PRINCIPIUM

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Scientia ad sidera
Knowledge to the stars

Editorial

Welcome to issue 31 of Principium, the quarterly about all things interstellar from i4is, the Initiative and Institute for Interstellar Studies.

Our lead feature this time is *Interstellar Objects and Sample Returns* by Adam Hibberd based on work submitted by i4is and associates to the US 2023-2032 Planetary Science and Astrobiology Decadal Survey.

Our front cover image is a worldship interior envisaged by Michel Lamontagne, whose thinking on worldships will appear in our next issue. The back cover image is the first ever image of a multi-planet system around a Sun-like star by ESO. Much more about both inside the back cover.

As promised we have a review of *Extraterrestrial Languages* by Daniel Oberhaus postponed from the last issue and more from our ISU elective. We have a report on i4is participation in the Starshot Communications Workshop and an introductory piece on the tough job of getting data and pictures back from light years away, *The Interstellar Downlink* and a News Feature on the May 2020 *Breakthrough Starshot Communications Workshop* and i4is team contributions to it. We have the first set of reports by multiple writers on the International Astronautical Congress 2020. We have 15 items of *Interstellar News*. We conclude our reports of the i4is-led 2020 ISU Masters Elective Module. We have news features *Hints of life on Venus* and on i4is Project Glowworm and the i4is Technical Team - and a letter from Prof Greg Matloff proposing an efficient means of shielding humans from galactic cosmic rays.

The regular Members Page includes a request to help our Education and Outreach Activities and our *Become an i4is member* feature illustrates videos of presentations we have delivered worldwide in recent months.

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More in *The i4is Members Page* - page 65

Our next issue, February 2021, will include a new study of Worldships by Michel Lamontagne, a book review of *The Generation Starship in SF* by Simone Caroti (see also the report of his contribution to the 2020 ISU Masters Elective Module in this issue). And we will wrap up our reporting of the 71st International Astronautical Congress 2020.

If you have any comments on Principium, i4is or interstellar topics more generally, we'd love to hear from you!

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

Membership of i4is

Please support us through membership of i4is. Join the interstellar community and help to reach the stars! Privileges for members and discounts for students, seniors and BIS members. More at i4is.org/membership.

Please print and display our posters - we have new versions in this issue our general poster on pages 26 (black background) and 42 (white)- and student posters on pages 66 (black) and 4 (white).

All our poster variants at -

i4is.org/i4is-membership-posters-and-video

Balloons over Venus. Credit: Adrian Mann

See *Hints of life on Venus* in this issue.

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

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

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Interstellar Objects and Sample Returns

Adam Hibberd

The i4is Project Lyra team have worked with international colleagues to deliver *Interstellar Now! Missions to and Sample Returns from Nearby Interstellar Objects* and *Exobodies in Our Back Yard: Science from Missions to Nearby Interstellar Objects* a Science White Paper submitted to the 2023-2032 Planetary Science and Astrobiology Decadal Survey.

Principium readers will be familiar with the work of Adam Hibberd in Project Lyra. Here he walks us through the basics of missions to Interstellar Objects (ISOs) including the possibility of a sample return - and the additional challenges it poses.

