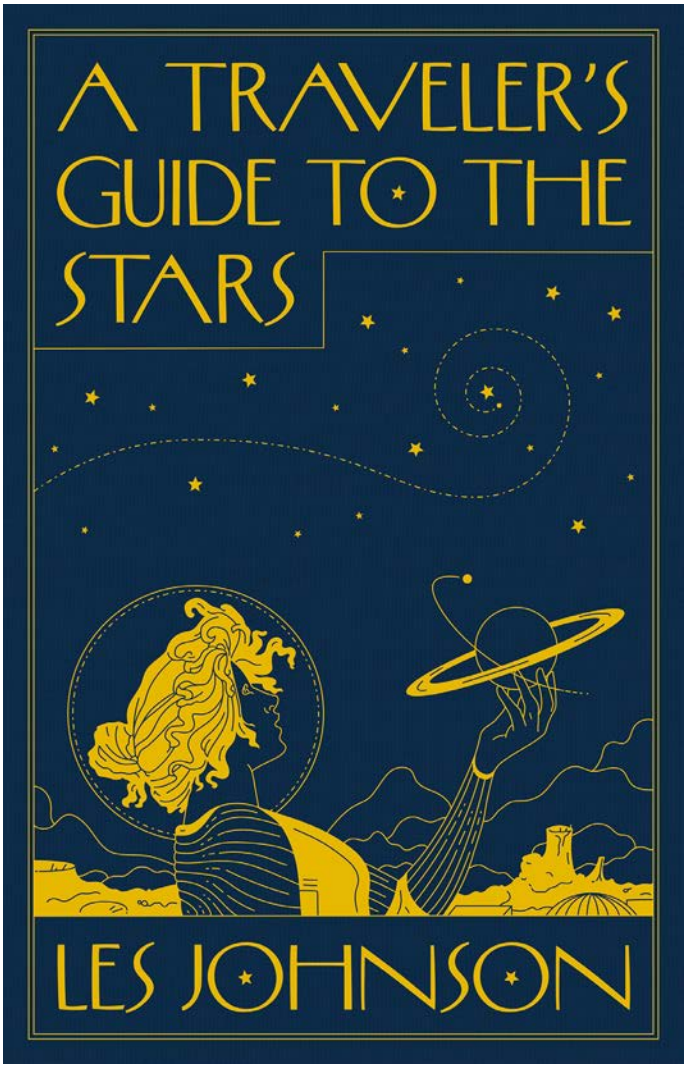
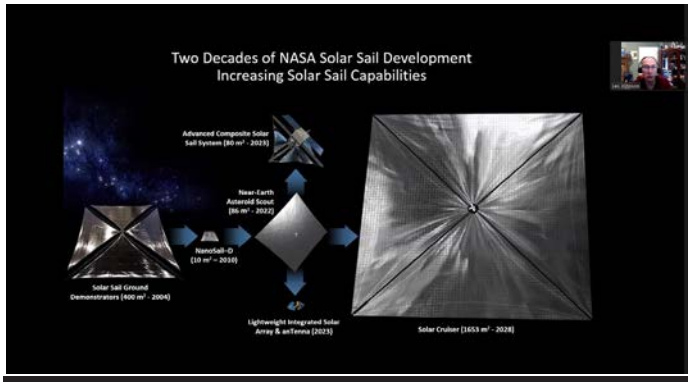
John I Davies reports on recent developments in interstellar studies

The Possibilities of Interstellar Exploration

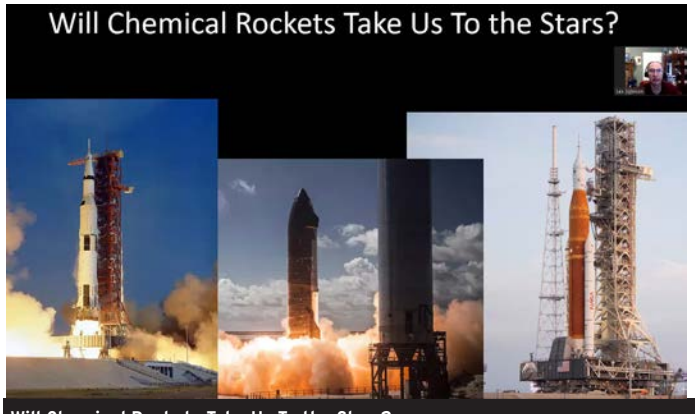
Les Johnson [1] is a 15 year NASA veteran with an outstanding record in interstellar studies. He has recently been on a book tour in support of *A Travellers Guide to the Stars* (Princeton University Press). We'll be reviewing this latest of his books in our next issue.
In the meantime here some shots from his presentation at the BIS 5 April 2023.



Les's intro slide with Zoom participants Alistair Scott (BIS President), our own Rob Swinney and Les Johnson



Two Decades of NASA Solar Sail Development; Increasing Solar Sail Capabilities



Will Chemical Rockets Take Us To the Stars?

>5322 Exoplanets Known Today

[1] Scientist, author, futurist, and space technologist. lesjohnsonauthor.com/

2023 Canopus Award Winners

We reported the Canopus Awards and NEXUS™ NAIROBI in our last issue, Principium 40. The 2023 Award winners include -
In the category of "Published Long-Form Nonfiction" Les Johnson for *A Traveler's Guide to the Stars*, see previous article. In the category of "Published Short-Form Nonfiction" the winners are Alex McKenzie and J Punske for "Language Development During Interstellar Travel," originally published in Acta Futura (the ESA technology journal), 2020 with runner up *Artificial Intelligence for Interstellar Travel*, Andreas M Hein and Stephen Baxter (Journal of the British Interplanetary Society 2018).
The full list is at canopusawards.org/

Another tool in the SETI toolbox

In *Multibeam Blind Search of Targeted SETI Observations toward 33 Exoplanet Systems with FAST* [1] a team from Beijing Normal University, University of Glasgow, Beijing Academy of Science and Technology, Dezhou University (China), Qilu Normal University (China), Breakthrough Listen and University of California Berkeley use a new technique, multibeam coincidence matching (MBCM) blind search mode to search for narrowband drifting signals across 1.05–1.45 GHz in two orthogonal linear polarisation directions separately. They are using the 19 simultaneous beams possible in the new Five-hundred-meter Aperture Spherical radio Telescope (FAST) [2]. The FAST 19-beam receiver allows them to minimise false positives more efficiently than the traditional on/off strategy (which checks directions other than the initial candidate source) while also spotting additional possible sources such as exoplanets in the target system and eliminating intermittent false signals whose interval just happen to coincide with switch between on and off in the traditional on/off strategy. Thanks to Fraser Cain at Universe Today for flagging this [3].
One minor error - the picture captioned "Frank Drake by the Green Bank Telescope. Credit: NRAO/ NSF/AUI" in the Universe Today article looks like Drake but the telescope shown is not the giant one the public knows but probably the 85-foot Tatel Telescope (en.wikipedia.org/wiki/Green_Bank_Interferometer) he used in his pioneering SETI search, more in our Interstellar News, *Frank Drake 1930-2022*, Principium 39, November 2022 [4].

Explanation for orbit of 1I/'Oumuamua?

In *A surprisingly simple explanation for 'Oumuamua's weird orbit* [5] the news site, ScienceX, references a new paper *Acceleration of 1I/'Oumuamua from radiolytically produced H_2 in H_2O ice* [6] - by Jennifer Bergner, UC Berkeley, and Darryl Seligman, Cornell University, about 1I/'Oumuamua, our first detected interstellar object (ISO). A conversation with Darryl Seligman (co-author of one of the earliest astronomical papers on 1I [7] brought their respective chemistry and physics knowledge together. It was known that galactic cosmic rays acting on icy bodies would produce molecular hydrogen which would then be trapped in the ice. So 'Oumuamua began as an icy planetesimal that was irradiated at low temperatures by cosmic rays during its interstellar journey, and experienced warming during its passage through the Solar System.
Does this solve the mysteries around this ISO? They imply it is a comet, conventionally a "dirty snowball", but it was shaped more like an elongated rugby ball than a tennis ball so not snowball shaped. So its tumbling motion should have pulled it apart, but it didn't.
There is a rebuttal - *Implications of evaporative cooling by H2 for 1I/`Oumuamua* (arxiv.org/abs/2303.13861). Here Thiem Hoang and Abraham (Avi) Loeb argue that the earlier paper, Bergner & Seligman, calculation of surface temperature ignored the crucial cooling effect of evaporating H_2. This reduces the surface temperature by about one order of magnitude and thus the evaporative effect by a factor of 3.
There remains no strong consensus on the nature of our first observed ISO. Time to start planning a mission!

[1] Xiao-Hang Luan et al arxiv.org/abs/2301.10890
[2] see *The FAST radio telescope works with Breakthrough Listen to push SETI forwards* in Principium 29 May 2020 page 54
[3] *The World's Largest Radio Telescope Just Scanned 33 Exoplanets for a Signal From Aliens*, Matt Williams, February 7, 2023, www.universetoday.com/159855/the-worlds-largest-radio-telescope-just-scanned-33-exoplanets-for-a-signal-from-aliens/
[4] i4is.org/wp-content/uploads/2022/11/interstellar-news-Principium39-2211291202opt-2.pdf
[5] phys.org/news/2023-03-simple-explanation-oumuamua-weird-orbit.html
[6] Jennifer B Bergner & Darryl Z Seligman, Nature volume 615, pages 610–613 (2023), https://arxiv.org/abs/2303.13698
[7] *The Feasibility and Benefits of In Situ Exploration of `Oumuamua-like objects*, Darryl Seligman and Gregory Laughlin, arxiv.org/abs/1803.07022

Exploring an exoEarth using the Solar Gravitational Lens

Expeditions to Brazil and the South Pacific in 1919 [1] confirmed Einstein's conjecture that mass would bend light. This prediction of an effect of general relativity makes it possible to use the nearest very massive object to hand, the Sun, as the focussing component of a 650 AU long telescope. Slava Turyshev of NASA JPL proposes a multi-satellite project to allow us to image exoplanets at a resolution of 15 to 25 km - or even better. Bruce Dorminey of Forbes magazine describes the proposal *Radical New Space Observatory Would Gravitationally Lens Exoearths* [2].
The *Solar Gravitational Lens Foundation*, due to launch in June, will promote the idea and seek funding to plan it. Both image and spectroscopic study at this resolution are likely to confirm, or possibly deny, the presence of life on an exoplanet.

Extraterrestrial Artificial Intelligence

In *Extraterrestrial Artificial Intelligence: The Final Existential Risk?* [3], Wim Naudé, Rheinisch-Westfälische Technische Hochschule Aachen (RWTH) suggests that the possibility that artificial extraterrestrial intelligence poses an existential threat to humanity is neglected. It is also the case in economics, where both AI existential risks and the potential long-term consequences of an AGI are neglected. This paper presents a thought experiment to address these neglected areas.
Naudé argues that it is likely that any advanced extraterrestrial civilization that we may encounter will be an AGI, and such an AGI will pose an existential risk.

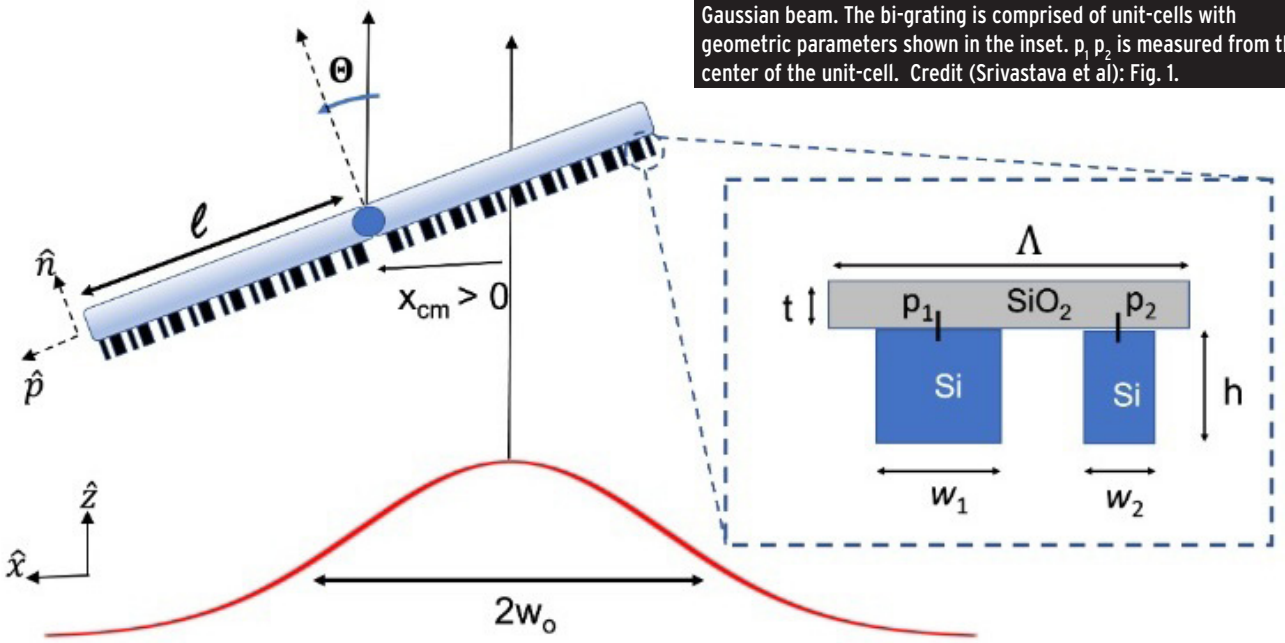
The paper presents two arguments for this;
• The Dark Forest Hypothesis [4]
• The Galactic Colonization Imperative [5]
The latter is also a key plot element in the SF novel, Neptune's Brood by Charles Stross [6].
Naudé suggests -
- accelerating the development of AI as a precautionary step
- maintaining economic growth until we attain the wealth and technological levels to create AGI and expand into the galaxy
- putting more research and practical effort into solving the Fermi Paradox.

Naudé cites sources for the problem that AI's values may not align with humanity's, an alignment problem. Even if the terrestrial alignment problem can be solved there remains the possibility of an extraterrestrial AI which no human would have been able to "bring up properly".
This very brief review has not done justice to Naudés paper and we will be returning to this subject in a later issue of Principium.

Feminism and ETI scenarios

In *Feminism and gender in thinking about extraterrestrial intelligence* [7]
Konrad Szocik (Yale) and Rakhat Abylkasymova suggest that our attempt to understand a prospective ETI have been biased towards a thinking driven primarily of individualism, abstractionism, rationality and exposition of autonomy. They suggest a broader, feminist, approach would be a useful addition to our ways of attempting to understand a prospective ETI since we cannot even imagine it based on any analogies with human history. One interesting consequence they believe may arise from this is a scepticism about applying the precautionary principle.

[1] *General Relativity and the 1919 Solar Eclipse*, www.royalobservatorygreenwich.org/articles.php?article=1283
[2] www.forbes.com/sites/brucedorminey/2023/04/22/radical-new-space-observatory-would-use-sun-to-gravitationally-lens-exoearths/
[3] Institute of Labor Economics discussion paper February 2023, IZA DP No. 15924: www.iza.org/publications/dp/15924/extraterrestrial-artificial-intelligence-the-final-existential-risk
[4] See *Cassidy Cobbs - Bioscientist - Part 2* interviewed by Robert Kennedy and John Davies in Principium 30, August 2020 and Chao Yu and Jiajun Liu, *The Dark Forest Rule: One Solution to the Fermi Paradox*, JBIS V68 #5/6, May/Jun 2015
[5] See *The Theory of Interstellar Trade*, Paul Krugman, in *Economic Inquiry* V48 #4, October 2010 www.princeton.edu/~pkrugman/interstellar.pdf
[6] See Crib Sheet: Neptune's Brood By Charlie Stross, www.antipope.org/charlie/blog-static/2014/09/crib-sheet-neptunes-brood.html
[7] International Journal of Astrobiology 2023 www.researchgate.net/profile/Konrad-Szocik/publication/367450644_Feminism_and_gender_in_thinking_about_extraterrestrial_intelligence/links/63f9d9a0b1704f343f803e3e/Feminism-and-gender-in-thinking-about-extraterrestrial-intelligence.pdf



High contrast metasurface bi-grating configuration propelled by a Gaussian beam. The bi-grating is comprised of unit-cells with geometric parameters shown in the inset. p_1 p_2 is measured from the center of the unit-cell. Credit (Srivastava et al): Fig. 1.

High Forward Thrust Metasurface Beam-Riding Sail

The possibility of laser sail propulsion as a means of reaching the nearest stars well with a human lifetime is what drives a great deal of research and the beginnings of development by researchers, much of it through finance and initiatives from *Breakthrough Starshot*. There are many challenges to achieving this and a major one is that, given a laser beam of sufficient power, how do we provide a sail which can use that power to propel our interstellar probe. Stability of the sail (and the attached probe) in the beam is a major element of the problem. In the paper *High Forward Thrust Metasurface Beam-Riding Sail*, Srivastava et al [1], researchers from Rochester Institute of Technology and the University of Utah supported by NASA and Breakthrough Starshot consider a metamaterial composed of Si -SiO_2. Metamaterials are materials deliberately manufactured to have properties different from those naturally in the constituent molecules. The researchers explain how the proposed metamaterial provides both the very high reflectivity required and inherent self-correcting forces, both linear and rotational, against small destabilising forces. They also suggest that this approach obviates the need for any separate supporting structure for the sail.

Their diagram (above) shows the structure composed of two different panels L (left) and R (right) each of length l. Each unit-cell of which is a ridge-width-modulated high contrast grating with silicon (Si) nano-pillars on a low index SiO_2 substrate. They state that this structure gives stable levitation thrust, optimal thermal management via radiative cooling and may be easily realised with existing e-beam lithography technology.

They conclude with some reservations including -

• the design is very sensitive to wavelength and becomes unstable for Doppler-shifted wavelength in the case of relativistic sails of Breakthrough Starshot

• The design is (only?) ideal provided a tunable phased-array laser becomes a reality.

Interstellar Objects and Exocomets

A new paper by Alan Fitzsimmons, Queen's University Belfast, Karen Meech, Institute for Astronomy, Honolulu, Luca Matrà, Trinity College Dublin and Susanne Pfalzner, Forschungszentrum Julich, Germany reviews our knowledge of our galaxy's cometary population outside our Oort Cloud - *Exocomets and Interstellar Objects (ISOs)* [2]. This is a review chapter to appear in the book, *Comets III*.

[1] arxiv.org/abs/2303.06793
[2] arxiv.org/abs/2303.17980

At the time of publication of the predecessor book, *Comets II* [1], the presence of cometary bodies around other stars had been well established. But the existence of ISOs was merely hypothesised in Comets II, although their discovery was widely anticipated. Detection of ISOs passing through the Solar system would in principle allow remote (and eventually in-situ) sampling of bodies from other planetary systems. The surety that such a discovery would eventually occur grew with increasingly refined models of planetary system evolution, and a growing understanding of how cometary bodies are lost to interstellar space and potential evolutionary processes.

Some of the most important questions about the first ISO include: (1) Where did it come from? and (2) What is it made of? As the authors point out, we still don't know the answers to these questions. 1I/'Oumuamua was easily observable from the ground for a little over a week, but as it moved away from the Earth it faded quickly, and large telescopes were able to observe for only about 1 month. The last Hubble Space Telescope observations were made in Jan 2018. It is remarkable that we know as much about this object as we do, because all of the large telescope time had to be secured through Director's requests. In total approximately 100 hrs on 2.5-10-m ground-based telescopes were devoted to characterizing this exceptional object. To date, over 200 refereed papers have been written on both interstellar objects, and nearly 450 papers. This review highlights key papers and some reviews of the field. It also mentions concepts for missions to reach 1I/'Oumuamua including Seligman and Laughlin, The *Feasibility and Benefits of In Situ Exploration of 'Oumuamua-like Objects* (2018), discussing launch-on-detection scenarios (implying assumptions about future sightings of Oumuamua-like ISOs), and the numerous i4is Project Lyra papers - mainly concentrating on the one such object we know of, Oumuamua itself.

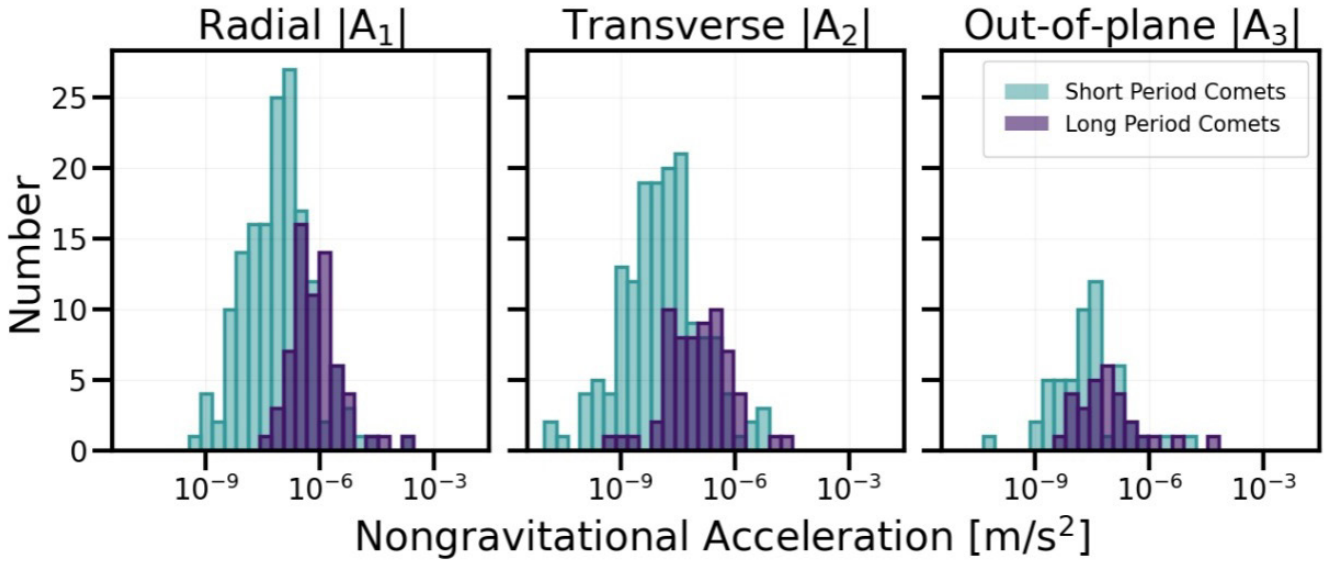
ISOs from Broken Dyson Spheres

Avi Loeb comes up with another striking speculation. In *Interstellar Objects from Broken Dyson Spheres* [2], the distinguished Harvard scientist, asserts that without extensive maintenance, Dyson spheres will inevitably disintegrate by asteroid impacts over billions of years and the resulting fragments would appear as anomalous interstellar objects, potentially sharing the unusual shape and motion of 1I/'Oumuamua or the unusual material strength of the first two interstellar meteors, IM1 and IM2.

He observes that Olaf Stapledon's novel "Star Maker", imagined the use of a technologically-manufactured shell of matter to tap the energy output of a host star. The concept was subsequently formalised by Freeman Dyson. Dyson reasoned that as the energy needs of humanity will steadily increase, our civilisation might aspire to tap all the energy output of the Sun. Loeb reasons that if Dyson spheres existed to serve their civilisations for a limited time, most of them would have disintegrated within billions of years in the absence of extensive maintenance and that their ejected fragments could appear as interstellar objects. He also recalls that Robert Forward proposed a tiled structure for a Dyson sphere [3], with each component functioning as a solar sail for which the star's gravity is exactly balanced by the star's outward radiative push, thus maintaining a fixed position without orbiting the star. If disintegration occurred then these components of the sphere would inevitably have sail-like properties, possibly accounting for the anomalous acceleration observed in Oumuamua.

As Clarke remarked in his first law "When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong". Avi Loeb is only 61 so is not yet elderly but he is certainly distinguished. We should therefore consider carefully if his idea fits the facts - and to gather facts we need closer observation of this single instance of such an anomalous object. i4is Project Lyra has a continuing mission to help to explore such strange new worlds.

[1] Reviewed in the the *Journal of the British Astronomical Association*, britastro.org/journal_old/pdf/116-3shanklin.pdf
[2] curiosmos.com/wp-content/uploads/2023/02/Dyson_arXiv.pdf
[3] *Statite - A spacecraft that does not orbit*, Forward, Journal of Spacecraft and Rockets, 1991



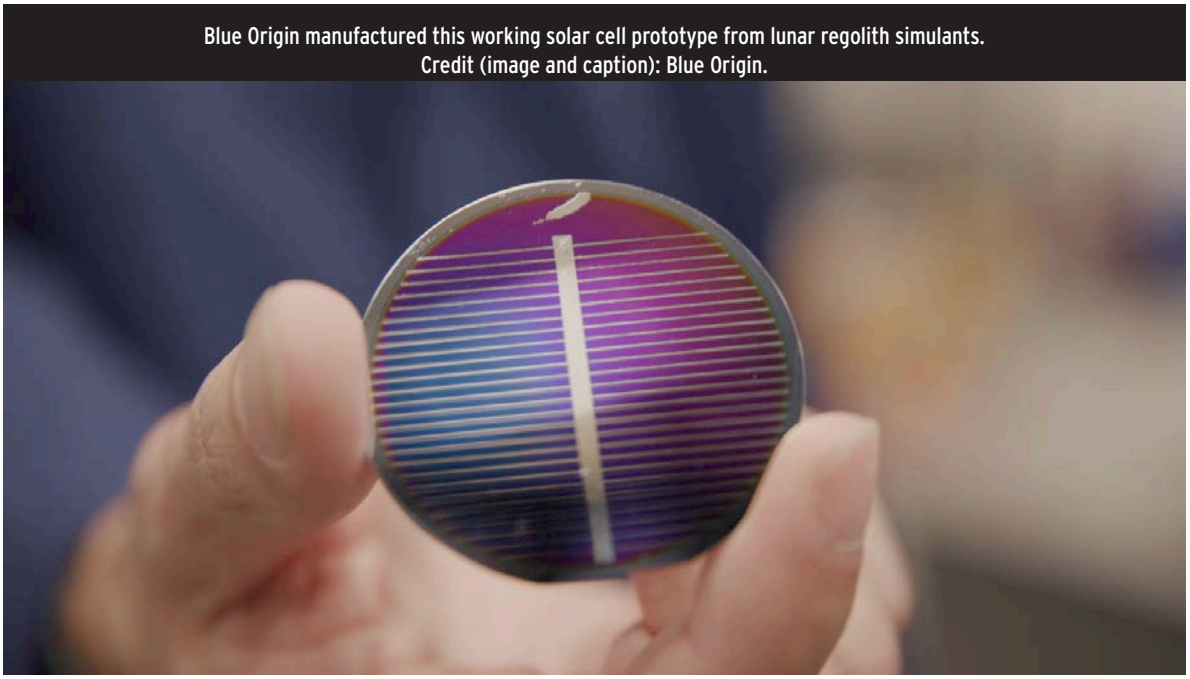
The measured non-gravitational accelerations of Short-Period Comets (teal) and Long-Period Comets (purple). The three panels show the radial (left), transverse (middle) and out-of-plane (right) components of measured accelerations. Non-gravitational accelerations are taken from the JPL Small Body Database.
Credit (image and caption): Seligman and Moro-Martin Figure 1.

Number of ISOs

A new paper by Darryl Z Seligman (Cornell University) and Amaya Moro-Martin (Johns Hopkins University), *Interstellar Objects* (arxiv.org/abs/2304.00568) makes the following bold statement (in the abstract) "We describe 1I/`Oumuamua and 2I/Borisov in the context of active asteroids and comets in the Solar System. The discovery of these two objects implies a galactic-wide population of 10^{26} similar bodies.". They discuss cometary outgassing as a contributor to non-gravitational acceleration (as in 1I/'Oumuamua). They use a graphic from the JPL Small Body Database to show the distribution of these accelarations in Solar System comets (above) and describe the sublimation processes for various constituents which typically occur in Solar System comets. They go through the observations of 1I/'Oumuamua in some detail observing that "Some of these provided critical upper limits on the production rates of dust and certain volatile species." (ie typical cometary outgassing) and report that observations produced no detectable outgassing. And even the dimensions of 1I remain uncertain with the long dimension uncertain by a factor of at least two. They cite a couple of elongated Solar System asteroids including 216 Kleopatra (en.wikipedia.org/wiki/216_Kleopatra) which is quite elongated but may be a close or contact binary object [1] and 1998 KY26, which radar imaging shows is irregular but not elongated [2]. The authors mention a number of Solar System objects which may have similar acceleration properties to 1I, these include active asteroids and dark comets. The Japanese probe JAXA Hayabusa2 will rendezvous with 1998 KY26 in 2031 [3].

The paper also deals extensively with the interstellar comet 2I/Borisov and discusses the galactic population of interstellar objects in terms of numbers, kinematics, origin determination, size-frequency distribution, the possible presence of captured ISOs in the Solar System and the possibility of interstellar planetesimals seeding planet formation. There is some discussion of future detection of ISOs and a brief mention of the planned ISA Comet Interceptor mission but nothing on other interceptors apart from a brief mention of Seligman's own 2018 paper (with Greg Laughlin) *The Feasibility and Benefits of In Situ Exploration of 'Oumuamua-like Objects* in The Astronomical Journal (iopscience.iop.org/article/10.3847/1538-3881/aabd37/pdf).

[1] Shepherd et al, *A revised shape model of asteroid (216) Kleopatra*, 2018 facstaff.bloomu.edu/mshepard/research/kleopatra/Shepard_Kleopatra_revised_shape_model_2018.pdf
[2] en.wikipedia.org/wiki/1998_KY26 - also Ostro et al *Radar and Optical Observations of Asteroid 1998 KY26* 1999
[3] en.wikipedia.org/wiki/Hayabusa2



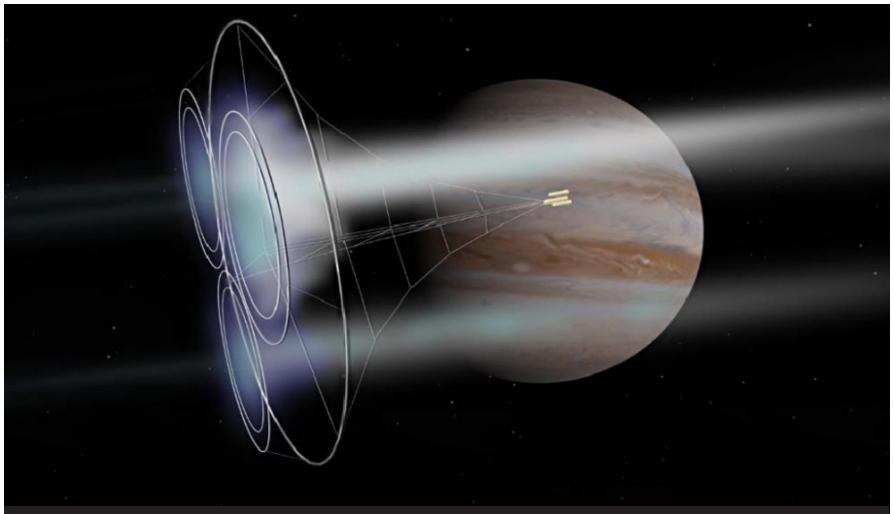
Blue Origin manufactured this working solar cell prototype from lunar regolith simulants.
Credit (image and caption): Blue Origin.

Photon Sailing to Proxima B

In March 2023, TU Delft published a notable master thesis by Tim Rotmans titled *Photon-sail trajectories to exoplanet Proxima b using heteroclinic connections*. The paper investigates photon-sail trajectories towards a rocky, Earth-like exoplanet, Proxima b, located in the habitable zone of the star Proxima Centauri. While much research has been done on designing interstellar missions to go to Proxima Centauri, the same cannot be said of Proxima B. Since Proxima Centauri is part of a binary star system, this presents a unique challenge when it comes to determining the orbital trajectory of such an interstellar spacecraft.
To solve this issue, the paper uses heteroclinic connections to search for a link between the equilibrium points of both stars in the system and to find transfer trajectories from the AC-A/AC-B star system towards Proxima B. The paper suggests using the colinear Lagrange points AC-A/AC-B to allow the probe to escape the orbit of Proxima Centauri and travel to Proxima B. The paper provides a detailed breakdown of how a solar sail probe would have to be designed to be suitable for such a trajectory, exploring multiple sail configurations and their pros and cons. The thesis also uses a genetic algorithm to model potential missions and provide quantitative descriptions of their feasibility. The full paper can be found here: repository.tudelft.nl/islandora/object/uuid:f1784fa7-2c8c-47fb-b2a9-d79d1153aeef?collection=education.

Printing solar cells on the Moon

Our interstellar colleague, Gerald D Nordley, has drawn our attention to a significant breakthrough in lunar resource utilisation from Blue Origin, Jeff Bezos' launcher development company. They have succeeded in printing solar cells from printstock manufactured from lunar regolith simulant (www.blueorigin.com/news/blue-alchemist-powers-our-lunar-future). He observes -
"Many scenarios for interstellar settlement, from getting the energy needed for beam-pushed propulsion, to living off the land when one gets there and getting back again are greatly enhanced, if not enabled, by robotic replication and the exponential growth it permits. Of course, making solar power satellites from lunar regolith could be a game-changer in many other things as well. This prototype cell represents a major step toward the kind of robotic production capacity needed for beam-rider starships traveling near the speed of light, and is happening years before many of us thought it would happen."
A Solar System economy is a vital foundation for really serious interstellar activity by our species and this development is a significant step in that direction.

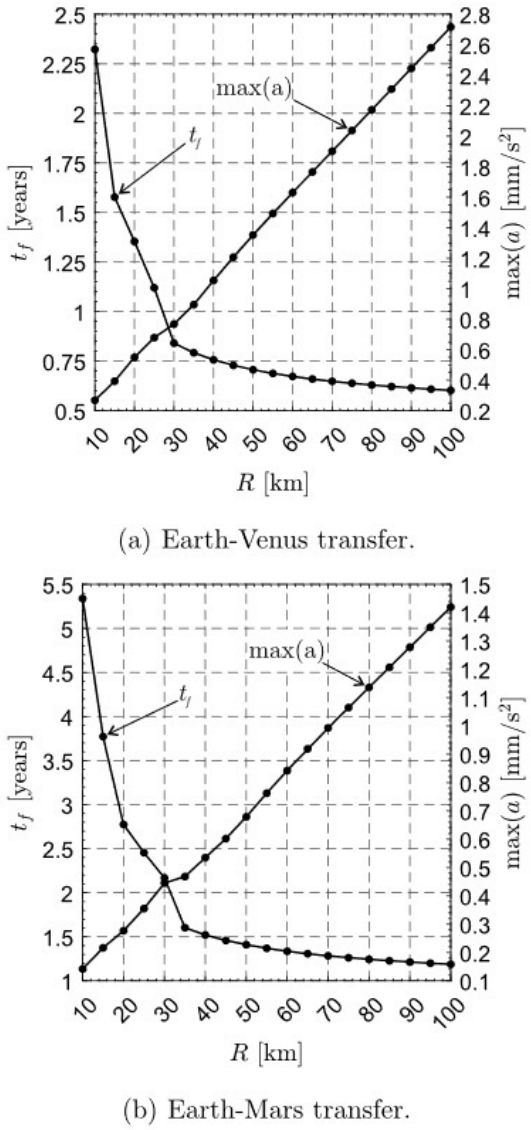


A three coil magsail at Jupiter. Note the payload attached by tethers. Credit: Steve Bowers [1]

Pushing against the solar wind

In *Refined MagSail thrust model for preliminary mission design and trajectory optimization*, Bassetto et al [1] by a team including Nikolaos Perakis of i4is, has produced a refined model of magnetic sailing. A MagSail uses thrust against charged particles of solar wind to generate thrust using only electrical energy and thus requiring no propellant. This could enable intra-solar system transport driven entirely by energy from solar panels or nuclear reactions. It is not a candidate for long duration thrust in an interstellar role but it does have potential application in decelerating a lightweight interstellar probe such as implied by Breakthrough Starshot (widely covered earlier issues of Principium) and early i4is studies Project Dragonfly (see Principium Issue 11 November 2015 and subsequent issues) and Project Andromeda (see Principium Issue 14 August 2016 and subsequent issues).

The authors present a single-loop Assail thrust model based on the numerical and experimental results obtained in the last decade.
They present results for Earth-Mars and Earth-Venus transfers for a range of magsail radii.
They suggest that "the proposed thrust model can be easily implemented in a simulation code for trajectory optimization and, in this sense, it represents an effective tool for preliminary mission analysis."



(a) Earth-Venus transfer.

(b) Earth-Mars transfer.

Fig. 11. Variation of t_f [journey time] and max(a) [acceleration] with R[magsail radius] when f = 0.8.
Credit (image and caption): Bassetto et al, Fig 1

[1] Steve Bowers is a member of the Orion's Arm Universe Project, orionsarm.com/
[2] Marco Bassetto, Alessandro A Quarta and Giovanni Mengali (all University of Pisa) and Nikolaos Perakis (Technical University of Munich and Initiative for Interstellar Studies). Aerospace Science and Technology, Volume 133, February 2023, 108113. www.sciencedirect.com/science/article/abs/pii/S127096382300010X, full text via lnkd.in/d7Zgxph2

i4is at the Royal Institution

This will be our fourth i4is Summer School at the Royal Institution of Great Britain, Faraday's old place! This year the Royal Institution has invited us to extend our Skateboards to Starships summer schools to two younger age groups, ages 7–8 and 9–11. Reserve at -

Skateboards to Starships (ages 12–14) Tue 15 Aug 11.00–15.00

www.rigb.org/whats-on/holiday-workshops-skateboards-starships-ages-12-14

Skateboards to Starships (ages 7–8) Wed 16 Aug 11.00–13.15

www.rigb.org/whats-on/holiday-workshops-skateboards-starships-ages-7-8

Skateboards to Starships (ages 9–11) Wed 16 Aug 14.15–16.30

www.rigb.org/whats-on/holiday-workshops-skateboards-starships-ages-9-11

Skateboards to Starships (ages 15–18) Thu 17 Aug 11.00–15.00

www.rigb.org/whats-on/holiday-workshops-skateboards-starships-ages-15-18

More about past summer schools in *News Feature: The Third i4is Summer School at the Royal Institution* - in Principium 39 November 2022 (i4is.org/wp-content/uploads/2022/11/News-Feature-%E2%80%93-The-Third-i4is-Summer-School-at-the-Royal-Institution-Principium39-2211291202opt-3.pdf).

All revenue from the Summer Schools goes to the Royal Institution minus modest expenses.

1I/'Oumuamua: reasoning from a single instance

In *Statistical implications of the n = 1 observation of 1I/'Oumuamua*, Eirik Grude Flekkøy (University of Oslo) and Renaud Toussaint (University of Strasbourg) [1] "obtain the exact statistical distribution of expected detection rates that may be obtained from the detection of 'Oumuamua which currently belongs to a class of objects that is only observed once in our Solar system". They apply the Poisson distribution, Bayes theorem and Shannon's information theory. They state that probability depends on the estimates of detection rates that existed prior to the 'Oumuamua observation but unless the constraints given by these model-based estimates are within an order of magnitude of the actual detection rate, they have a negligible effect on the probability of making a second observation so their results are generalised to the expected future case where more than one observation exists.

Their main purpose is to obtain the exact distribution $P_n(\lambda)$ for the expected observation rate λ after $n \geq 1$ observations are made so that the correct a priori assumption is identified, and thus obtain the expected recurrence time of objects similar to 'Oumuamua by the Vera C Rubin Observatory/Large Synoptic Survey Telescope (LSST) programme. They point out that "It is important to distinguish between a priori assumptions based on model-dependent estimates and a priori knowledge, as only the latter may be used as hard constraints in the $P(\lambda)$ distribution". They nevertheless conclude that "Another observation similar to that of 'Oumuamua is expected within 5 yr at a confidence limit of 90 per cent." - with the underlying assumption that the LSST is operating.

Two answers to - Where is everybody?

A couple of new clues on the old Fermi question. In *Beyond Mediocrity: How Common is Life?* (arxiv.org/abs/2305.05395) Amedeo Balbi, Università di Roma and a friend and colleague of i4is, Manasvi Lingam, Florida Institute of Technology, are sceptical.

But in *Could AI be the Great Filter? What Astrobiology can Teach the Intelligence Community about Anthropogenic Risks* (arxiv.org/abs/2305.05653) Mark M Bailey suggests that the hypothesised Great Filter, extinguishing intelligence before it reaches the stars, may come upon us through the further development of forms of artificial intelligence,

Balbi and Lingam suggest that appealing uncritically to some version of the "Principle of Mediocrity" - namely, the supposed typicality of what transpired on Earth – is problematic on empirical or logical grounds. They adopt a Bayesian [2] statistical approach to put on rigorous footing the inference of lower bounds for the probability of abiogenesis (biology arising from a non biological source), based on current and future evidence. They conclude that if habitable worlds are uncommon, for an agnostic prior, a deterministic scenario for the origin of life might be favoured over one where abiogenesis is a fluke event.

We certainly can't build much on the single instance we know, ourselves, as we also see in the uniqueness of 1I/'Oumuamua as an ISO.

Bailey is more pessimistic still. He also uses the toolkit of Thomas Bayes to point out that the probability of finding evidence for a globally catastrophic event having occurred (*a posteriori* evidence) will never be more than the *a priori* probability of that event occurring. The implication is that we underestimate the probability of any global catastrophic event occurring that could wipe humanity off the face of the planet. He worries especially about recent AI developments.

Bailey is Chair of the Cyber Intelligence and Data Science Department at National Intelligence University and Co-Director of the Data Science Intelligence Center. This is therefore the view of what an old colleague used to call "the Paranoia Brigade" - which is not to disparage them - the colleague was himself an established member of the "Brigade".

[1] MNRAS 523 doi.org/10.1093/mnrasl/slad049 Advance Access publication 2023 April

[2] The idea of probabilities based on prior evidence. For example the vaccine-sceptical idea that more people than the general population died after vaccination but the jab was given preferentially to those with other health problems - the prior probability of them dying was already higher than the general population en.wikipedia.org/wiki/Bayes%27_theorem

Transmitter rate of extragalactic civilizations

In *Upper limits on transmitter rate of extragalactic civilizations placed by Breakthrough Listen observations* (arxiv.org/abs/2304.02756), another investigation sponsored by Breakthrough Listen, researchers from National Chung Hsing University and National Tsing Hua University, Taiwan, The Australian National University and National Astronomical Observatory of Japan have used results from the Green Bank (USA) and Parkes (Australia) telescopes to constrain the possible existence of highly advanced civilisations in the observable universe, This continues the work begun by Professor Mike Garrett (University of Manchester) and colleagues for example in a paper *SETI radio surveys of the distant Universe* presented at the 69th International Astronautical Congress, Bremen 2018. Their research suggests that the existence of KII-type civilisations [1] are extremely limited, and the search for radio transmissions should continue.