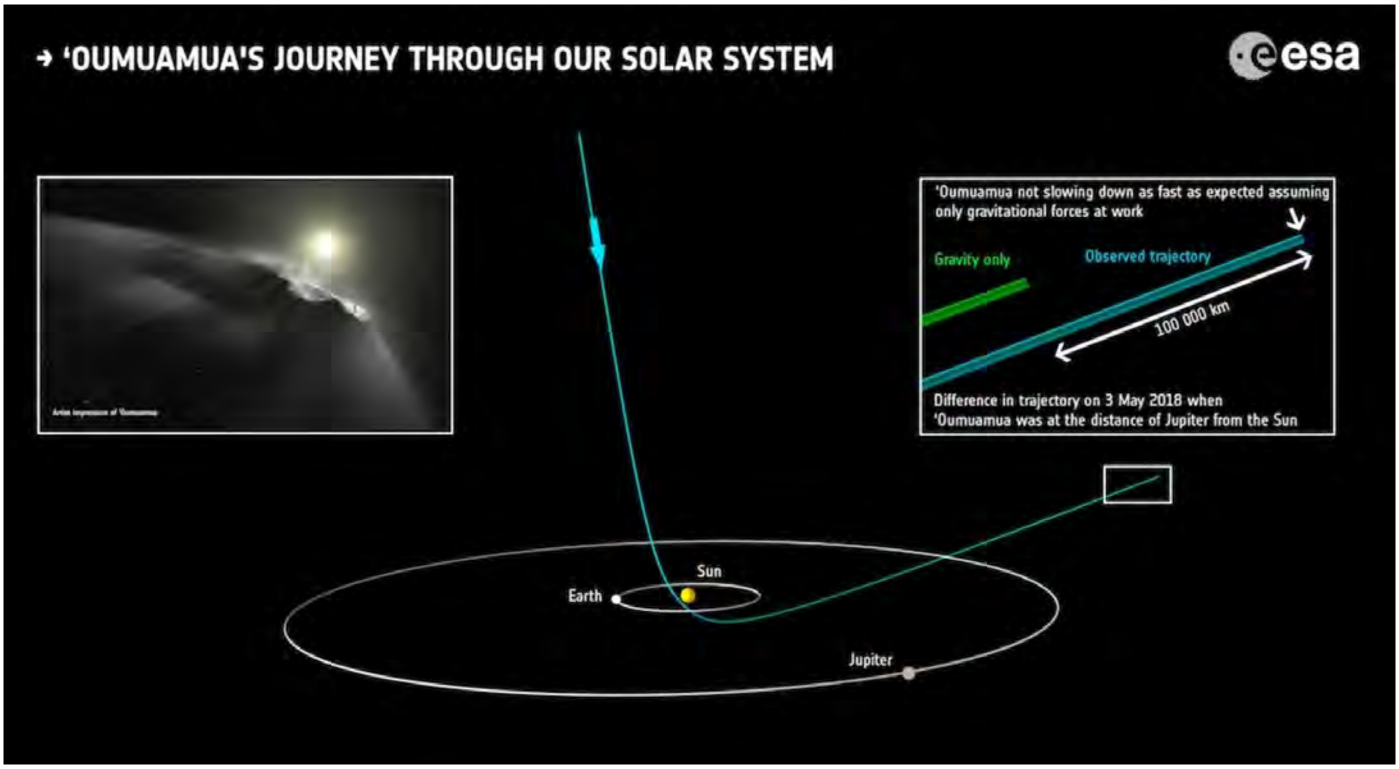
Introduction

What do we know of the Solar System to which our planet Earth belongs? Well we know Earth is not alone - in our Solar System it is surrounded by other celestial bodies. For example, most of us are aware that there are seven other known planets, and they can be considered our siblings - born and brought up in the same familiar surroundings, formed from the same proto-planetary disc which surrounded our host star, the Sun. How do we know this? There is an abundance of scientific evidence which allows us to reach this inescapable conclusion. Two of the most compelling pieces of evidence are firstly that they are in orbits bound to the Sun. In fact the orbits are elliptical so that each planet has its own unique 'orbital period', the time taken for it to return to the same point in its orbital path around the Sun. Secondly, they all follow an anticlockwise rotation around the Sun (looking down on the Solar System from above the Earth's North Pole). This direction is known as prograde. This is too much of a coincidence to happen randomly and originates in the spin orientation of the Sun's proto-planetary disc. Indeed if we change our perspective and look at objects at smaller scales then we generally observe them to follow the same sorts of orbits, elliptical and bound to the Sun and also with the same orbital spin orientation, anticlockwise (a notable exception will be discussed later). The orbital path of an object under the influence of some dominant gravitational force is characterized by a set of 5 or 6 numbers known as its orbital parameters (or orbital elements) each of which say something different about the orbit and stay pretty well fixed. Given a series of observations of the location of an object in the night's sky and using equations derived long ago by scientific mavericks and geniuses, the object's associated orbital parameters can be determined. Amongst these is a parameter known as eccentricity (a unitless parameter given the symbol e). For an elliptical orbit, e has a value somewhere between zero and one. Historically, save for a small number of exceptions (like certain comets which actually originate in the distant reaches of the Solar System called the Oort Cloud), when an object is discovered and the value of its parameter e is calculated, the solution has inevitably and consistently confirmed to lie within this range of values. Conclusion? Ostensibly, it would seem that everything we can observe in our Solar System originates therein.*

On October 19th 2017 an object was discovered in the Solar System with an e calculation of significantly greater than one. What does this mean? It means that the object is not in an ellipse, it is not bound to the Sun, it therefore does not have an orbital period. It did not originate in our Solar System, it is in fact in a hyperbolic orbit and approached the Sun from a great distance and will necessarily depart with the same speed with which it approached, around 26 km/s. This value is known as the heliocentric hyperbolic excess of the object, generally given the symbol V_∞. It thus probably started its life born in some planetary system somewhere else in our galaxy, from which it