Human 2.0 to the stars?

What might we need to do ourselves to get to the stars? Papers identified by the indispensable Interstellar Research Group (IRG) alert service aspect of this question.

In *The final frontier: what is distinctive about the bioethics of space missions? The cases of human enhancement and human reproduction* [2] Konrad Szocik (Yale University) and Michael J Reiss (University of Information Technology and Management in Rzeszow, Poland) examine the bioethical issues that arise from long-duration space missions, asking what there is that is distinctive about such missions. Longer term self-sustaining space settlements may require human enhancement and reproduction in space. Is space bioethics analogous to the extremes of military bioethics? They cite a number of ethical philosophers including Derek Parfitt (see his book, *Reasons and Persons*) and Joseph Rotblat (a nuclear weapons scientist who turned to both ethics and biomechanics). They discuss radical human enhancement interestingly and at some length but don't mention Tsiolkovsky who opposed the reaction of cultural critics like John Ruskin (1819 – 1900) lamenting the artificiality of industrial civilisation "In ethereal space this artificiality will simply be extended to the very limit, but then man too will find himself in conditions that are most favourable for him" [3]. They also explore the rationale for space missions as a significant factor in space bioethics.

And in *Bioethical Issues in Human Modification for Protection against the Effects of Space Radiation*, Szocik (as above) and Martin Braddock (Mansfield and Sutton Astronomical Society, UK) [4] examine the possible justification of human enhancement as a measure against the currently intractable problem of space radiation, principally galactic cosmic radiation (GCR). They use a hypothetical scenario of a long duration mission with long term effects of GCR still largely unknown. They consider scientific, commercial, motivations for missions, tourism and settlement as motivations. As in the other Szocik paper, the military analogy is seen as relevant but differences are clear.

[1] Kardashev scale 2, defined as using all the available power of their home star, about 2 billion times as much as our own early Kardashev type 1 civilisation
[2] Monash Bioethics Review (2022) https://link.springer.com/article/10.1007/s40592-022-00164-6
[3] see *Tsiolkovsky - Interstellar Pioneer* in Principium 20 February 2018.
[4] Space Policy 2022, www.sciencedirect.com/science/article/pii/S0265964622000315

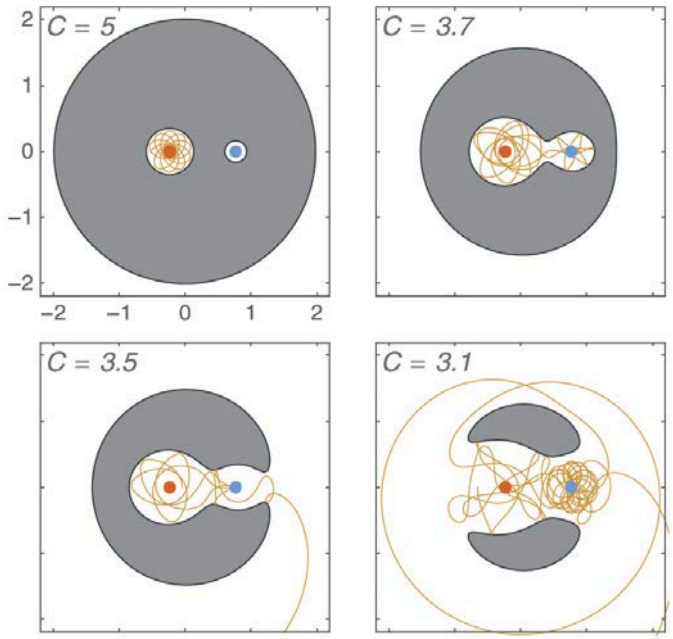
Planetary PinBall

Once in a while we come across a science fiction story which prefigures some science. In the twin 1950s stories, *The Man from Nowhere* and *Rogue Planet*, the central character, Dan Dare, and some of his regular companions are asked to save a peaceful planet from a malign planet which comes close to it over very long periods.

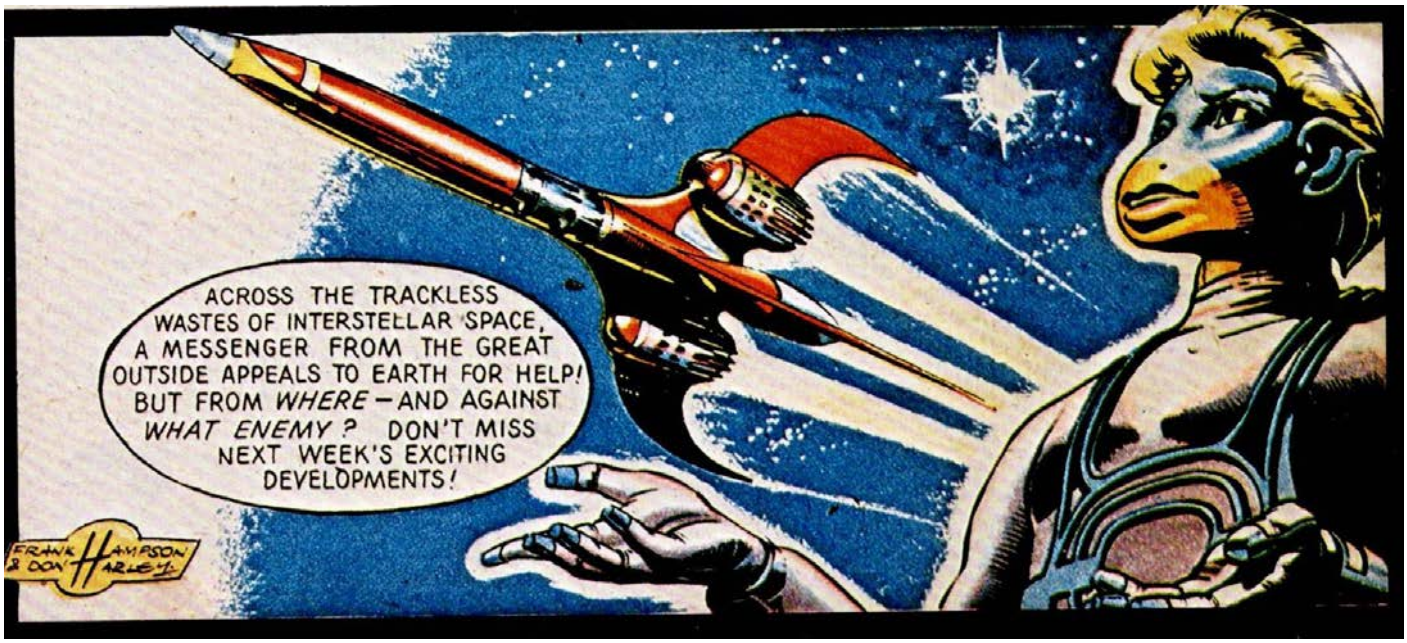
A recent piece by Sean Raymond, an American astrophysicist now living in Bordeaux, in his blog entry *Star-hoppers: planets bouncing between binary stars* [1], PlanetPlanet (planetplanet.net) refers to an odd astrodynamical situation where a planet can migrate between two star systems,

In this blog entry Raymond also cites an animation from the same source, see **exoplanets bouncing: 250 au binary, Solar mass stars**.

In the two Dan Dare stories the character Lero, of the exoplanet Cryptos, crashes into the Mato Grosso jungle from his starship, which ditches in the Tuscarora Deep. He explains that his planet is periodically subjugated by the dictatorship of the exoplanet Phantos when the two planets come close together every 10,000 years. The Crypts are pacifists and are incapable of resisting this.



Examples of planet orbits in a circular, coplanar binary star system (the stars are the large red and blue dots, with the red dot being a Sun-like star and the blue dot being about 30% as massive), for different values of the Jacobi constant C (which roughly corresponds to the orbital energy) [2]. Bouncing between stars happens when C=3.7.
Image credit: Moeckel & Veras , 2012 [3]
Caption credit: Sean Raymond



[1] planetplanet.net/2022/02/24/star-hoppers-planets-bouncing-between-binary-stars/

[2] en.wikipedia.org/wiki/Jacobi_integral

[3] Dimitri Veras is an astrophysicist at Warwick University, UK, researching the contents of planetary systems (including our own solar system) in a wide variety of contexts, across both time and space. warwick.ac.uk/fac/sci/physics/research/astro/people/veras/

Earth engineers help Lero to salvage and rebuild his starship. Dan and co return in it with Lero ...
....and save the day (of course).

The stories contain other SF ideas such as a ruling "god", Orak, which controls the Phants and instructs them to eat food which keeps them aggressive. Their "god" turns out to be an artificial intelligence built from transistors (in the early 50s a character saying "They never wear out." was not implausible).
The Crypts have food which makes them peaceful and the two species turn out to be less different than they appear.
The images from the *Eagle* are by Frank Hampson and Don Harley as published in the Dragon's Dream books. The publisher is sadly "dormant" according to Companies House, the UK regulator.

If Sean Raymond and his sources are correct we may well find such "pinball planets" - but what are the chances of life on them?

IRG23 Preview

8th Interstellar Symposium, McGill University, Montreal, July 10 – 13, 2023

John I Davies

The next IRG biannual symposium will be in July (irg.space/irg-2023/). Principium has previewed and reported these conferences since 2018. This is a glimpse of what will be happening in Montreal this year (Monday-Thursday, 10-13 July).

Background

The Interstellar Research Group is the business name of the Tennessee Valley Interstellar Workshop, a US-based not-for-profit. It was founded in 2014, based on informal gatherings in Oak Ridge, Tennessee, which began in 2004. It became the Interstellar Research Group (IRG) in 2020.

Speakers and Abstracts

The pre-announced speakers and presentations (as of 14/4/23) are summarised below with recent relevant publications. Note the abstracts here are abbreviated and the full abstracts will appear on IRG website before the symposium.

Alex Ellery	Hybrid Symbolic-Neural Approaches to Artificial Intelligence for Interstellar Missions	

Interstellar flight represents an unforgiving environment for autonomous operations with many unknowns imposing the necessity for advanced artificial intelligence (AI). Evidently, interstellar distances preclude any human intervention from Earth. We take the view that the interstellar transit phase of an interstellar mission may be accommodated with a mixture of pre-programmed reactive symbol-manipulation-based intelligence implementing traditional Kalman filter-like algorithms. However, for in-situ exploration at the destination extrasolar system, near-human level capabilities will be required for full autonomy. The paper reviews and assesses state-of-the-art AI to enable robotic machines to perform complex interactive tasks on exoplanetary environments at near human-level competence concluding that this reveals several shortcomings in AI methods but hybridisation presents one approach that may be promising.
Professor Alex Ellery, Carleton University, is Canada Research Professor, Department of Mechanical & Aerospace Engineering and Director, Centre for Self-Replication Research.
He is author of *Curbing the fruitfulness of self-replicating machines* [1], International Journal of Astrobiology V21#4 2022 and *Self-replicating probes are imminent – implications for SETI* [2], International Journal of Astrobiology V21#4, 2022.

Robert M Freeland II	Infrastructure Development Leading to the First Long-Duration Interstellar Probe	

Long-duration interstellar probes - like the Z-pinch fusion-powered Firefly vessel developed through Project Icarus - would benefit significantly from the use of He3 as a fuel additive, yet He3 is almost completely non-existent in the inner Solar System. Moreover, the mass of deuterium required for these probes presents significant cost and environmental-impact concerns if sourced from Earth. This paper describes a step-wise plan connecting our current infrastructure to an infrastructure supporting long-duration interstellar exploration yielding a plausible, efficient road map for interstellar exploration that major space agencies might consider actually funding.
Robert M Freeland II was Deputy Project Leader and Board Member, Icarus Interstellar and primary architect of the Icarus Firefly interstellar probe study.
He is author of *Plasma Dynamics in Firefly's Z-pinch Fusion Engine* in JBIS V71 August 2018 and *Project Icarus: Communications Data Link Designs between Icarus and Earth and between Icarus spacecraft* (co-author with Peter Milne and Michel Lamontagne) JBIS, V69, 2016

[1] scholar.archive.org/search?q=Curbing+the+fruitfulness+of+self-replicating+machines

[2] scholar.archive.org/search?q=Self-replicating+probes+are+imminent+%E2%80%93+implications+for+SETI

Louis Friedman	Real Interstellar Exploration Will Be Virtual	

Use of the solar gravity lens is the only practical way we can achieve multi-pixel images of exoplanets. Solar sails with advanced technology materials and smallsat payloads can achieve fast velocities (>25 AU/year) to make use of the solar gravity lens practical. By sending small sailcraft with modest telescopes to the solar gravity lens foci of potentially habitable planets, we can explore them systematically and in detail for signs of life – the ultimate goal of space exploration.

Dr Louis Friedman is Executive Director Emeritus and Founder of The Planetary Society and Former Manager of Advanced Programs at NASA JPL.

Dr Friedman is a co-author of *Solar Sail Propulsion by 2050: An Enabling Capability for Heliophysics Missions* - 2023 (arxiv.org/abs/2301.01297) and of *A fast response mission to rendezvous with an interstellar object* - 2022, Experimental Astronomy volume 53, pages 945-960 (arxiv.org/abs/2106.14319).

Alex Gmerek	Searching for Extrasolar Life – An Astrobiology Payload for Interstellar Missions	

To date, only one astrobiology-focused payload has flown to an extraterrestrial environment – Viking to Mars in 1976. These were highly specific to the search for photosynthetic activity as an example of universal biology. Recent more contextual developments have searched for water, be it extant or extinct. The paper will examine the type of biomarkers that can be searched for and in what context. It will propose astrobiology instruments at multiple scales - infrared/visible/ultraviolet panoramic camera; close-up imager for bio-morphological investigation; combined infrared Raman spectrometer laser-induced plasma spectrometer confocal microscope and tuned diode laser absorption spectrometer; protein chip to detect specific proteins; a nanopore instrument to detect charged backbone linear molecules (such as DNA, RNA, PNA, etc).

Alex Gmerek is currently a MASc. student at Carleton University and a researcher for the CEnter for SElf Replication (CESER).

Jeffrey Greason	Sunbeam: Near-Sun Statites as Beam Platforms for Beam-Driven Rockets	

Photon, particle, or macroscopic pellet beamriders have long been recognized as one of the key approaches to interstellar flight but previous solutions limit their application to either very small (gram scale) payloads or such large power levels as to constitute prohibitive capital costs to construct the required beam infrastructure. We sought solutions with very long beam ranges and very high specific power to produce beam solutions for macroscopic spacecraft to interstellar-relevant velocities. Relativistic electron beams appear to have potential for extreme range , potentially up to 100 AU. The challenge to make use of this technology is efficient and lightweight conversion of the electron beam to thrust.
Jeffrey Greason is Chief Technologist of Electric Sky, Chairman of the Tau Zero Foundation and a Commercial Space Industry Entrepreneur (XCOR Aerospace, Rotary Rocket).
He is co-author of *Wind-pellet shear sailing*, Acta Astronautica V197, 2022 (arxiv.org/abs/2205.14117) and *Dynamic Soaring as a Means to Exceed the Solar Wind Speed*, 2022 (arxiv.org/abs/2211.14643) also reported in Principium 40, February 2023, *Faster than the (Solar) Wind*.

René Heller	Maneuvering Interstellar Light Sails	

With an intended speed of 20% c, the currently envisaged interstellar probes using photon sails would traverse the Earth-Moon distance in just about six seconds, with little time left for high-quality close-up exploration, for example of the planet Proxima b. However the stars α Cen A and B can be used as photogravitational swings to decelerate an incoming light sail and deflect it into a bound orbit around Proxima. Numerical simulations of the photon pressure and the gravitational force in the α Cen A, B, and C triple system show that an autonomous photon sail could be maneuvered through the system and into a bound orbit without the need for onboard fuel.
Dr Rene Heller is an Extrasolar Planet Researcher at Max Planck Institute for Solar System Research.
Dr Heller is a co-author of *TOI-2525 b and c: A Pair of Massive Warm Giant Planets with Strong Transit Timing Variations Revealed by TESS*, The Astronomical Journal, Volume 165, Number 4 2023 (iopscience.iop.org/article/10.3847/1538-3881/acba9b/meta) and *Pandora: A fast open-source exomoon transit detection algorithm*, Astronomy & Astrophysics, Volume 662, June 2022 (www.aanda.org/articles/aa/pdf/2022/06/aa43129-22.pdf).

Pascal Lee	N ~ 1: Alone in the Milky Way	

The Search for Extraterrestrial Intelligence (SETI), as well as popular sci- fi culture, often premise that the number N of advanced civilizations in our Galaxy is large. A large N, however, is at odds with observation, hence the Fermi Paradox. This study reevaluates N on the basis of latest knowledge of the different factors affecting its value, using available data only and avoiding a priori biases. This study results in the adoption of likely values for R*, fp, ne, fl, fi, fc, and L of 20, 0.5, 1, 0.5, 2x10-4, 0.1 and 104, respectively, which yields N ~ 1 and thus that intelligent societies in our Galaxy, and by extension in any galaxy, are likely few at any given time therefore SETI efforts should focus on extragalactic searches for greater chances of detection.

Dr Lee studies the most Mars-like places on earth—including Antarctica (5 visits) and the Haughton crater in the Canadian Arctic exploring how life thrives in such places, while refining our techniques for use in upcoming explorations on Mars.

Dr Lee is a planetary scientist at the SETI Institute, the Mars Institute, and the NASA Ames Research Center. He is co-author of *Handling Qualities Flight Test Techniques for Astronaut-Operated Unmanned Aerial Vehicles for Mars Exploration*, AIAA AVIATION 2020, and *A virtual REU program in Astrobiology and Planetary Science* at the SETI Institute, AGU Fall Meeting 2020.

Philip Lubin	Large Scale Directed Energy for Relativistic Flight	

Recent advances in photonics and directed energy systems now allow us to realize the ability to project the high power over vast distances that is needed for space applications, including the ability to achieve relativistic flight among many other applications.

Our system consists of a phased array of optical amplifiers in a MOPA (Master Oscillator Power Amplifier) topology. This allows a completely modular and scalable approach with every sub-element being of modest power and size with the advantage of mass production and photonic integration. The same core technology can be used for many other purposes including planetary defense, stand-off composition analysis, space debris mitigation, power beaming to long range spacecraft and other distant assets, LEO and GEO power beaming from Earth and space among many others. This allows for a logical roadmap where milestones are immediately useful as the technology is matured.

Professor Philip Lubin is Director, Experimental Cosmology Laboratory, University of California Santa Barbara (UCSB). Professor Lubin pioneered photon sail propulsion for interstellar missions. He is co-author of *Relativistic propulsion using directed energy*, Proceedings of SPIE 8876, Nanophotonics and Macrophotonics for Space Environments VII, 2013 (core.ac.uk/download/pdf/19485607.pdf) and *Asteroid interception and disruption for terminal planetary defense*, Advances in Space Research Volume 71, Issue 3, 2023 (www.sciencedirect.com/science/article/pii/S0273117722009395). You will find numerous reports of Professor Lubin's work in past issues of Principium.

Gregory Matloff	Aerographite: A Candidate Material for Interstellar Photon Sailing	

Aerographite has been suggested in a recent paper as a possible candidate for interstellar photon sailing. This paper begins by presenting known properties of this extremely low density, light absorptive, material. After a review of analytical tools, a number of possible interstellar missions are then considered. The first confirms that a thin-film Sun-accelerated probe deployed at the 0.4-AU perihelion of an initially parabolic solar orbit could reach Proxima/Alpha Centauri after a voyage duration of about 2 centuries. The next case examined is a thin-film probe accelerated to about 0.033c by an in-space laser array. Finally, it is shown that a combined aerographite-graphene hollow-body solar-photon sail may have significant advantages in accelerating a generation ship to an interstellar cruise velocity in excess of 900 km/s. Some of the unknowns regarding this substance that must be addressed before this material can be applied to interstellar sail application are also discussed.
Professor Greg Matloff is Emeritus Associate and Adjunct Associate Professor of physics at New York City College of Technology (NYCCT).
Prof Matloff has been involved in the interstellar endeavour for several decades. He is co-author of the "book on the subject", *The Starflight Handbook: A Pioneer's Guide To Interstellar Travel*, co-authored with Dr. Eugene Mallove, Wiley Science Editions, 1989 and numerous papers, most recently *Von Neumann probes: rationale, propulsion, interstellar transfer timing*, International Journal of Astrobiology 21, 2022 (www.cambridge.org/core/journals/international-journal-of-astrobiology/article/von-neumann-probes-rationale-propulsion-interstellar-transfer-timing/5202679D74645D3707248FE5D5FA0124) and *The Solar-Electric Sail: Application to Interstellar Migration and Consequences for SETI*, Universe 2022 (www.mdpi.com/2218-1997/8/5/252).
Co author of this paper is Dr Joseph E Meany - see his information under his paper *Mapping Nutrient Cycles for Establishing Extrasolar Colonies.*

Joseph Meany	Mapping Nutrient Cycles for Establishing Extrasolar Colonies	

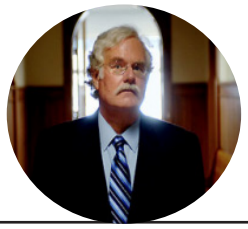
A transition from colony ship to the new planet surface will require careful stepwise development, wherein scavenged elements should be brought to bear to allow for sustainable habitation. The paper will include an outline of critical technical and biochemical cycles and a suggested roadmap for expansion of a crewed mission to develop on-planet extrasolar habitats.
Dr Joseph E Meany is Associate Consultant at Booz Allen Hamilton. His recent works include *Quantitative characterization of photonic sail candidates using nanocantilever displacement*, Acta Astronautica 2022 and *Verification and Temperature-Dependent Rectification by HBQ, the Smallest Unimolecular Donor-Acceptor Rectifier*, American Chemical Society Omega, 2022 (pubs.acs.org/doi/full/10.1021/acsomega.2c01182).

Other key Programme items

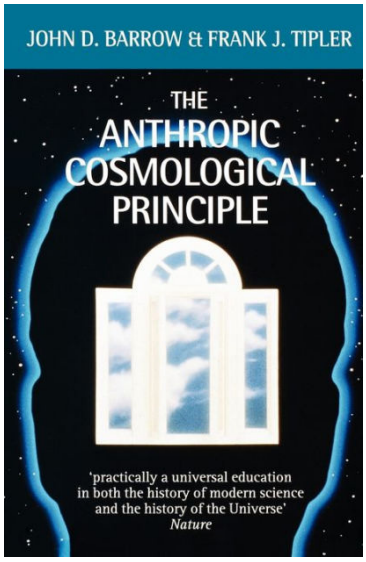
Abstracts were not yet available for these papers at the time of writing.

Rebecca McCauley Rench	The Search for Life and Habitable Worlds at NASA - Past, Present, and Future	

Dr Rebecca (Becky) McCauley Rench is Program Scientist for the Curiosity and New Horizons missions, Planetary Science Division NASA Headquarters.
Dr Rench is co-author of *Microbial population structure in a stratified, acidic pit lake in the Iberian Pyrite Belt*, Geomicrobiology Journal 2020 and *Global Extinction or a Space-Industrial Complex* STEPS Issue 3 2016 (www.potomacinstitute.org/steps/images/PDF/Articles/HertzlerSTEPS_2016Issue3.pdf).

Frank Tipler	The Ultimate Rocket and the Ultimate Energy Source, and Their Use in the Ultimate Future	

Professor Tipler will announce a new approach to space propulsion, "the ultimate rocket".
Professor Frank J Tipler (www.franktipler.com/) is Professor of Mathematics and Physics at Tulane University, New Orleans. He has been a visiting academic at universities in Austria, Germany, Belgium, UK and several US universities. He is perhaps most famous for his work in reconciling theology and cosmology (the Omega Point cosmology) - and for his book (with the late John D Barrow), *The Anthropic Cosmological Principle*, OUP 1986.



Professor Tipler is the author of *Many-Worlds Quantum Mechanics is Neither Mathematically Nor Experimentally Equivalent to Standard Quantum Mechanics*, 2021, (arxiv.org/abs/2105.10431) and *Quantum nonlocality does not exist*, in Proceedings of the National Academy of Sciences 2014, (www.pnas.org/doi/abs/10.1073/pnas.1324238111).

Stephen Webb	Silence is Golden: SETI and the Fermi Paradox	
Dr Stephen Webb is at the University of Portsmouth, UK. Dr Webb is author of *If the Universe Is Teeming with Aliens ... WHERE IS EVERYBODY?: Seventy-Five Solutions to the Fermi Paradox and the problem of Extraterrestrial Life*, Copernicus Books / Praxis Publishing Ltd 2002 and *Pondering the Fermi Paradox*, in *Searching for Extraterrestrial Intelligence*, Springer 2011.		

In addition to the above papers there will be a Sagan session addressing the question "How would you select a crew of one hundred people for the first interstellar mission?" and, of course, a lot of informal conversation and gatherings of those interested in specific topic areas.

Join the Interstellar Community

You can be there for all these presentations and more. Perhaps as importantly you can participate in the informal conversations - see "The Hallway is More Important than the Podium..." in Principium 36 February 2022. Here is Joe Meany's shot from the 2021 symposium in Tucson, Arizona. Register at irg.space/irg-2023/. Students pay $125 CAD before May 31 and $150 CAD later, others pay $550 CAD and $600 CAD.

See you there!

News Feature: Rob Swinney at the Royal Aeronautical Society

John Davies and Rob Swinney

The Isle of Wight (IoW) branch of the Royal Aeronautical Society (RAeS) has an illustrious history, being founded in 1937 and originally based around the Design and Development staff of the Saunders Roe company - famous for its flying boats. For those of us old enough to recall the giant Saro Princess flying boats rusting away on the IoW shore in the fifties it's something we will never forget.

However the IoW RAeS is a forward looking outfit and they hosted a talk by Rob Swinney of i4is titled *Interstellar Human Travel* in November last year (2022). This was one of Rob's most comprehensive lectures and we thought it would be useful to review it here although this article features just a small selection of his material.

Introduction and Background

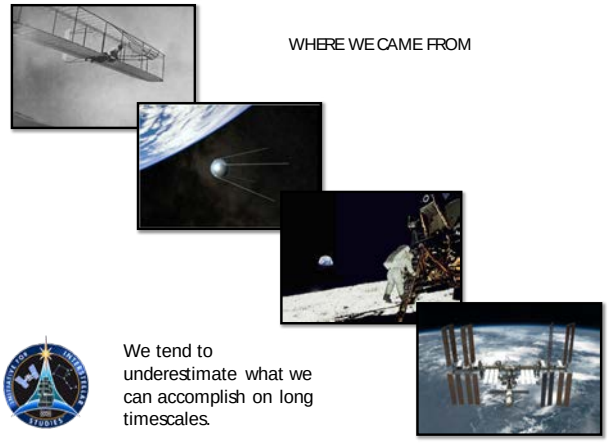
Rob covered -

- Introduction and Background
- Tipping Point?
- Long distance, close up or landers?
- The scale of the problem
- Justifications
- How might we do it?
- Projects Daedalus and Icarus
- Some alternatives
- Summary

Human exploration of the Outer Solar System and to the Stars!

Rob Swinney BSc MSc² MIET FBIS CEng RAF (ret'd)
Deputy Executive Director i4is
Initiative for Interstellar Studies (i4is)™
Contact: rob.swinney@i4is.org
www.i4is.org

Presented to the RAeS Isle of Wight Branch Nov 2022



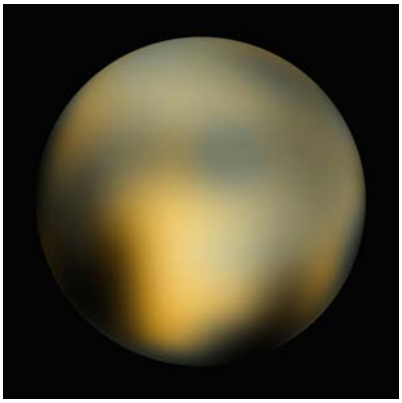
In one hundred years we have progressed from the first powered flight to Moon landing and a space station in Earth orbit - what can we achieve in another hundred years?

Cheap access to low Earth orbit can be that tipping point which will change everything. SpaceX and Blue Origin can offer this and others will come along. Since Rob's talk China has announced a launcher on a similar scale to the SpaceX Starship, featuring a reusable 10m diameter first stage[1] so we can expect a competitive market in super heavy lift launchers in the near future.

[1] Long March 9 en.wikipedia.org/wiki/Long_March_9

Rob illustrated the advantages of going to the most distant objects rather than using telescopes with images of Pluto from the Hubble telescope and the New Horizons probe -

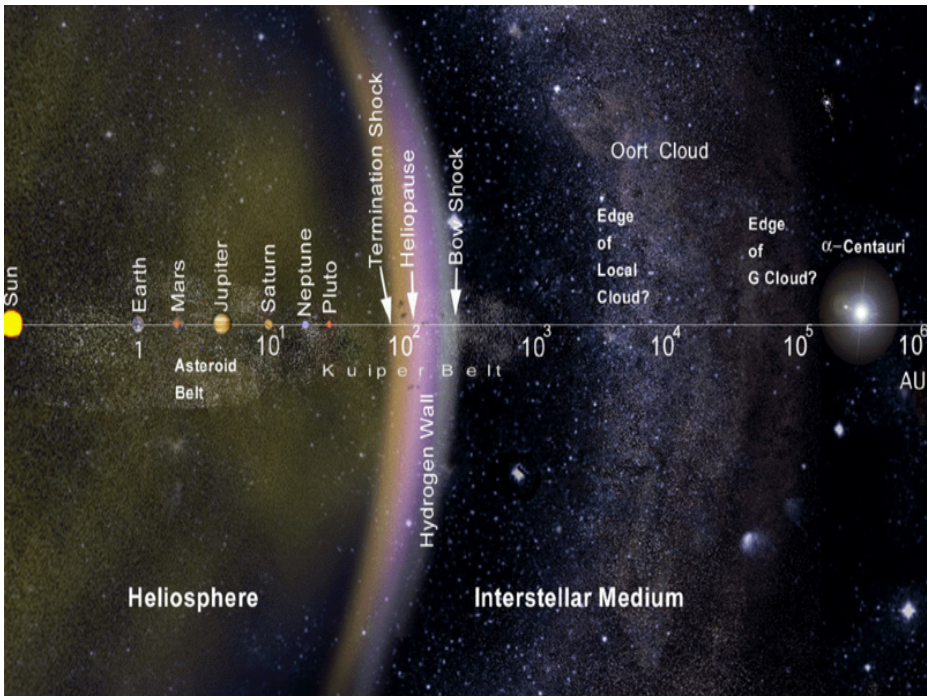
THE BEST IMAGE FROM HUBBLE..?



FROM NEW HORIZONS

- *High Resolution with Enhanced Color*

But getting to even the nearest stars needs a logarithmic scale to illustrate it, as in this image from the Johns Hopkins University Applied Physics Laboratory -



But Rob pointed out the fundamental limitation of all rocket propulsion, the Tsiolkovsky rocket equation. The velocity obtainable (Δv) is limited by our difficulty in either generating very high exhaust velocities (v_{ex}) or in practically using a very high ratio of fuel mass (m_o) to dry mass (m_f.) with only nuclear processes reaching the very high exhaust velocities required for practical travel to even the nearest stars.

$$\Delta v = v_{ex} Ln\left(\frac{m_o}{m_f}\right)$$

Konstantin Tsiolkovsky
Formulated the "*aviation formula*" in 1887

However, the latest generation of serious interstellar studies, beginning about 10 years ago, is looking again at the serious possibilities for a probe.
Here's the group which met in 2014 and 2015 hosted by the California Institute of Technology (CalTech) and NASA's Jet Propulsion Laboratory (JPL) [1].

KECK INSTITUTE OF SPACE STUDIES WORKSHOPS, 2014 AND 2015

Stone, E, Alkalai L, Friedman L, 'Science and Enabling Technologies for the Exploration of the Interstellar Medium', Keck Institute of Space Studies report, 6th November 2015.

Prominent here are Ralph McNutt (Johns Hopkins University - Applied Physics Laboratory - JHU-APL) on the far left and next to him on the front row Philip Lubin (University of California at San Diego - UCSD) and on the far right Claudio Maccone (chair of the SETI Permanent Committee of the International Academy of Astronautics). McNutt represents the source of some of the most advanced thinking for upcoming missions beyond our solar system. Lubin leads a team which has pioneered the detailed study of laser propulsion for very high speed missions to interstellar space. Maccone is a founding father of the serious study of how to find extraterrestrial intelligences. Others here are many of the people active in the current wave of interstellar studies. When the history of our outreach to the stars is written these will be many of the people who will be credited.
In the short term we can reach the nearest parts of interstellar space using conventional rocket propulsion and various slingshotting techniques around planets (notably Jupiter) and even the Sun. McNutt's team at JHU-APL propose a mission to the interstellar medium, a "pragmatic interstellar probe" for the next round of major NASA funding. There are even objects in our system which may have an interstellar origin including centaurs amongst the outer planets and Jupiter's distant Trojan companions. And of course we have now found at least two interstellar objects (ISOs) entering our system, 1I/'Oumuamua and 2I/Borisov. i4is Project Lyra includes mission planning studies to reach them.

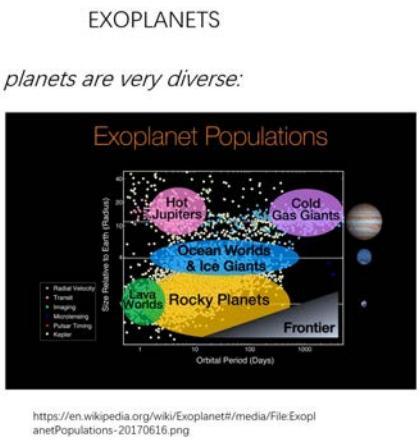
[1] the Keck Institute of Sapce Stdies report (KISS) studies resulted in a probe to go to 200 AU, the JHU-APL Pragmatic Interstellar Probe is the latest design now targetting 1,000 AU.

Better telescopes and techniques have now shown us that almost all other star systems have planets so our own solar system is again shown to be just a normal sort of place - distinguished mainly by our presence.

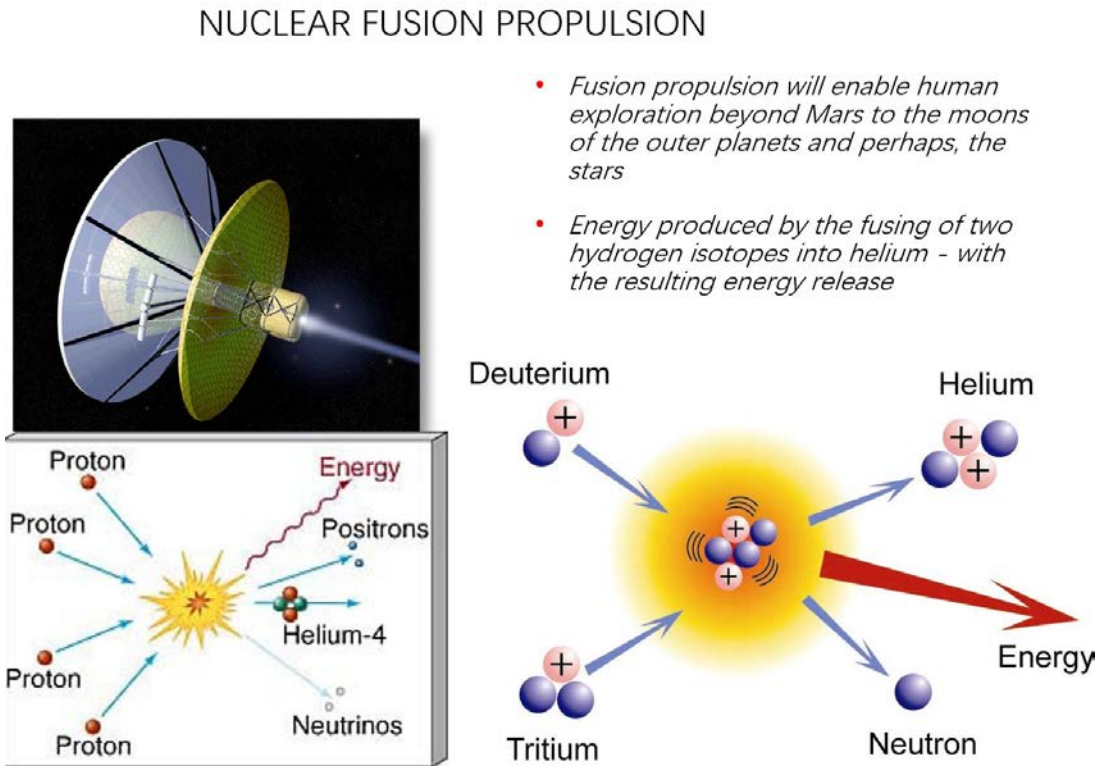
So what are the more efficient ways of propelling our probes? They must be enormously more efficient than our current rockets if we are to reach even the nearest stars in human timescales.

Electric propulsion uses charged particles expelled by an electric field to provide thrust. It is very fuel efficient but does not provide the large thrust required.

VASIMR (Variable Specific Impulse Magnetoplasma Rocket) is an electrothermal mechanism to provide greater thrust at similar fuel efficiencies but it also has thrust limitations.



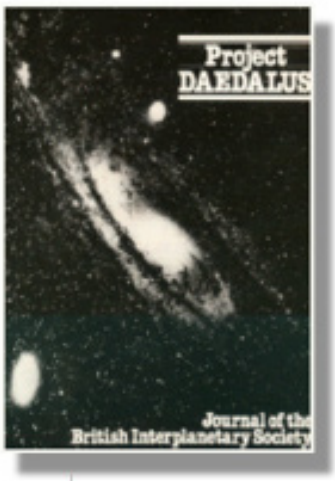
https://en.wikipedia.org/wiki/Exoplanet#/media/File:ExoplanetPopulations-20170616.png

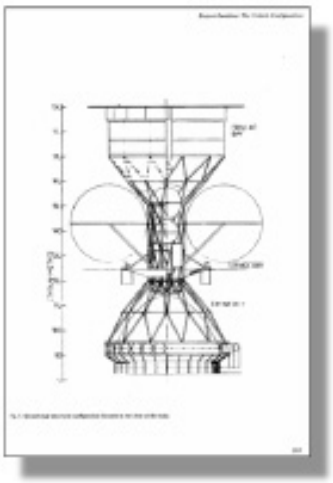


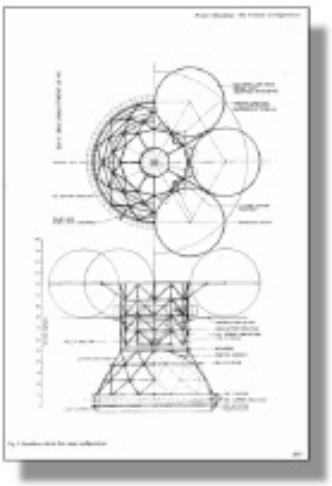
Nuclear fission, as in our power stations, may be enough to get us efficiently to the outer solar system but we need to go further! Nuclear fusion is our most plausible technology for a rocket both efficient and powerful enough to get us to the nearest stars in just a few decades.

Here we see two fusion mechanisms - four protons at very high velocity fuse to produces a Helium4 nucleus, a lot of energy, some much lighter positrons and the "almost not there" particle, neutrinos. This is the mechanism which Robert W Bussard proposed to yield a rocket propelled by protons from the interstellar medium itself. The other mechanism uses propellants we would have to supply, Deuterium and Tritium, to propel our rocket via a magnetic nozzle controlling the ionised Helium produced. Sadly there seem to be fundamental reasons why the Bussard idea, the Bussard ramjet, would not work.

BIS PROJECT DAEDALUS: 1973-78







Bond, A et al., *Project Daedalus: The Mission Profile*, Final Study Report, JBIS Special Supplement, pp.S37-S42, 1978.

The other mechanism is the foundation of many of our fusion rocket ideas and as far as we can tell it would work.

The most detailed study so far of a fusion propelled probe remains the 1970s work of the British Interplanetary Society (BIS) team led by Alan Bond and Tony Martin, Project Daedalus. All the papers from Project Daedalus are available in a BIS book obtainable via bis-space.com/shop/product/project-daedalus-demonstrating-the-engineering-feasibility-of-interstellar-travel/. This was a one-way fly-through mission travelling at 12% of the speed of light so if you do the calculation 0.12*300 thousand = 36,000 km/sec. So if our own system were the target then the transit time across the whole diameter of the Earth's orbit, 300 million km, would be only 300 million/36 thousand = 300/36 thousand seconds = 8,333 seconds = about 2.5 hours. Not long after a journey of around 40 years!

In the past 10 years Project Icarus has aimed to revise the Daedalus design and several teams have worked on different propulsion approaches. The most fully developed of these has been Icarus Firefly which suggests use of a Z-Pinch fusion rocket. Here's how a z-pinch works -

If the powerful current from a lightning strike finds its way to earth via a hollow conductor like this copper tube then the inward force produced by any current will be enough to squeeze the conductor. If a current flows through a plasma then the plasma will be squeezed. Given a strong enough current in a plasma with the right elements the squeezing will lead to fusion. Since the plasma is confined by the squeezing the resultant very high velocity particles have only one way out - in the direction of the plasma flow.

NATURAL PINCHES

Pinches occur naturally, with the most familiar being lightning.

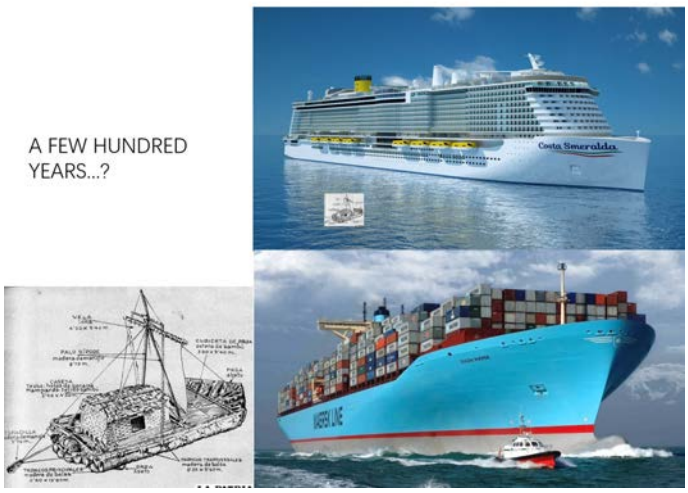
The copper tube at the right (currently on display at the School of Physics, University of Sydney, Australia) was studied by Pollock and Barraclough in 1905 after it was struck by lightning.