*However an important caveat should be inserted at this point in that although this is generally the case, the stability over time of the Solar System is actually uncertain and it is perfectly possible for objects to encounter our Solar System and be captured into it, by gravitational influences such as that of Jupiter. We shall touch on this possibility later. Conversely, it is also possible that the accumulation of gravitational resonances acting on a Solar System object over time could eventually lead to it being ejected out into interstellar space.

was expelled by a gravitational perturbation. It eventually encountered our own system, drawn in by the pull of the Sun and some days after passage through its perihelion (its closest approach to the Sun) it was spotted by a telescope in Hawaii and eventually given the Hawaiian name ‘Oumuamua, receiving the official designation 1I (one eye), the first interstellar object known.



‘Oumuamua’s journey through our Solar System
Credit: ESA

Project Lyra

Project Lyra, a campaign to research the viability of spacecraft missions to 1I/’Oumuamua was instigated by the Initiative for Interstellar Studies, i4is, soon after its discovery and by this time in the same year I had developed my Optimum Interplanetary Trajectory Software (OITS) and had begun using it to conduct my own separate research into missions to 1I/’Oumuamua. These two parallel lines of research progressed entirely independently until my discovery of Project Lyra, and for that matter i4is, via a Google of ‘Oumuamua on the internet. I then contacted Andreas Hein of i4is and things progressed from there. Now several papers have been published on the subject, with me as part of the i4is Project Lyra team. Since that time, a second interstellar object was discovered in 2019, designated 2I/Borisov, and needless to say an article has been published on missions to this also.

But why are missions to interstellar objects so important? Well ask yourself, how else would a scientist be able to study material from another planetary system up close? A journey to the nearest star to our Sun would take tens of thousands of years using current chemical rocket technology, and that ain’t gonna happen! These interstellar visitors have been kind enough to spare us the trouble and in addition arrive with great gifts of tales to tell, waiting for scientists to uncover. Questions which could be answered:

1) Where might they have originated?

2) What is their composition?

3) Do they contain simple and/or complex organic compounds?

4) How were they formed?

5) What has been the effect on them of travelling long distances through the Interstellar Medium?

6) Specifically in the case of 1I/’Oumuamua, what was the cause of the non-gravitational force detected on it as it encountered the inner Solar System?

7) Etc.

Decadal Survey

This is all very well in theory, but exactly how is a mission going to happen? Would a space agency like NASA take on the challenge? Well no doubt space scientists around the world, with all kinds of expertise, are clamouring for the attention of NASA, trying desperately to receive much-needed funding for their particular line of research. At this point, in weighs a publication known as the 'Decadal Survey of Planetary Science and Astrobiology' which is a report undertaken by the National Academy of Sciences in the US every ten years (as you might expect). You could be forgiven for thinking that this sounds very much like another unnecessary layer of bureaucratic red tape. However its purpose is extremely important, it is exactly to prioritise the fields of interest in the planetary sciences, in order that NASA and indeed other US government agencies can better decide which areas of research (conducted either on Earth or in space, in the form of spacecraft missions) are most salient and could therefore potentially be ear-marked for investment. The process is to solicit white papers from the scientific community. Each scientist or group of scientists submitting a white paper must elaborate on the precise nature of their scientific research, the knowledge they wish to acquire, their mission goals, and they may of course wish to justify why precious funding should be channelled towards their specific line of research. Clearly a positive result from the Decadal Survey does not guarantee funding but does make this funding far more likely.

Since the discovery of 1I/'Oumuamua, interstellar objects (ISOs) have been the topic of the moment, the subject of intense scientific enquiry and even heated debate. With the work of Project Lyra under the banner of i4is, it seemed to various scientists associated with this research, as well as some more from various other prestigious organisations, that one way of increasing the likelihood of a mission to an ISO and realising what up to that point had only been words on paper, would be to construct between them a white paper for the Decadal Survey. In fact, this goal was accomplished with two submissions, one for the science category and the second for the mission category, my main contribution was for the latter. In what follows, I shall elucidate on the content of the mission white paper, entitled 'Interstellar Now! Missions to and Sample Returns from Nearby Interstellar Objects'.

What is an ISO?