This is an extremely powerful long thin rocket which looks like it has a glowing tail - hence the label Firefly. Robert Freeland and Michel Lamontagne led a small team which envisioned this resulting in a proposed probe which would not only reach the nearest stars but also decelerate so that observation of the target system can be extended, probably to months or years. Here is the most recent visualisation of the probe -

The z-pinch beam is unshielded and the fuel and payload occupy the long vehicle body ahead of a shadow shield to protect them. It would not be wise to be, quite literally, "within a million miles" of this vehicle! More about Firefly in a review paper by Patrick Mahaon in Principium 22 [1]. Advances in all forms of fusion technology have been substantial in recent years and both magnetic confinement and inertial confinement fusion have approached the break even point where they start to produce more energy than they demand to drive them,

Once we learn to build our vehicles in space then there is no practical limit to their size. The issue is more like the marine case -

And look what our species has achieved from the balsa rafts and multi-hull canoes with which we settled the Pacific islands about 1,000 years ago to the cruise and container behemoths which now carry us across the same ocean. In space the 50,000 tons of Daedalus or the 25,000 tons of the Icarus Firefly can be just the beginning of vehicle and structures which will make our largest ocean ships look as small as the Kon Tiki raft that took Thor Heyerdahl and his crew across the Pacific just to prove that this way of populating our largest ocean really was possible.



But we are not there yet with in-space construction or mature fusion propulsion technology so how can we send probes using what we already have and know? And the answer is photon propulsion. We have already shown how photons from the Sun can provide small but usable amounts of thrust - Japan's Ikaros probe and the Planetary Society Lightsail-2 have shown this can work. But to reach the nearest stars our light source must be much brighter than the Sun. In 2014 i4is sponsored a student competition to design a vehicle to be propelled by very powerful lasers, Project Dragonfly, and teams from UK, Germany, USA and Egypt submitted designs.

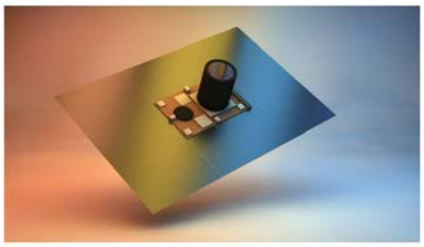
[1] *Reaching the Stars in a Century using Fusion Propulsion - A Review Paper based on the 'Firefly Icarus' Design,* Patrick J Mahon, Principium 22 August 2018 (i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/).

In early 2016 an (almost) chance encounter with a recently retired senior NASA administrator led to a request to design a probe to reach Alpha Centauri. The time available was three days and the entire resources of i4is produced the Project Andromeda design in that time.

I4IS ANDROMEDA PROBE

	Mass [g]
Payload	
Sensor package	4
Nano FPGA-based OBDH	30
Power	
Graphene supercapacitors	25
Nuclear battery	40
Structure	5
Communications RF	26
ADCS	10
Startracker / camera + telescope	20
Radiation protection (Polyethylene)	20
Interstellar dust protection	20
Bus mass	200
Sail	80
Total mass	280
50% margin	140
Mass with margin	420

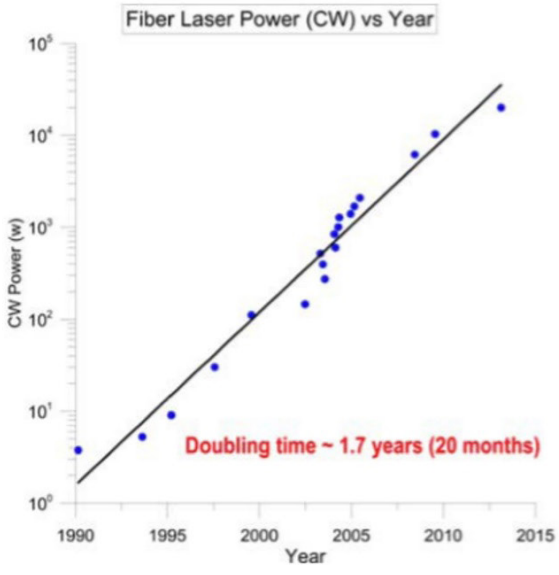
Spacecraft subsystem	Technology	[g]
Payload	MEMS camera + aperture, various MEMS sensors	2,4
OBDH	FPGA-based microcomputer	1
Power	Graphene supercapacitors (storage) and electromagnetic tethers (power generation)	6.5
Structure	Rigid Graphene matrix	0,1
Communications RF	Foldable phased-array antenna + transceiver	3
ADCS	Momentum wheels, MEMS FEEP thrusters	1
Navigation	Use of camera	-
Interstellar dust protection	Graphene Whipple shield	2
Bus mass		***15***
Sail	4-layer Graphene sandwich (Radius: 34m)	8
Total mass [g]		***23***

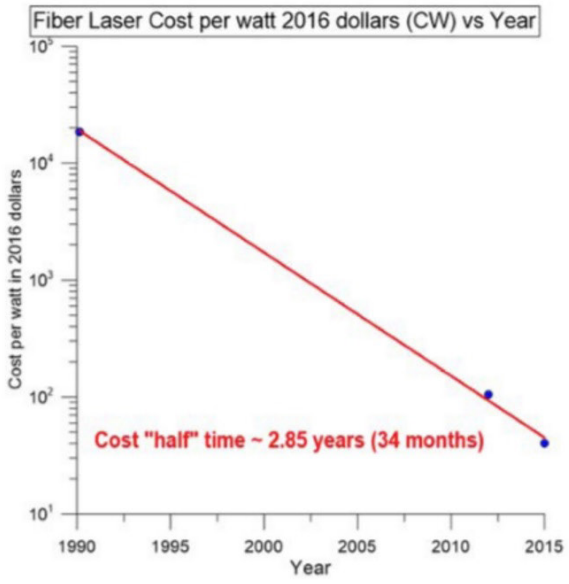


The left hand table was our first attempt which came back with the comment 'too heavy'at 420 g, so it was redesigned in to the version on the right at only 23 g.

The request had been somewhat mysterious but all was revealed when Internet entrepreneur Yuri Milner announced Breakthrough Starshot, a $100m investment in design effort to achieve such a probe.
Trends in maximum achievable laser power and costs support the conclusion that this will soon be feasible -

BREAKTHROUGH STARSHOT





- Laser **power** is rising exponentially
- Laser **costs** are falling exponentially

Laser Trends…

Early requirement values for the Starshot probe included -
• Mass of nanocraft 1 gram
• Acceleration time 2 minutes
• Launch distance 60,000 km
• Speed 60,000 km/s
• Launches per day 1

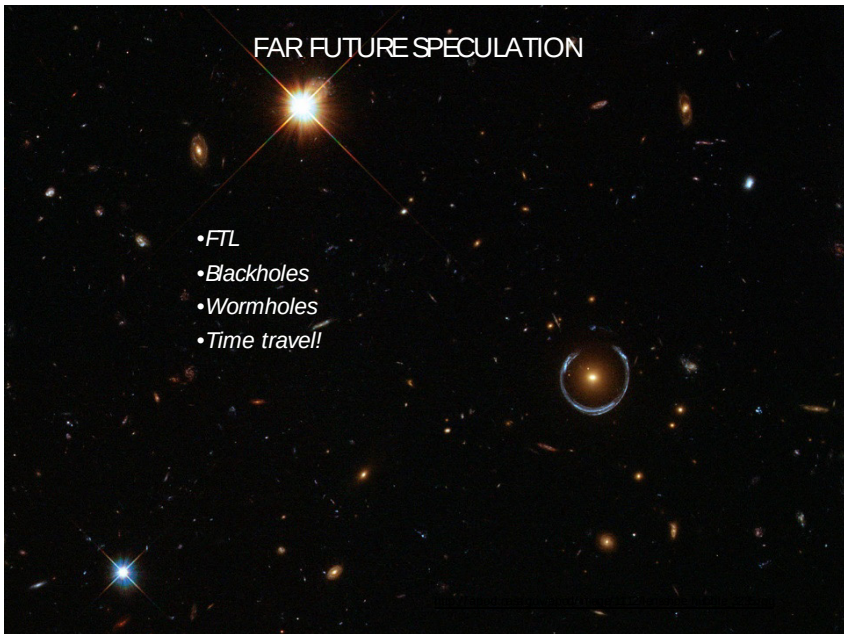
Among many challenges to build such are craft are the sheer acceleration demands of reaching 60,000 km/s in 2 minutes = 60,000,000 /120 = 0.5 million metres per second per second. The acceleration due to gravity at the Earth's surface is about 10 metres per second per second so our tiny probe will experience 0.5/10 million metres per second per second which is 50 thousand million g. The only places to find this naturally are close to neutron stars or black holes so the materials science challenge is considerable.

The overall challenges anticipated when this was first proposed were -

1. Light beamer: cost, combining beams & atmospheric effects
2. Light beamer cooling
3. Precision pointing of light beamer
4. Pointing during acceleration of nanocraft
5. Aiming trajectory at exoplanet
6. Sail integrity under thrust
7. Sail stability on the beam
8. Interstellar dust
9. Interplanetary dust
10. Interstellar medium & cosmic rays
11. Maintaining functionality over decades in space
12. Pointing camera at planet
13. Pointing transmitter at Earth
14. Sending images using laser as transmitter & sail as antenna
15. Receiving images with light beamer
16. Power generation & storage
17. StarChip components at gram scale
18. Launch safety & space debris
19. Policy issues

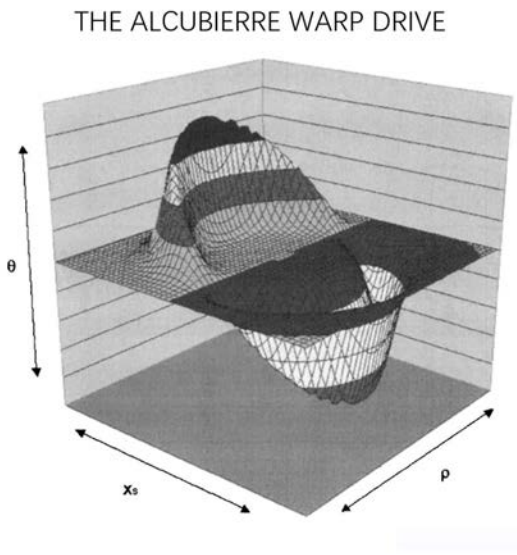
Of these the only one we have achieved (although for two much larger craft) is number 11 - since the Voyager craft are still operating despite having been launched in 1977, 46 years ago [1].

This sort of technology can get tens of thousands of tiny probes to the nearest stars in about 20 years but can we go further?



[1] A literature search on the above list to 19 challenges will be featured in the next issue of Principium - unless of course some one does this first.(please let us know!).
Breakthrough published papers and discussion (breakthroughinitiatives.org/challenges/3).

In 1994 Miguel Alcubierre published a paper, *The Warp Drive: Hyper-fast travel within general relativity* (but of course Star Trek fans knew about this back in the sixties…)

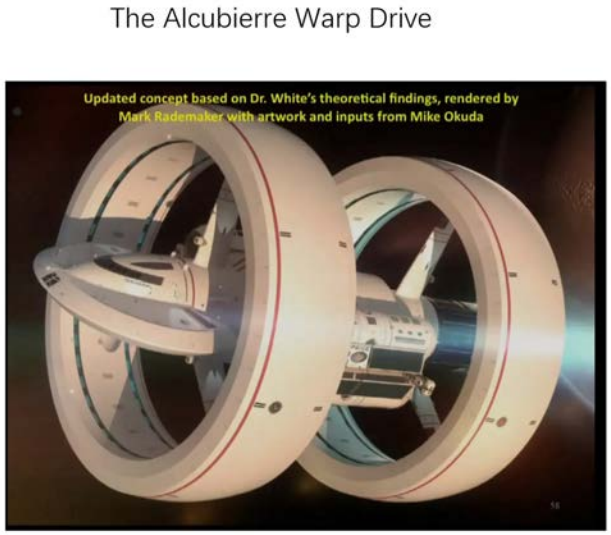


- First figure is York time visualization of spacetime distortion
- Second figure is resulting required distribution of mass
- *f*– shape function: includes wall thickness, radius of warp bubble
- r_s is Euclidian distance in local reference frame
- Reduce mass requirements: (still need between Jupiter and Voyager 1 mass amount)
    - Thicker torus
    - Oscillate York time magnitude
- Examples of negative energy:
    - Casimir effect
    - Gravitationally squeezed electromagnetic zero-point fluctuations (close to black hole event horizon)
    - Certain electric/magnetic field configurations

Dark matter surrogates

We need a Minkowski diagram - a two-dimensional depiction of a portion of Minkowski space (en.wikipedia.org/wiki/Minkowski_space).
Ship outraces its own photons: so at some point they arrive from two "directions" which looks like time travel but we can still infer that ship travels forward in time.

Here is a conception of the required vehicle. I4is Deputy Technical Director, Dr Dan Fries, will be discussing the current "state of the art" in FTL in the next issue of Principium.



In SUMMARY -
There is a long history of people thinking about extreme deep space travel – and a lot of ideas.
A major tipping point has been reached with low cost to orbit arriving.
Major technology advances are foreseen.
The problems seem challenging but will be conquered given time – there are no physical barriers.
The i4is team is dedicated : ***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.***
Find out more in our quarterly free magazine, *Principium*. Access and subscription at i4is.org/publications/principium/.

Frant cover of Principium 39 (P39) celebrating our tenth anniversary

And we do work with universities, schools, astronomical societies, science societies, engineering societies and others to raise awareness of the potential for interstellar.
Here we are at the UK Royal Institution - as they say "Science lives here!"

SUMMER SCHOOL AT THE ROYAL INSTITUTION - LONDON

News Feature: i4is delivers Communications Study to Breakthrough Starshot

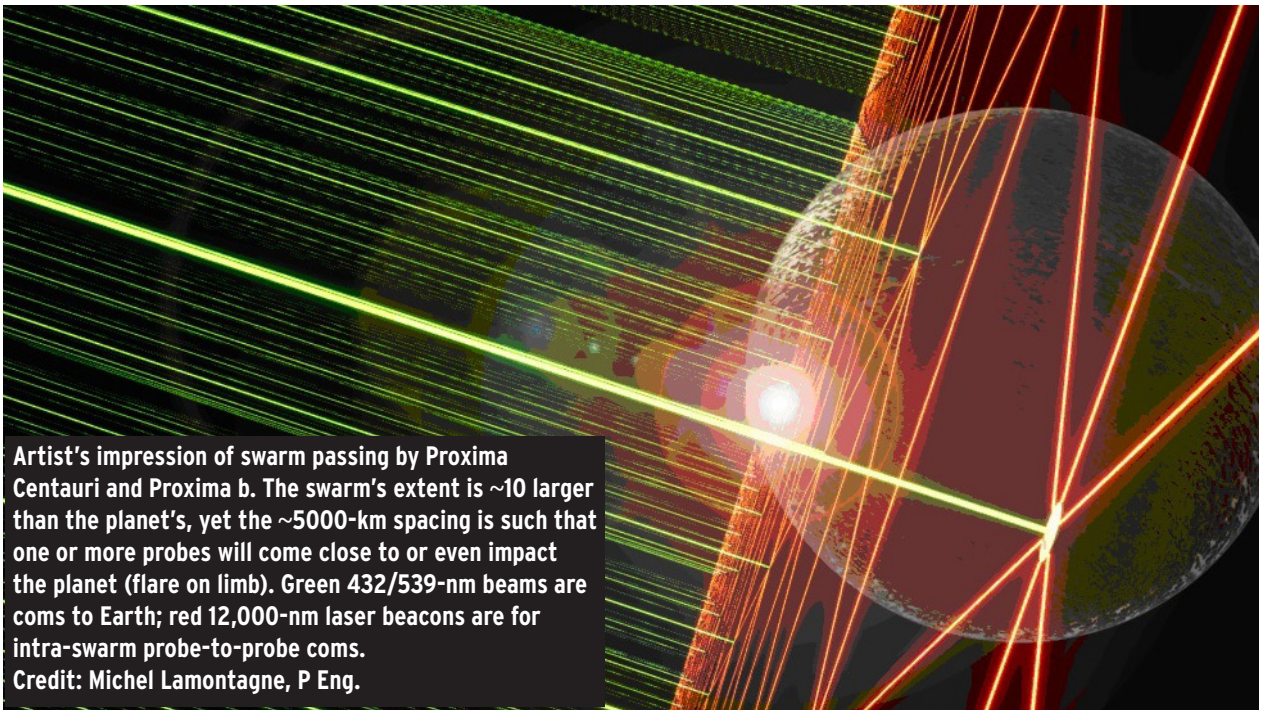
Swarming Proxima Centauri: Optical Communication Over Interstellar Distances

John I Davies and Robert G Kennedy

Pushing an interstellar lasersail with beamed power in order to fly by Earth's closest neighbour Proxima b, four light-years away at near-relativistic speeds is less than half the battle. With such a tiny mass budget – 1 gram payload per probe – the bigger challenge is getting back any data at all [1].

Introduction

On Monday 24 April 2023, after a year of preparation and a year-and-a-half of contracted work, Institute for Interstellar Studies-US delivered its final systems engineering analysis and conceptual design to the Breakthrough Starshot Foundation. Our work, which contains six broad innovations, demonstrates that it is not impossible to get optical data back from a large swarm of gram-scale probes flying by Proxima Centauri b four light-years away at 20% of light speed.



Artist's impression of swarm passing by Proxima Centauri and Proxima b. The swarm's extent is ~10 larger than the planet's, yet the ~5000-km spacing is such that one or more probes will come close to or even impact the planet (flare on limb). Green 432/539-nm beams are coms to Earth; red 12,000-nm laser beacons are for intra-swarm probe-to-probe coms.
Credit: Michel Lamontagne, P Eng.

[1] The challenge is outlined in *The Interstellar Downlink, Principles and Current Work* in Principium 31 November 2020 i4is.org/wp-content/uploads/2021/08/The-Interstellar-Downlink-Principium31-print-2011291231-opt.pdf

The team was composed of:
- T Marshall Eubanks, President, Space Initiatives Inc – Principal Investigator.
- Andreas Hein, PhD, Executive Director, Initiative for Interstellar Studies – Systems Engineering.
- Robert G Kennedy III PE, President, Institute for Interstellar Studies-US – Systems Engineering.
- W Paul Blase PE, Space Initiatives Inc – Systems Engineering.
- Adam Hibberd, Initiative for Interstellar Studies – Trajectory Dynamics.

Credit also to the remarkable Michel Lamontagne, PEng, our French-Canadian artist-engineer.