So firstly what is an ISO? Before careering head-long into a spacecraft mission definition, it may be worth gathering our wits and systematically subdividing ISOs into various categories. Table 1 is based on the white paper and attempts to do exactly this.

Type	Definition	Orbital Characteristics	Examples/Candidates
1	Clear extrasolar origin with definite hyperbolic orbit.	Value of e much larger than 1 and $V\infty$ 1 km/s	1I/'Oumuamua, 2I/Borisov
2	Extrasolar origin but with weakly hyperbolic orbit.	Value of e only slightly larger than 1 and $V\infty$ around 1 km/s	C/2007 W1 Boattini?
3	Galactic Stellar Halo objects, low spatial density, of order ≤1% of Galactic Disk ISOs.	e & $V\infty$ are extremely large	Yet to be detected
4	Comets captured in the Oort cloud at the formation of solar system.	Semi-major axes of 1,000 AU – 200,000 AU, $e < 1$	Population unknown, possibly a significant fraction of the long period comets (which originate in the Oort Cloud).
5	Material captured primordially by gas drag in early inner solar system.	$e < 1$	Unclear if any has survived until now.
6	Captured objects in retrograde and other unusual orbits.	$e < 1$	Some Centaurs; retrograde objects such as (514107) Ka'epaoka'awela.
7	Sednoids, three body traded objects, special case of case 4 or case 6.	Perihelion 50 AU and a semi-major axis 150 AU.	Sedna, 2014 UZ224, 2012 VP113, 2014 SR349, 2013 FT28.

The layperson may have difficulty in totally comprehending Table 1 but let us, for the moment, take it as read that there are seven categories of ISO. Let us instead negotiate the issue of what different types of spacecraft mission can be conducted to an ISO. Well the white paper mentions three sorts of mission which in order of ascending level of scientific return are as follows:

A) Intercept

B) Rendezvous

C) Sample Return

Intercept (A) is defined as a spacecraft mission which eventually arrives at the ISO but does NOT change its velocity in order to stay with it and proceeds to leave the ISO with a departure velocity equal to the approach velocity.

Rendezvous (B) is defined as a spacecraft mission which eventually arrives at the ISO and then applies thrust as it approaches (generally to slow down) in order that the spacecraft stays with the ISO in its journey either through and out of the Solar System (ISO types 1, 2 & 3), or around the Sun (ISO types 4, 5, 6 & 7).

Sample Return (C) is defined as a spacecraft mission which encounters the ISO, in some way extracts material from the ISO and then returns to Earth with a sample of the ISO onboard for scientists to study.

(C) is clearly the holy grail of scientific outcomes. Imagine! – particles of material from some distant planetary system, on Earth for scientists to analyse with the full might and multiplicity of scientific instruments at their disposal. But how can this be achieved? I decided to use OITS to conduct some research into how a sample return might be undertaken to a type 1 ISO such as 1I/’Oumuamua or 2I/Borisov.