Background and Remit

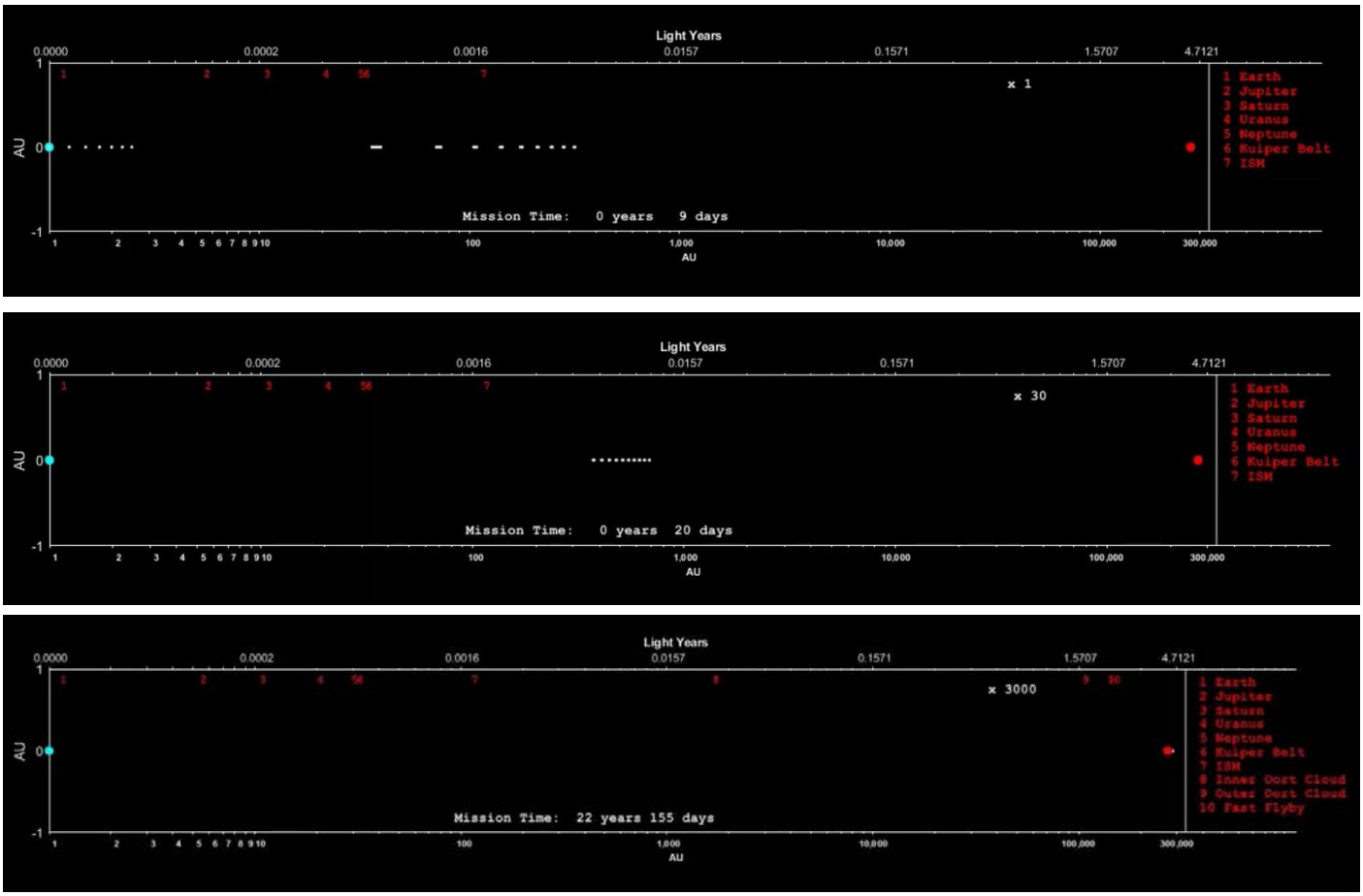
i4is, on both sides of the Atlantic, started preparing for this opportunity from the Breakthrough Starshot (BTS) Foundation in 2017 long before it was awarded to the "American branch", ie Institute for Interstellar Studies-US (I4IS-US). We won this contract in February of 2021 in an open competition with first-rank research institutions world-wide. The contract between I4IS-US and BTS was formally executed by both parties on 21 June 2021. Several dozen other teams, broadly divided into Launch, Power and Communications groups were contracted by BTS as well. Our remit during this "Phase 1" work was to find any "showstoppers" in the communications challenge, an analysis that ultimately necessitated we independently develop a full system concept, still compliant with the basic givens and constraints (one gram payload per probe, 150K data return within one year of encounter), which informed a mass partition and defensible power budget. On 10 March of this year, having satisfied the requirements of the contract, I4IS-US was paid in full by BTS. We continue to participate in periodic technical meetings of the Communication Group, and have established relationships with other teams, to prepare for possible follow-on opportunities.

The Study

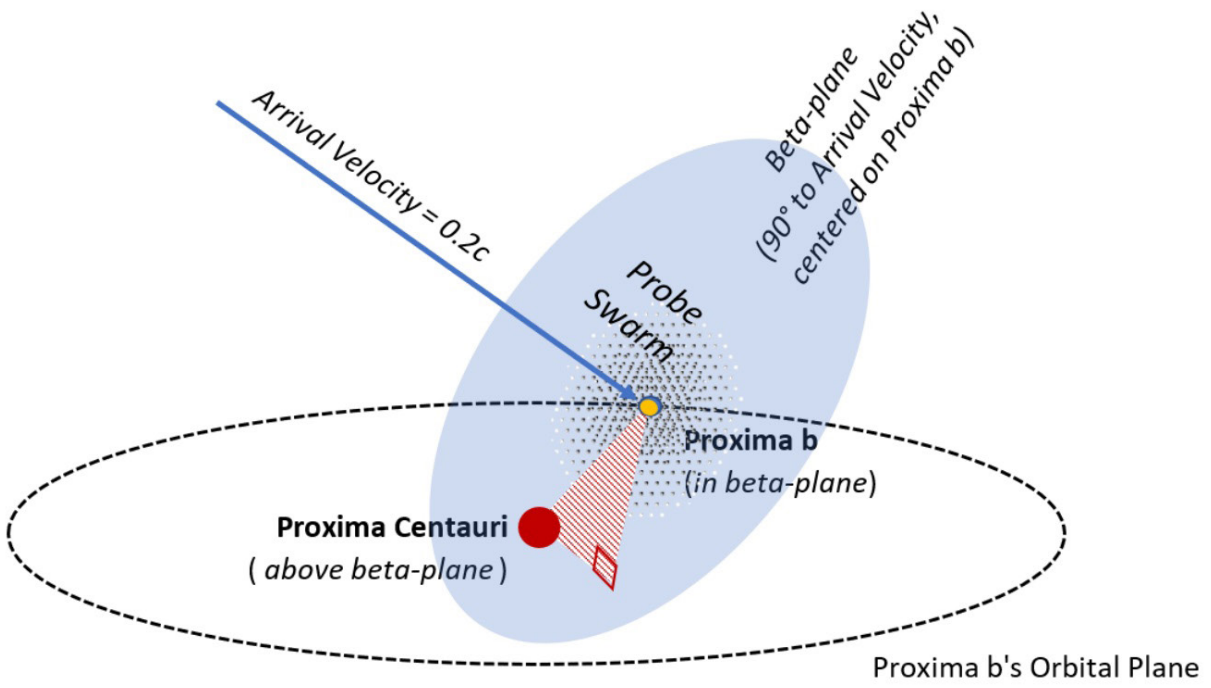
The i4is team concluded that interstellar optical communications are achievable with gram-scale spacecraft using swarm techniques introduced herein if an adequate energy source, clocks and a suitable communications protocol also exist. The team showed that the challenge could be met applying six broad innovations that they developed:

- In the first place, rather than sending a single lasersail, launch a string of 100s–1000s of spacecraft in order to mitigate collision risk during boost and attrition during cruise. Synchronise the probe swarm during flyby to optically transmit a useful number of primary signal photons (~10^{19} per bright short nanosecond "chirp" at Proxima b, a few hundred photons of which could be caught by ~1 km^2 of cheap "light buckets" on Earth) supplemented by digital signal processing (DSP) that is effectively infinite and free. Thus a swarm provides the basis for an optical comlink that easily satisfies the requirement to receive a minimum 100-kilobyte image with a year after encounter.
- Forming up the swarm utilizing the military time-on-target (ToT) technique by grossly modulating the initial velocity of each probe during launch in 2050 such that the tail of the string swarm catches up with the head during cruise resulting in a swarm.
- Autonomously applying a finer "velocity-on-target" (VoT) technique to dump speed during the two decades of cruise by adjusting each probe's attitude with respect to the interstellar medium (ISM) in order to keep the swarm together after it coalesces. Note each disc-shaped probe must fly edge-on most of the way to minimise the extremely high radiation dose (~100 gigarad) induced by travelling through the ISM at 20% of light speed. Even a single neutral hydrogen atom packs a 20-MeV punch at this relative velocity. Full autonomy is necessary because remote control with feedback from Earth will rapidly become impractical due to latency that is continuously increasing at the rate of 4.8 hours of time-lag per day of flight, to an 8-year round-trip delay by the time of flyby.

- Establishing secondary communication within the swarm by infrared (IR) optical means for probes to discover each other and coalesce a mesh network – in effect a distributed "hive mind" – and then use that swarm as a synchronized optical signalling array for data return back to Earth on the primary near-UV channel.
- Applying state-of-the-art microminiaturized space-rated optical clock metrology combined with time- and frequency-bandpass filtering to improve data collection and downlink signal-to-noise ratio. Squeezing a given number of signal photons into a very short transmission window of order nanoseconds wide by synchronizing them greatly increases the brightness of the "chirp" by ~2 orders of magnitude relative to the background noise from Proxima Centauri and the Milky Way as a whole. Assuming continual albeit time-lagged coms with Earth, and extrapolating 80 years of monotonically-increasing progress in the horological art, we can expect that the Swarm will always know exactly what time it is (within ~10s of picoseconds inside the Swarm) and therefore exactly where it is (range within order ~4000 km, about the size of our Moon), even with 4.24 years of time-lag by flyby in 2070.
- Rediscovering an extremely compact long-lasting form of onboard energy storage at nuclear energy density, solid state with no moving parts, namely a betavoltaic cell consisting of the common cheap strontium-90 isotope derived from nuclear waste sandwiched between common photovoltaic material, sufficient to provide ~10 milliwatts of electric power per probe for decades of autonomous operation, timekeeping, computing, and ~1 mW per probe for signalling, ie ~1 watt optical power for the swarmfleet. Such a cheap simple long-lasting nuclear battery could be ready for market within a decade for a modest engineering effort, say low $10s of million. This capability would have profound utility for deep-space exploration missions inside our own solar system.



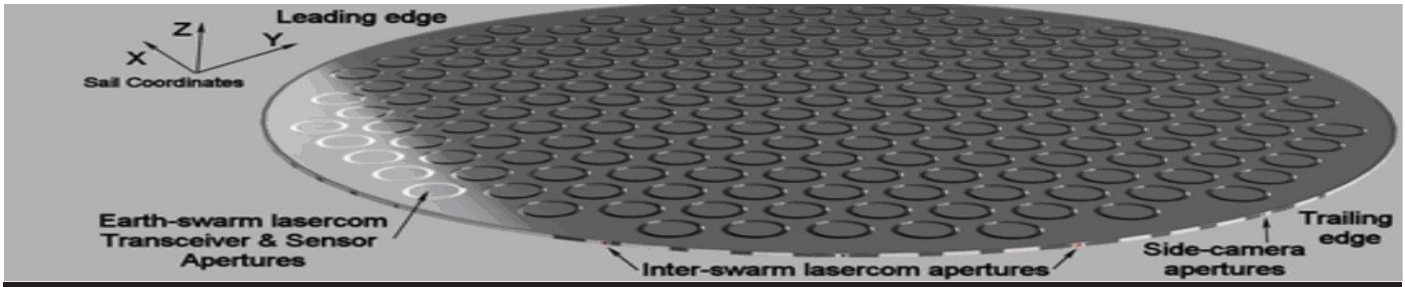
The probes are launched one at a time from Earth and assemble into a cohesive mesh network en route. Note the distance scales (AU and light years) are logarithmic - image based on CG animation at www.youtube.com/watch?v=jMgfVMNxNQs
Credit: Adam Hibberd



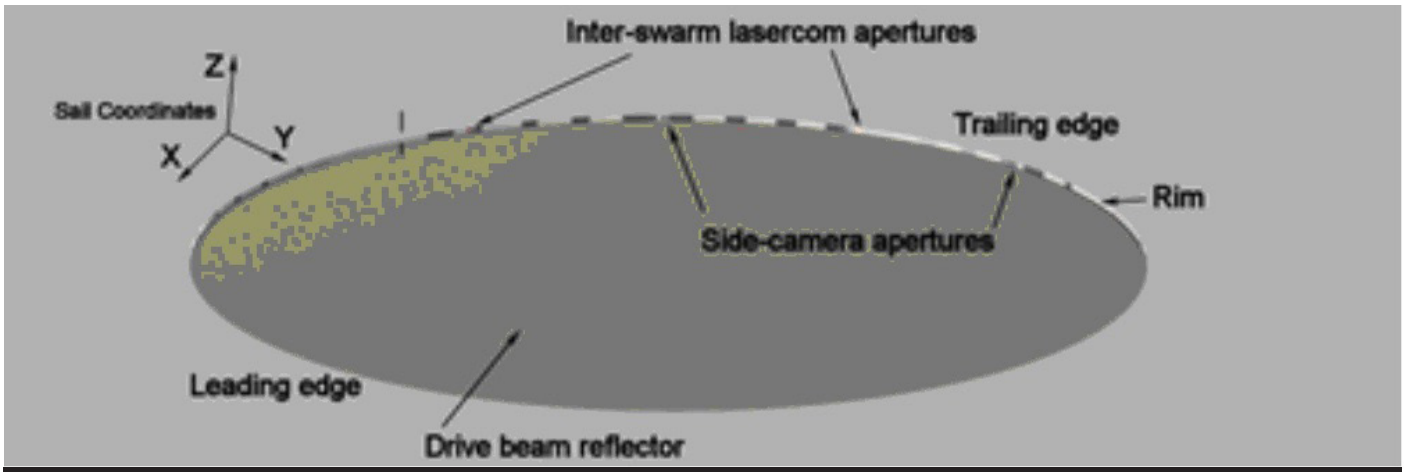
Geometry of swarm's encounter with Proxima b in gibbous phase. Host star Proxima Centauri is in advance of the Encounter Beta-Plane, the orientation of which is not known at this time! Defining Proxima b's ephemeris requires getting to work now! Text relating to the swarm italicized; text relating to objects in the Proxima system bolded.
Credit: Adam Hibberd

The team also conceived and proposed utilizing the 100-gigawatt (GW) beamer on Earth: (a) at lower power during the two-decade cruise for one-way in-flight coms and synchronizing time between the Swarm Fleet and Earth and (b) at full power, also as an "interstellar flashlight" to illuminate the path ahead in real time to identify dark objects and for obstacle avoidance. Upon the Fleet's arrival, the 100-GW beamer on Earth would have more than enough optical power if fired 4.24 years ahead of time to serve as an adjunct external apparatus to support science at the target system, such as transmission spectroscopy, which could not be provided in any other way by instruments limited to a point of view only from Earth.

Under i4is's concept, each 4-m diameter probe would have to be fabricated as single monolithic device based on additive techniques at atomic scale, similar to the wafer-scale-integration that produces 30-cm-diameter supercomputer chips today. For redundancy, resilience, and radiation hardness enroute, a probe has no heart, rather its important bits (isotopic batteries, ultracapacitors, computation, infrared lasers for inter-probe/intra-swarm coms, conductive paths for same) are distributed around the thickened "armoured" 2-cm rim, resembling a red blood cell. Inside the rim the central disk consists of a thin membrane of aerographene – a high-strength extremely-low-density meta-material, about the same density as helium gas at STP (!) sculpted to atomic precision in order to eliminate mascons during the 100,000-g launch – composing a phase-coherent array of flat optics roughly similar to a compound Fresnel lens (247 individual 25-cm diameter optical wells pictured), for both imaging the target and transmitting the data and picture(s) back to Earth. Although we assess by launch in 2050 that space-rated clocks will not be quite small/reliable enough to make the entire 100,000-km diameter swarm phase-coherent during flyby in 2070, the arrays on each individual 4-m diameter probe would be phase-coherent, which greatly increases pointing and signal:noise ratio.



Oblique view of the top/forward of a probe (side facing away from the launch laser) depicting array of phase-coherent apertures for sending data back to Earth, and optical transceivers in the rim for communication with each other.
Credit: (image and caption) W Paul Blase



Oblique view of bottom / aft of a probe (side facing the launch laser) depicting dielectric boost layer and and optical transceivers in the rim.
Credit: (image and caption) W Paul Blase

Conclusion

Our results contained in this 30-page work are enough to inform at least three separate professional papers in this field.
Please stay tuned to the pages of this magazine.

Cost-Optimal System Performance Maps for Laser-Accelerated Sailcraft

Adam Hibberd

Dr Kevin Parkin's systems engineering thinking has been fundamental to the work driven by Breakthrough Starshot. Our interstellar colleague Dr Al Jackson reviewed Dr Parkin's paper to the 2022 International Astronautical Congress 2022 in Principium 40, February 2023, page 24. Here Adam HIbberd takes a more extended look at this paper [1]. If we are to send probes to the nearest stars in the relatively near future then systems thinking must be an early and vital contributor to planning for this.

Dr Parkin's previous paper [2] assumed a 'point design' of 0.2c/1 gram and a precursor mission at 0.01c/7 mg.

The paper reviewed here covers a wide range of designs from 0.1 mg microbiome (a community of organisms) payloads to 100 kiloton payloads and from 0.0001c to 0.99c cruise velocities.

The main driver for what is possible in a design is its cost.

His previous paper analysed cost-optimal strategies using numerical techniques to model all the infrastructure (including the laser sail design) as well as the laser deployment and acceleration of the sail. This resulted in various issues, the main one being that the number-crunching to solve each problem was rather protracted.

Various developments since the construction of his previous paper have motivated him to develop alternative software which has improved convergence and a performance map over both payload mass and cruise velocity.

SYSTEM MODEL: This describes the propagation of a beam from a director at ground-level to a sailcraft, and that craft's resulting motion. Two objective functions are minimization of system capex (capital expenditure) and opex (operational expenditure).

Clearly the important factor for modelling the acceleration of a sailcraft is the light flux – that is the power per unit area - on its sail. Summed over the area of the sail we get the total power incident on the sail. Ideally all the light - and therefore power - generated by the beam director will impact on the sail. In practice there are various losses like for example due to spillage of the beam around the edges of the sail & attenuation due to Earth's atmosphere etc.

Imagine now a line extending in the direction from the beamer to the spacecraft (s/c) and beyond (and static wrt the beamer), with tick marks located at equidistant points along the way. What we have defined is the 'quasistatic' frame mentioned in the paper. The paper labels this direction 'z' and, as the laser beam accelerates the s/c, there will be a time lag between the power emitted by the beamer and that received by the s/c.

[1] IAC-22-D4.4.5 Cost-Optimal System Performance Maps for Laser-Accelerated Sailcraft, Kevin L G Parkin Parkin Research LLC, San Francisco, USA (arxiv.org/abs/2205.13138)

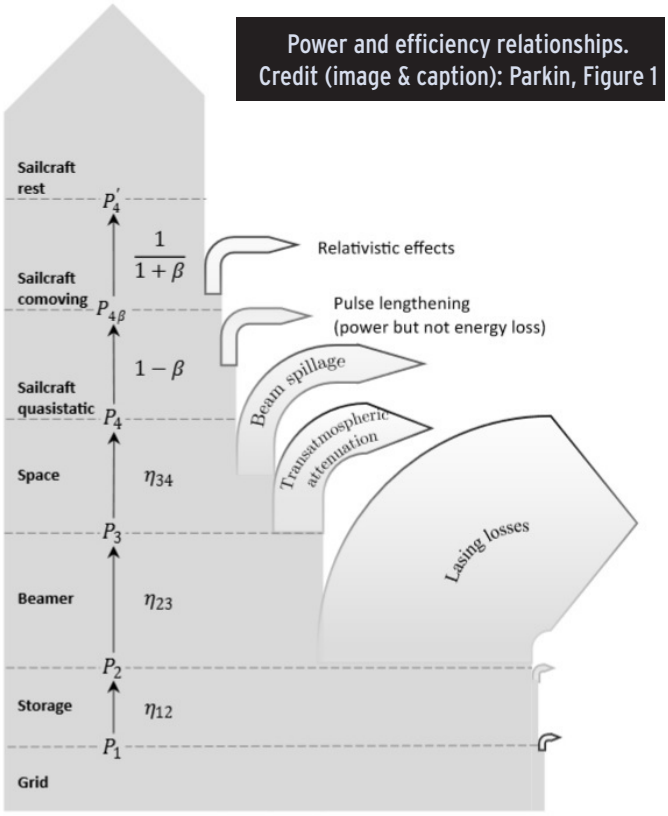
Now imagine the s/c is actually travelling at a velocity v somewhere along z, then we can define the co-moving frame as the instantaneous frame which is moving with the s/c at this velocity. The power received by the s/c in this frame is reduced by a factor (1-v/c) = 1-β. Furthermore Doppler shift (ie the increase in wavelength of light received by the s/c due to the receding velocity of the s/c) will introduce a further power loss in the from of (1/(1+β)).

Of course with the s/c travelling so quickly, we need to take into account relativistic effects in a relativistic rest frame at rest with the s/c. When this is all implemented, we get the overall factor (1-β)/(1+β), which happens to be the relationship between power in a relativistic frame compared to a stationary frame, as derived by Einstein himself.

Next the optics need to be modelled, more specifically the fractional transmission of beamer power to the s/c over the course of distance z. There are various models and they vary in the validity of their assumptions, and the degree of fudge which can be tolerated. Suffice to say a model which contains around 3% fudge is chosen for ease of analytical computation.

Now we can address the equations of motion, which require the force delivered to the s/c, and the paper makes the point that the force exerted is independent of reference frame, but is dependent on the power (after the respective losses mentioned above which change with z). Also the material for the sail is important in the form of its reflectance R and absorptance A. The equations can be derived by implementing the rate of change of momentum which of course is dependent on the rate of change of mass (through its relativistic connection with speed) as well as the rate of change of speed itself. It should be noted here that speed is not used directly but instead its ratio with the speed of light, β, and the well-known Lorentz Factor $\gamma = 1/\sqrt{(1-\beta^2)}$ [1].

Anyone with any experience of spacecraft trajectories will know that the equations of motion, which are usually in the form of an equation for the second derivative of position over time (in this case d^2z/dt^2) need to be integrated wrt time to get first velocity and then, when integrated again, position. However the paper asserts that the particular form of the equations lend themselves better to integrating the first derivative of velocity (or β actually) wrt position (so dβ/dz), which will provide β as a function of position, z.



Power and efficiency relationships. Credit (image & caption): Parkin, Figure 1

First however to do this, simplifications need to be made, particularly that of assuming the power incident on the s/c is actually constant (rather than changing with z), since any amplification may induce temperatures which cannot be tolerated by the sail material – the so-called temperature-limited regime. Optionally, the power of the beam itself may be limited, due to physical constraints on the laser infrastructure, which gives us the alternative power-limited regime. Either of these simplifications yield closed solutions for the integrand of dβ/dz, in turn giving β as a function of z.

Next we address the total energy required from the beamer and straightforwardly enough, it is simply the integral of power over time (as power is obviously rate of change of energy). It so happens that the equations yet again transform readily from a function of time to one of velocity (again as β actually), allowing a numerical integration to be conducted. It is this energy, Q, which must be minimized of course to minimise cost.

The system model can now be actuated via an algorithm explicitly defined in the paper. It amounts to using the beamer power-limited regime when the s/c's temperature so permits (ie is safely below an upper limit); but the temperature-limited regime when the s/c's temperature reaches a maximum

[1] As has been previously stated, the power incident on the s/c is essentially dependent on z only and thus an integration scheme based on the β as a function of z would seem more conducive to analysis than as a function of time.

limit, the former is a constant whereas for the latter the power incident on the s/c is constant.
Now fully equipped with a system model in closed form it can be compared with that of Parkin's previous system model, and reassuringly trajectory curves are similar, though do differ in line with the fudge factor of 3% already highlighted above.
Next the cost. There are two broad costs which need to be expressed algebraically, firstly CAPEX, which is the prior outlay needed for a particular beamer/lightsail combination. This is expressed as a linear function of three basic parameters, the total energy stored Q_2, the peak power taken in real-time from the grid, P_3+ (not factored in previous papers) and lightsail area A_3. Secondly the OPEX cost, which is the cost of firing the beam, is proportional to total radiated energy, Q_1.
So what are the results? Essentially the most crucial is that laser power storage dominates the CAPEX and that increasing grid power provision reduces the CAPEX for lasersail masses up to 10 grams. Grid capability is limited by power generation capacity and the maximum total energy which can be drawn from the lines. Three point designs are outlined in three separate tables to analyse their respective merits.
So what conclusions can be drawn from all this detailed analysis? Firstly the closed form solutions of the system model which have been derived has resulted in useful reduction in the complexity of the software used by the author as well as allowing for a dramatic reduction in optimization time (1-2 orders of magnitude faster). Furthermore the results are valid, if one bears in mind the aforementioned fudge factors adopted. The new development enables investigation of entire performance maps over a huge range of parameters, as opposed to the old model which was confined to determining point designs.
As far as precursor interstellar and solar system missions are concerned, where the requirements are high mass and low speed, inclusion of power drawn straight from the grid allows a reduction of costs of typically 1-3 orders of magnitude. A case in point is provided of a mass of 10 kg beamed to a speed of 0.001c (63 au/yr), with a destination of say Neptune. This would need a CAPEX of $610M, way lower than the previous $26B, where all laser power was drawn from storage.
Smaller and larger missions were also analysed. A disadvantage of the former is the long time to accelerate the laser sail taking hours to days. If one looks at the future potential of larger spacecraft missions with say 7.4km 100kt vessel accelerated to 0.07c, that would also require long beam durations of around 20 days . Further ahead 380 PW peak radiated power can be envisioned and can also be simulated by the model derived by Parkin, but such missions would need power levels of twice that incident upon the Earth from the Sun, so new power sources would need to be developed eg nuclear fusion or space solar power.

Table 1: System model constants

1.06 μm wavelength
60 000 km initial sail displacement from laser source
0.2 g m^{-2} areal density
10^{-8} spectral normal absorptance at 1.06 μm
70% spectral normal reflectance at 1.06 μm
625 K maximum temperature
0.01 total hemispherical emittance (2-sided, 625 K)
\$0.01 W^{-1} laser cost (k_l)
\$500 m^{-2} optics cost (k_a)
\$50 kWh^{-1} storage cost (k_s)
\$0.1 kWh^{-1} grid energy cost (k_g)
100% grid to storage efficiency (η12)
50% storage to laser efficiency (η23)
70% transatmospheric propagation efficiency (η_a)
100 operations included in cost minimization (n_o)

System model constants.
Credit: Parkin

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

One issue of JBIS (online) has appeared since the report in our last issue, P40. Later issues are in print but not yet online.

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

JBIS VOLUME 75 NO.12 DECEMBER 2022		
Transitioning from First to Second Generation Lunar Infrastructures	Mark Hempsell	Hempsell Astronautics Ltd

At some point the transportation infrastructure that supports the initial phase of human exploration of the Moon should either transition to, or be replaced by, a second generation infrastructure to support early permanent occupation and exploitation. This transition was explored as part of the Scorpion studies, moving from a transport infrastructure based on a single transport system (the Scorpion) which is supported in Low Earth Orbit by the Skylon launch system, to an infrastructure using multiple systems (with several transport and fixed elements) and the exploitation of lunar resources. While most of the conclusions are specific to the assumptions of the study, one conclusion, that second generation landers should be chemical and utilise in-situ lunar oxygen, would seem to apply regardless of other aspects of the infrastructure architecture. More generally, the main study conclusion is that there is considerable value to conducting such second generation studies if they can have a substantive input during the first generation development. They can establish the framework for technology projects conducted during first generation operations, establish the requirements for first generation systems and components that can have a second generation role, and define the hooks and scars needed for the transition from one generation to the next.

Will Cardiovascular Adaptations to Hypogravity Impair a Human Mission to Mars? An Analysis	Brett Gooden	International Space University

The total exposure to hypogravity of a crew on a Mars landing mission is estimated to be just less than three years. Such a mission could consist of 18 months of weightlessness during the interplanetary transits and 17 months at one third Earth gravity on Mars. The cardiovascular effects of years of continuous hypogravity during such a mission are presently unknown. This paper reviews the current state of research on the cardiovascular adaptations to weightlessness, which is based largely on mission times of up to six months and examines the aetiology of these adaptations. It considers how these adaptations relate to the clinical phenomena of current concern, namely fluid shift, Spaceflight-Associated Neuro-ocular Syndrome (SANS), jugular venous thrombosis and orthostatic hypotension. Methods used in an attempt to prevent or attenuate the occurrence of the cardiovascular adaptations during weightlessness, and orthostatic hypotension on re-entry, landing and post-flight, are examined. Based on this analysis, the potential cardiovascular risks to the crew undertaking a landing mission to Mars are discussed, and possible directions for future research into the effects of years of continuous hypogravity on the cardiovascular system are outlined.

Acta Astronautica

Title	Number+date	Author	Affiliation
System analysis of an ISRU production plant: Extraction of metals and oxygen from lunar regolith	Volume 203, February 2023, Pages 187-201	Hong-Xin Shen et al	Technical University of Munich, German Aerospace Center

A study was conducted to compare the performance of three different ISRU production plants that extract metals and oxygen from regolith at the lunar South Pole. The processes selected were: (1) hydrogen reduction of ilmenite and carbonylation to produce low-carbon steels, (2) molten regolith electrolysis to produce ferrosilicon alloys, and (3) molten salt electrolysis, in particular the FFC-Cambridge process, together with vacuum distillation, to produce aluminum–silicon alloys. Holistic system sizing models, including excavation, beneficiation, handling, oxygen extraction and purification, metal processing, gas liquefaction and storage, thermal control, and power, were developed to determine the overall ISRU mass and power budgets. The most effective ISRU production plant preliminarily requires 6776 kg of hardware mass to produce 25 t/a of ferrosilicon alloys from Highlands regolith through molten regolith electrolysis. This facility coproduces 23.9 t/a of oxygen, presenting a total mass payback ratio of 0.14 kg of hardware/(kg of product/a). Sensitivity analyses are presented for the initial ilmenite and anorthite concentrations in regolith. The salt ratio (kg of molten salt per kg of regolith) of the FFC-Cambridge process and the degradation rate of the molten regolith electrolysis reactor are identified as key parameters that determine the feasibility of these ISRU processes. The mass and power of the production plants exhibit a slight economy of scale, indicating that larger amounts of metals and oxygen can be produced more efficiently.

Solar sail with inflatable toroidal shell	Volume 202, January 2023, Pages 17-25	Francisco J Guerrero-Gonzalez, Paul Zabel	City University of New York / Samara National Research University, Russia

In the framework of a strict mathematical approach based on classical theory of elasticity we present an idea of the deployment and stretching of the circular solar sail attached to the inflatable toroidal shell. 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 shell are derived. The analytical expressions can be applied to a wide range of solar sail sizes. Numerical calculations for the sail of radii up to 100 m made of CP1 membrane and attached to the toroidal shell with the varied cross-section radius are presented. The normal transverse vibration modes of the sail membrane under tension caused by gas pressure in the shell are calculated. The feasibility of deployment and stretching of a solar sail with a large size circular membrane attached to the inflatable toroidal shell is demonstrated.
No open access found.

Pressurized lunar lava tubes for habitation	Volume 204, March 2023, Pages 157-174	Raymond P Martin, Haym Benaroya	Blue Origin, Rutgers (State University of New Jersey)

Lava tubes are subterranean tunnels that form as a result of lava flows and appear to extend for long distances beneath the surface of a planet. They are a naturally occurring feature of the Moon. For decades these cave systems have piqued the interest of researchers, not just for their geological complexity, but also for their potential as a habitation site when humans return to the Moon. The internal environment of a lunar lava tube promises to be a benign alternative to the harsh lunar surface; it can provide natural protection from radiation, micrometeoroids, and extreme temperature fluctuations. This paper furthers the study of lunar lava tubes by presenting the possibility of pressurizing them with breathable air. Using a 2D ANSYS simulation model, a range of lava tube sizes are subjected to varied magnitudes of internal pressurization. It is ultimately concluded that it is possible to pressurize a small lava tube while maintaining its structural integrity.
Full text available via: scholar.archive.org/work/4nugy7qwqjadnbtpm4bruyl4oq/access/wayback/https://rucore.libraries.rutgers.edu/rutgers-lib/67372/PDF/1/

Analyzing the engineering feasibility of the direct fusion drive	Volume 206, May 2023, Pages 57-71	Yuvraj Jain, Priyanka Desai Kakade	Manipal Institute of Technology (India). Sheffield Hallam University (UK)
The Direct Fusion Drive (DFD) and its terrestrial counterpart, the Princeton Field Reversed Configuration (PFRC) reactor, have seen significant developments in the past decade. Various groups conducted detailed research on the required specifications of the engine and associated technology for power delivery to onboard avionics and payloads. Multiple studies have also addressed the thrust generation mechanism using empirical specific power scaling relations and plasma flow simulations. Recent studies have designed spacecraft for missions to Earth's second Lagrange point, Mars, transneptunian bodies like Pluto, and the neighboring star systems Alpha Centauri A and B. However, significant work is needed to design the engine components in detail using scientific scaling relations and ab inito calculations to develop the physical systems for prototyping and testing. After critically analyzing the reference design of the DFD and the underlying fusion reactor, this paper addresses the technological gaps and suggests avenues to improve specifications toward targets outlined in previous studies while considering costs. Further, the authors present a prototype engine and magnetohydrodynamic power conversion system design to study the engineering hurdles relevant to the practical implementation of the DFD. No open access found.			

Near-term strategies to rendezvous with an interstellar object	Volume 206, May 2023, Pages 133-143	Damon Landau, Benjamin Donitz, Reza Karimi	JPL
Interstellar Objects (ISOs) offer a unique opportunity to answer fundamental questions about the nature of objects that originate outside our Solar System. Only two members of this new class of mission target have been identified: asteroid 1I/'Oumuamua in 2017 and comet 2I/Borisov in 2019. Many more are expected to be found with the introduction of the Vera C Rubin Observatory motivating the formulation of mission concepts to investigate future ISOs. While fast flyby missions are technically feasible today, rendezvous missions that orbit or even land offer the only means for literal ground truth into the nature of these objects. Mission design and propulsion capability are current challenges due to the brevity of ISO paths through the Solar System. These challenges may be overcome with a trade space of detection capabilities, launch vehicles, trajectory designs, and near-term spacecraft technology development. In particular, the combination of Jupiter gravity assist and nuclear electric propulsion provides the highest likelihood of delivering a spacecraft to match the orbit of an ISO. No open access found.			

The inferred abundance of interstellar objects of technological origin	Volume 208, July 2023, Pages 124-129	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. Full text available via: arxiv.org/abs/2209.11262			

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Project Lyra: What SpaceX could do

The Way to Go and the Launcher to Get There

Adam Hibberd

The Initiative & Institute for Interstellar Studies (i4is.org) recognised the significance of the first discovery of an Interstellar object (ISO), 1I/'Oumuamua, within days of the announcement from the Pan-STARRS system at Haleakalā Observatory, Hawaii, on 19 October 2017. i4is initiated Project Lyra and published the first study of a mission to 1I within three weeks of the announcement [1]. Since then our team have been the most active organisation in both studying missions to ISOs and advocating missions to them.

Here our primary mission planner, Adam Hibberd, addresses the question of which of the larger SpaceX launch vehicles might be best suited to the purpose. This prefigures a journal paper which Adam is preparing covering all the heavy launchers which might be considered for such a mission [2].

1I remains enigmatic, with a number of possible explanations for its properties and behaviour battling in the court of scientific opinion. Only by a mission to this strange object can we definitely determine its nature.

1 Introduction

Project Lyra is the feasibility study of missions to the first interstellar object to be discovered, 1I/'Oumuamua.

The Lyra papers have addressed various possible trajectory options ('the way to go' in the title) but have largely skirted the issue of which launcher should carry the Lyra spacecraft payload by assuming one or two select launchers. The NASA Space Launch System Block 2 is the outstanding candidate for such a mission due to its 'super-heavy lift' credentials.

Broadly speaking there are three possible trajectory options available to a putative craft destined for 'Oumuamua:

1. The Solar Oberth Manoeuvre (SOM)
2. The Jupiter Oberth Manoeuvre (JOM)
3 The Passive Jupiter Gravitational Assist (PJGA)

Since 'Oumuamua is on a hyperbolic orbit (by definition), has passed perihelion, and is now heading away in excess of 26 km/s (equivalent to 5.5 au/year), an intercept mission must seek ways to rapidly escape the Solar System with a heliocentric excess speed of at least this value, in order to stand any chance of catching it up.

It so happens that theoretically the SOM above is optimal for achieving this requirement, that is if one ignores practicalities such as the necessity for a heat shield to protect the craft from the powerful solar flux associated with the close slingshot of the Sun. The early Lyra papers naturally adopted the SOM as the optimal strategy for travelling to 'Oumuamua, and so therefore factored in a carbon-carbon composite heat shield (scaled up from the Parker Solar Probe's). The results using this option were relatively rapid intercept of the target (~22 years) but also have a rather lower technological maturity level (TRL) due to the innovative SOM requirement, a manoeuvre never so far implemented in any mission, and would require some technological advancement in the field.

In this document the SOM is excluded from the analysis, largely because reasonably effective missions using either the JOM or the PJGA can be realised by the powerful launchers to be considered here. Furthermore the PJGA and the JOM are, in that order, the priorities defined in the Interstellar Probe Project as is stated in the definition file produced by JHU APL.

[1] arxiv.org/abs/1711.03155 and subsequently in the journal Acta Astronautica, *Project Lyra: Sending a spacecraft to 1I/'Oumuamua (former A/2017 U1), the interstellar asteroid*, www.sciencedirect.com/science/article/abs/pii/S0094576518317004

[2] *Project Lyra: The Way to Go and the Launcher to Get There*, Hibberd, 4 May 2023 arxiv.org/abs/2305.03065

As far as the selection of a launcher is concerned, the reason for the narrow line of enquiry so far, is the abundance of information on the SLS made available by NASA. Moreover, in specific regard to escape missions – ie missions which escape the gravitational influence of our home world in order to travel to distant destinations in our Solar System - many launch vehicle user guides, especially future ones, give only a broad estimate of the capability of the vehicle in question.

In this article I shall attempt to redress this bias by investigating two SpaceX launch vehicles, Falcon Heavy and the Super-Heavy + Starship, for the purpose of a mission to 'Oumuamua. The latter has yet to accomplish a maiden flight-to-orbit but will likely be available in the Project Lyra launch timeline (ie 2026,2028-2033). There are of course various non-SpaceX launch options, and so I shall cover these in a more comprehensive science paper I am currently preparing on the subject.

For information, the main candidate launchers for Project Lyra, including the SpaceX ones, are outlined in Table 1. Grey shaded rows correspond to launcher capabilities which will expire in the near future and so will not be treated in the following analysis. Pink shaded launch vehicles will, in principle, be available by the time of Project Lyra.

Table 1 Current and Forthcoming Launch Vehicles

		LEO	GTO	Lunar	Mars	Jupiter
		C3 (km^2s^{-2}) [1]				
		-60	-16.3	0	12	84
Payload (mt)						
Heavy Lift Launch Vehicles						
Ariane 5[a]	Heavy Lift	20	9.2	6.6[b]	4.1	N/A
Ariane 6 4[c]	Heavy Lift	21.65	11.5	8.6	6.9	N/A
Delta IV Heavy	Heavy Lift	28.79[d]	14.22[d]	10[d]	8[e]	N/A
Falcon Heavy Exp.[f]	Heavy Lift	?	?	15.01	11.88	1.875
Near-Future Super-Heavy Launch Vehicles						
SH + Starship[g]	Super-Heavy Lift	150	21	?	?	?
Long March 9[h]	Super-Heavy Lift	150	?	54	44	?
SLS Block 2[i]	Super-Heavy Lift	130	58	46	37	8

a = Ariane 5 User's Manual Issue 5 Rev 1. www.arianespace.com/wp-content/uploads/2015/09/Ariane5_users_manual_Issue5_July2011.pdf

b = Sun/Earth Lagrange Point 2

c = Data from Ariane 6 User's Manual Issue 2 Rev 1. www.arianespace.com/wp-content/uploads/2021/03/Mua-6_Issue-2_Revision-0_March-2021.pdf

d = Delta IV Heavy User Guide 2013. www.ulalaunch.com/docs/default-source/rockets/delta-iv-user's-guide.pdf

e = Spaceflight Now, Justin Ray, "The Heavy: Triple-sized Delta 4 rocket to debut" www.spaceflightnow.com/delta/d310/041207preview.html

f = NASA Launcher Query Service. elvperf.ksc.nasa.gov/Pages/Default.aspx

g = SpaceX Starship User Guide Revision 1.0. www.spacex.com/media/starship_users_guide_v1.pdf

h = www.yangtse.com/zncontent/2767741.html (Translation: translate.goog/zncontent/2767741.html?_x_tr_sl=zh-CN&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc

i = NASA's Space Launch System: Capabilities for Ultra-High C3 Missions, Robert W Stough. assets.pubpub.org/luea28iw/11617915904169.pdf

Grey Shading indicate to be phased out in near future

Pink Shading indicate near-future launch capabilities.

[1] C3 is the 'characteristic energy' and a measure of the energy of the target orbit in question.
C_3= V_∞^2 for a hyperbolic orbit where V∞ is the hyperbolic excess relative to Earth, ie. the speed at which the payload exits Earth's Sphere-of-influence
C_3=-μ/a for an elliptical orbit where μ is the gravitational mass of the Earth and a is the semi-major axis of the elliptical orbit in question.

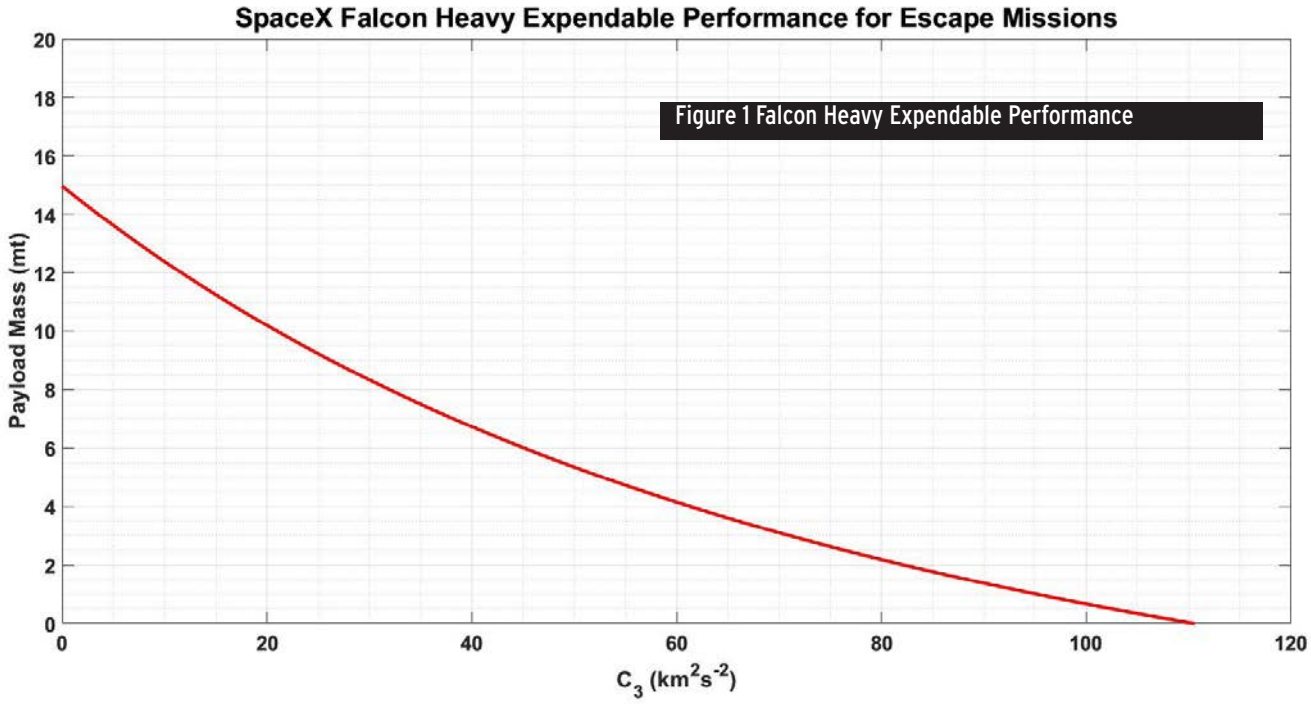


Figure 1 Falcon Heavy Expendable Performance

2 Falcon Heavy Expendable

The SpaceX Falcon Heavy is a super-heavy launch vehicle which, at the time of writing, has executed five successful launches. The fourth most powerful launcher of all time, that is until the SpaceX Super-Heavy + Starship achieves its maiden flight to orbit, this launch vehicle has two configuration options: either partially reusable or expendable, the latter more capable version is investigated here.

From Figure 1, a direct mission to Jupiter is feasible using this SpaceX rocket (the corresponding minimum energy Hohmann Transfer from Earth to Jupiter would require a C3 ≈ 77 km^{2}s^{-2}). The drawback is however that a payload mass of only around 2500 kg as indicated.

If we select a JOM (see Section 1) as our trajectory profile, then we must have attached to our spacecraft, a rocket booster less than this mass to fire at perijove. Table 2 provides a list of the candidates. Most of these are taken from the report on the Interstellar Probe project currently being pursued by JHU APL. We find that only the STAR 48B is light enough to deliver this kick, and it turns out that the overall flight time is rather too large to be practicable.

Table 2 Chemical Propellant Stages

Booster Stage	Exhaust Velocity (km/s)	Total Mass (kg)	Dry Mass (kg)	Propellant Mass (kg)	Height (m)
STAR 75	2.8225	8068	565	7503	2.59
STAR 63F	2.9106	4590	326	4264	1.78
STAR 48B	2.8028	2137	124	2013	2.03
ORION 50XL	2.8647	4306	367	3939	3.07
CASTOR 30B	2.9649	13971	1000	12971	3.5
CASTOR 30XL	2.8866	26406	1392	25014	6.0

Furthermore from Figure 1, we find that a C3 value of 100 km^{2}s^{-2}, which gets to Jupiter and more, can deliver a mass of 750 kg to the escape orbit from Earth. Is this sufficient to allow a mission to 'Oumuamua within a realistic timeframe? The answer is also a definite no. So what are we to do?

Rescue is at hand: there is an alternative way which requires lower C3 values and might enable some sort of feasible mission for this heavy lift launcher, and that is the V-infinity Leveraging Manoeuvre (VILM).

For a VILM, the spacecraft (s/c) embarks on an Earth-return heliocentric elliptical arc, with a time-period of n multiples of Earth's year (365 days), where n is a whole number, usually 1, 2 or 3. A VILM is a useful mechanism by which the speed of the s/c relative to the Sun can be augmented via exploiting the Earth's

mass with a gravitational assist (GA) of the planet. Table 3 spells out the three options n=1, 2 & 3, and provides not only the respective C3 values for each of these options, but also the Falcon Heavy payload lift capability to the escape orbits.

Table 3 Falcon Heavy payload performance to a range of VILM orbits.

n	Time Period (days)	Aphelion (au)	V∞ (km/s)	C3 (km2s-2)	FH Mass (mt)
1	365	1.0	0	0	15
2	730	2.2	5.140	26.42	10
3	1095	3.2	6.982	48.75	6

Table 4 highlights the results of this analysis, addressing each of the scenarios n=1, 2 & 3 in turn. As can be observed, the option n=2, hits the 'sweet-spot' for this Falcon Heavy launcher, with an overall flight duration of 28 years, and with the n=1 & 3 lagging quite significantly behind, at 54 years and 43 years respectively.

The n=2 scenario supposes that a STAR 63F and a STAR 48B are fired at the Earth return, and then a second STAR 48B is fired at perijove. Further an additional 0.5 km/s is applied at the DSM, the reason for adopting this value is so that a low-thrust, high specific impulse propulsion option, such as electric, would be able to deliver this ΔV velocity increment slowly over the course of the n-year Earth resonant orbit, if so desired.

Table 4 Results of missions to 'Oumuamua using Falcon Heavy and VILMs

n	Mass available (mt)	Stages	Mass used + Payload 100kg (kg)	ΔV at Earth Return (km/s)	ΔV at Earth Jupiter (km/s)	Flight Duration (years)	Launch Date
1	15	STAR 75 + STAR 48B	10,305	10.126	0	54	2029 DEC 19
2	10	STAR 63F + STAR 48B x2	9,857	3.6074	6.4499	28	2029 APR 08
3	6	STAR 48B x2	4,374	1.7282	6.4499	43	2027 FEB 25

Maiden launch of the Falcon Heavy, February 6, 2018 (including Musk's Tesla Roadster) Credit: SpaceX

3) Super-Heavy Starship

The SpaceX Starship will be a hugely capable launch vehicle, and as of the time of writing, has not yet achieved a maiden flight to orbit. The data on the internet is scant, but there is the User Guide.
With a good deal of reference to source documents on the internet, this has allowed me to construct the Table 5. The grey shaded areas are data that I have garnered from the internet. The mustard shaded areas are data which I have derived from the grey shaded parameters through appropriate calculations.
In Table 5, we are comparing the Starship with an SLS Block 1, as it is instructive, enabling us to make inferences from the comparison in order to have some idea as to the performance characteristics of the Starship.
We find that for an LEO, the SLS Block 1 and the Starship both have around the same calculated total ΔV, to around 0.05%.
For a Trans-Lunar Orbit (TLO) , however, where the C3 is around 0 km^2s^{-2}, the Starship is found significantly wanting, even with a supposed zero payload mass. And this would translate to an even larger degree of inadequacy for interplanetary missions.
Conclusion: Given the data we have at hand, the Super Heavy Starship is incapable of delivering a spacecraft directly to an Earth escape orbit. In fact this is not so surprising in that it is spelt out in so many words in the SpaceX Starship User Guide.
Let us instead look at the payload it can deliver to LEO, that amounts to an enormous 150 mt. However, the whole context of the Starship design is to allow the potential for in-space refuelling. Would this important asset permit missions to 'Oumuamua with much lower flight durations? We find that to entirely refuel a Starship in LEO, would need 8 launches of SH + Starship, each one carrying 150 mt of fuel.
Given that we have a fully refuelled Starship in LEO, what can we do to leverage this asset for a mission to 'Oumuamua via Jupiter? Figure 2 provides the necessary parameters for a Starship to exit LEO and carry a payload to Jupiter. The horizontal blue-dashed line is the minimum hyperbolic excess speed, $V\infty$, from Earth to travel along a Hohmann Transfer to Jupiter (ie the theoretical minimum 'energy' route to Jupiter). From this line we see that a fuelled Starship in LEO can send any mass up to around 170 mt to Jupiter.
This single important fact opens a wealth of options from which to choose in terms, for instance, of leveraging some combination of Booster Stages given in Table 2, to burn at perijove and arriving at 'Oumuamua extremely rapidly.
Let us address two such combination as example cases, Scenario 1 is a 2 stage option, and Scenario 2 is a 3 stage option (where in both cases the stages are fired at perijove).
Scenario 1 (2 stages):
We shall assume a payload mass of 860 kg (the same as the proposed Interstellar Probe). Together with a CASTOR 30XL and a STAR 75, this gives a total mass of 35.3 mt, and referring to Figure 3, this leads to a $V\infty$ of around 12 km/s. Not only that we have at Jupiter a ΔV for perijove of 8.632 km/s.
Results: Payload 860kg. Launch on 2031 MAR 01, Mission Duration = 23 years.
Scenario 2 (3 stages):
We shall again assume a payload mass of 860 kg. The three stages fired at perijove, in sequence are CASTOR 30XL, CASTOR 30B and then finally a STAR 48B. The total payload mass of all these stages corresponds to a $V\infty$ of about 11.8 km/s. The total ΔV at Jupiter is 9.829 km/s.
Results: Payload 860kg. Launch on 2031 FEB 28, Mission Duration = 20 years.

		SLS Block 1	SH + Starship	Notes
First Stage	Ve (km/s)	4.0479	3.2046 [g]	
	Mass Propellant (kg)	987471.0000 [b]	3600000.0000 [g]	
	Dry Mass (kg)	85275.0000 [b]	160000.0000 [g]	
	Burn time (s)	500.0000 [b]		
	Mass Flow Rate (kg/s)	1974.9420		
Strap-on Boosters	Ve (km/s)	2.6360 [c]		
	Mass Propellant (kg)	1451496 [c]		
	Dry Mass (kg)	200778.0000 [c]		
	Burn Time (s)	126.0000 [c]		
	Mass Flow Rate (kg/s)	11519.8095		
Second Stage	Ve (km/s)	4.5090 [d]	3.4300 [g]	
	Mass Propellant (kg)	29000.0000 [d]	1200000.0000 [g]	
	Dry Mass (kg)	3700.0000 [d]	100000.0000 [g]	
LEO	Payload Mass (kg)	95000.0000 [a]	150000.0000f	
	DeltaV Boosters On (km/s)	2.5745		
	DeltaV Boosters Ej (km/s)	6.0376		
	DeltaV First Stage (km/)	8.6120	3.7633	
	DeltaV Second Stage (km/s)	1.2238	6.0295	
	DeltaV Total (km/s)	9.7978	9.7928	Difference ~ 0.05%
Trans-Lunar	Payload Mass (kg)	27000.0000 [e]	*0.0000*	*Assuming NO MASS
	DeltaV Boosters On (km/s)	2.6786		To The Moon for
	DeltaV Boosters Ej (km/s)	7.2816		Starship*
	DeltaV First Stage (km/s)	9.9602	*3.9831*	
	DeltaV Second Stage (km/s)	3.1416	*8.7978*	
	DeltaV Total (km/s)	13.1018	*12.7809*	Difference ~ 2.5%

Table 5 Comparison of SLS and SH + Starship Performance

Yellow shaded data are calculated from grey shaded data
Grey shaded data are taken from various sources on the internet
*Asterisked data assume the SH + Starship has no payload mass to Trans-Lunar Orbit and demonstrates its lack of capability in this regard *
a= "The Great Escape: SLS Provides Power for Missions to the Moon" NASA, Aug 25, 2022, Jennifer Harbaugh, Brian Dunbar
b= "Space Launch System Core Stage", NASA, Oct 27, 2021, Jennifer Harbaugh, Brian Dunbar
c= "Space Launch System Solid Rocket Booster", NASA, Feb 11, 2022, Jennifer Harbaugh, Brian Dunbar
d="SLS Reference Guide 2022 V5 508", NASA
e= "America's Rocket for Deep Space Exploration", NASA, Jul 19 2022, Jennifer Harbaugh, Brian Dunbar
f= "SpaceX Starship User Guide Revision 1.0"
g= "Starbase Tour and Interview with Elon Musk", Everyday Astronaut, 11 Aug 2021, Trevor Sesnic

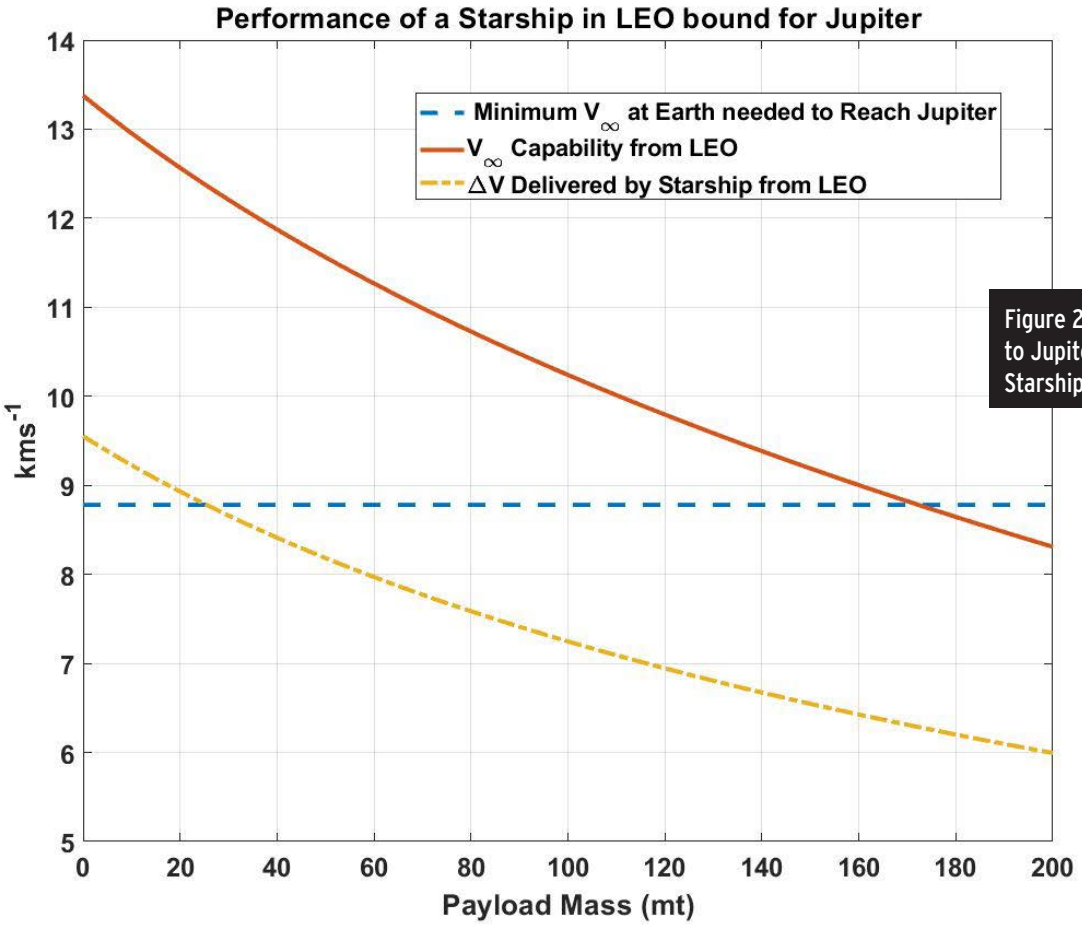


Figure 2 Performance to Jupiter for a Starship in LEO

4) Conclusions

Launch Vehicle	Additional Booster Stages	Payload Mass (kg)	Launch Date	Flight Duration (Years)	Cost/kg
Falcon Heavy*	STAR 63F + 2xSTAR 48B	100	2029 APR 08	28	$1500
Super Heavy + Starship	CASTOR 30XL + CASTOR 30B + STAR 48B	860	2031 FEB 28	20	$150

*With VILM

We have analysed two different launcher options which will be available for a mission to 'Oumuamua, 'Project Lyra'. Both trajectories exploited a Jupiter encounter with a powered Jupiter Oberth Manoeuvre, though with the Falcon Heavy, a *Vinfinity Leveraging Manoeuvre* was required to leverage sufficient hyperbolic excess at Earth to get to Jupiter.

We found by far the most powerful performance is provided by a refuelled Starship in LEO, the refuelling entails the launch of eight additional Starships with a propellant payload.

Currently a SpaceX launch on a Falcon Heavy is around $1500 per kg ($95M per launch), and the projected cost of a Starship launch is as low as $150 per kg ($22M per launch). Note however that SpaceX owner Elon Musk has big plans to reduce launch costs to $1M per launch, giving for the scenarios mentioned here, with 9 Starship launches, a total launch cost of $9M, also by far the cheaper launch option.

Falcon Heavy is a surprise because the combination of trajectory and solid booster stages considered hits a 'sweet spot' in terms of reaching 'Oumuamua particularly propitiously, faring well in comparison to the much more powerful Starship.

THE i4iS MEMBERS' PAGE

Parnika Singh

The i4is membership scheme exists for anyone 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 talks, a monthly newsletter, preprints, and access to the members-only area of the website which contains exciting new material added on a regular basis. If you are passionate about an interstellar future for humanity, joining our membership scheme will allow you to get more involved and help us take the vital early steps towards finally reaching the stars. To find out more, visit www.i4is.org/membership.
This issue of the Member's Page is edited by Parnika Singh who has been editing our member's email newsletter for several months. You will notice one small difference - American spelling! [1]

LSI Course Videos

The full set of our LSI (Limitless Space Institute) course videos is now available for all i4is members. This course provides a fundamental appreciation and basic knowledge of principal subjects, from setting the background and context to advanced propulsion, systems, concepts, and designs. A truly inspirational course, it contains 19 sessions-

1. *Introduction and Background*
2. *Aspects of Science*
3. *Case Study: ISRU as an Enabler*
4. *Case Study: The Next 400 Years: Humanity's Power Basis for Starfaring*
5. *Propulsion Introduction 101, The Absolute Basics*
6. *Electric Propulsion for Fast Missions to Mars, the Outer Solar System and Beyond*
7. *Space Propulsion concepts Based on Nuclear force or matter-energy conversion*
8. *Spacecraft Systems*
9. *Speculative Propulsion*
10. *Case Studies: Power, Thermal Control and radiation/Particle Shielding*
11. *Case Study: Meeting the Human Requirements*
12. *Special Guest Panel*
13. *Deep Space Design Methods and Principles*
14. *Nuclear Rockets and Other Large Concepts*
15. *Interstellar Starship in Science Fiction*
16. *Chipsats and Other Small Concepts*
17. *Discussion Meeting*
18. *Space Habitats, Settlements and Worldships*
19. *Visions of our Interstellar Future*

Find the link here: i4is.org/videos/lsi-course-2022/. Don't forget to login with your member id and password.

[1] Parnika Singh is based in Bellevue, Seattle. She is the author of *An analysis of interstellar exploration focused on propulsion technologies* jhss.scholasticahq.com/article/66203-an-analysis-of-interstellar-exploration-focused-on-propulsion-technologies

Members' Newsletter

The i4is Member's Newsletter is an exclusive newsletter keeping you up to date with compelling interstellar advances, research, and news.
Since the last Principium issue, two member newsletters have been delivered, including coverage of a variety of different developments pertaining to interstellar travel. This includes an announcement on the upcoming Interstellar Research Group's 8th Interstellar Symposium, which will take place from 10-13 July at McGill University in Montreal, Canada; summaries of exciting papers on the development of fission propulsion and anti-matter drives; a review of a paper on Project Lyra and how it may be improved, and much more. If you are interested, be sure to become an i4is member!

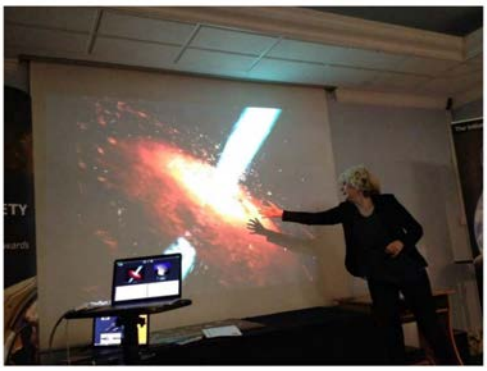
2021 Annual Report to Members

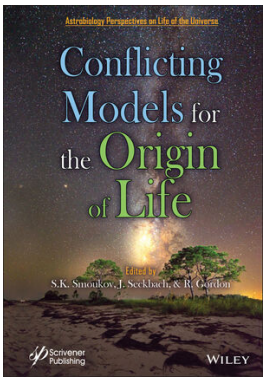
Our Annual Report to members for the year 2021 was published in our members' area in April 2023. This is the third Annual Report to Members of the Initiative and Institute for Interstellar Studies. It covers highlights from 2021, corporate and media activities, the work of the technical and education committee, and many organizational details with contacts for all our main activities.

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.

NEXT ISSUE





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

RIGHT: Conflicting Models for the Origin of Life
Alan Cranston will review.

- **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? Dr Dan Fries, Deputy Head of the i4is Technical Team, will review where things stand.
- **Book Review** - a review of the new book Conflicting Models for the Origin of Life, a new collection of papers discussing our own origins and those of non-humans, sentient and otherwise - by Alan Cranston
- A first report on **IRG23**, as previwed in this issue
- **A new way of finding out what's happening in interstellar studies**: We will announce this first to our members.

- - **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

JWST, Uranus, February 6, 2023

An image labeled “James Webb Space Telescope, Uranus, February 6, 2023.” The planet Uranus is on a black background just left of center. It is colored light blue and displays a large, white patch on the right side as well as two bright spots and a surrounding system of nested rings oriented vertically (It is the only planet in our system whose axis of rotation is akigned close to the ecliptic). Just below the planet at the 7-o’clock position is a faint blue point labeled Puck. Brighter blue points at 8 o’clock, 5 o’clock, and 3 o’clock are labeled Ariel, Miranda, and Umbriel, respectively. Farther from the planet, two additional blue points at 7 o’clock and 5 o’clock are labeled Titania and Oberon. Faint orange smudges are scattered in the background. At the bottom, two NIRCam filters are listed: F140M, coloured blue, and F300M, coloured orange.
Credit: Space Telescope Science Institute.

BACK COVER

The Icarus Firefly probe

Project Icarus was a series of studies aiming to build on the BIS Project Daedalus work in the 1970s. Rob Swinney, i4is Deputy Executive Director acted as Project Manager. The Firefly design was the most mature result of the Icarus programme and one of the design leaders, Michel Lamontagne, has produced a number of visualisations. This one shows the probe enroute near Jupiter.
Rob is organising a final gathering of Project Icarus results at the British Interplanetary Society and we will have more about this in the next issue of Principium,

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.

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

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

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