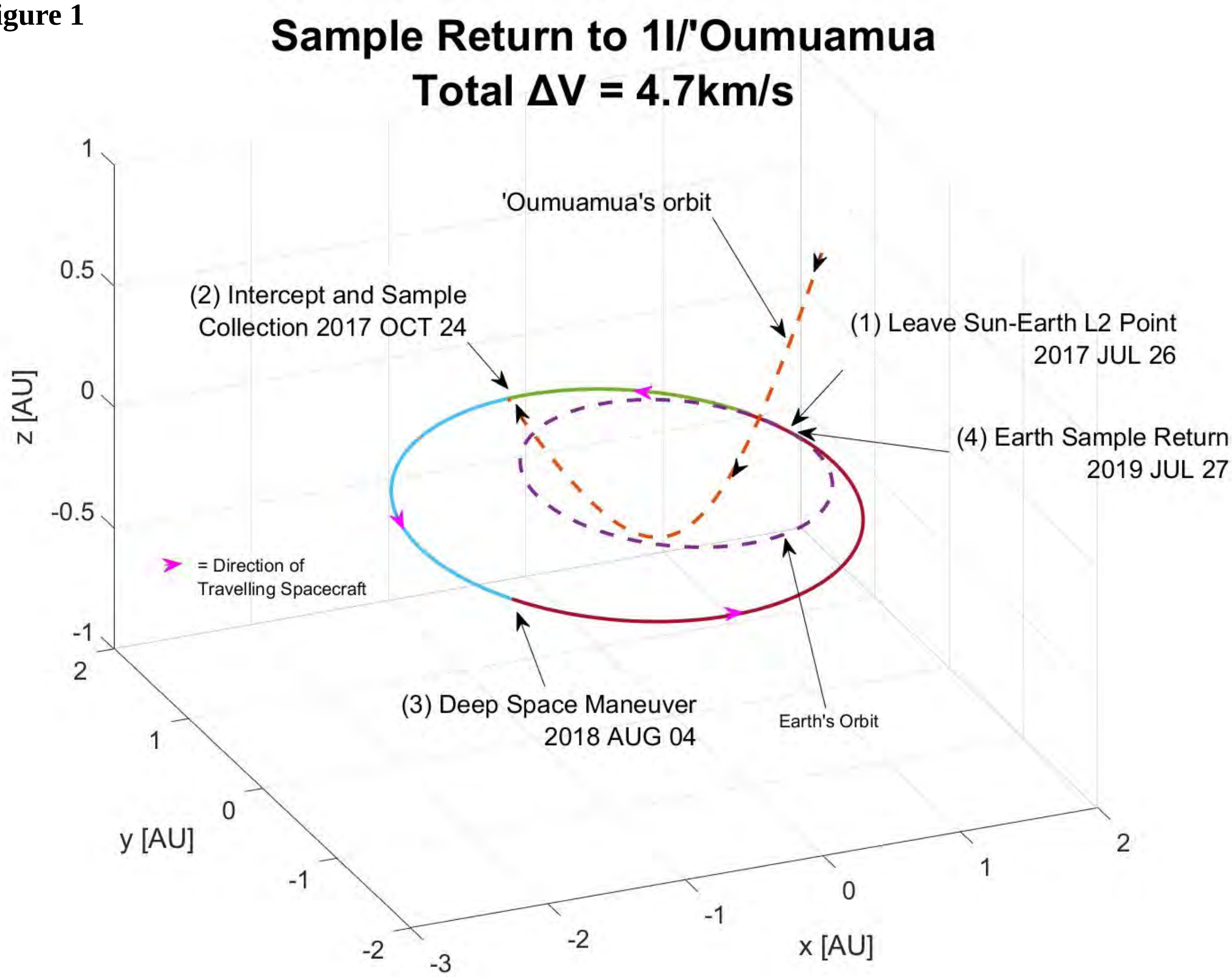
Sample Return to a Type 1 ISO like 1I/’Oumuamua

With a type 1 ISO there are two characteristics of its trajectory which are relevant. Firstly the trajectory entails the ISO to be travelling at a high heliocentric speed and secondly its orbital plane is at a high inclination to the ecliptic (the plane defined by Earth’s orbit around the Sun). This high inclination essentially means that the ISO spends a good extent of its time significantly displaced from the ecliptic, although it crosses the ecliptic at two points known as the ascending node and descending node. Efficient trajectories to encounter a type 1 ISO must take maximum advantage of Earth’s orbital velocity and as a result of this velocity lying in the ecliptic plane (by definition) results in the spacecraft encountering the ISO at one of its nodes. There is in fact an infinity of possible Earth launch dates and flight durations which would allow an encounter with a particular type 1 ISO, let us call the set of such combinations, S. There turns out to be only one member of S (so one combination of launch date and flight time) requiring least velocity increment, ΔV, from the travelling spacecraft’s rocket engines.

This is all fair and well but so far we have only considered how the spacecraft might achieve an intercept, how might it return to Earth? Well if we examine S and for the moment exclude the member with minimum ΔV, there are in fact other members of this set S which have a particular yet useful characteristic. If we take a random member of this set, this has an associated launch date and flight time to encounter, as mentioned. This turns out to be quite sufficient information to work out the time period T of the spacecraft’s orbit (please be reassured that it also turns out generally this will be an ellipse, bound to the Sun with $e < 1$ as has been discussed). Now certain members of S will have a time period, T, with a whole multiple n, of Earth’s orbital period, which is 365.25 days, one Earth year. Why is this relevant? It is because, without any subsequent application of thrust from the spacecraft’s engines (so a free ride) the spacecraft will rather neatly return back to Earth a whole number n years after launch, where Earth will be conveniently located at almost the exact same point in its orbit around the Sun as it was when the launch originally took place. Eureka! We have achieved a sample return!

For 1I/’Oumuamua a sample return trajectory utilising this technique is provided in Figure 1. There are four notable features to be considered. Firstly, the spacecraft begins its journey to 1I/’Oumuamua from the Sun/Earth Lagrange 2 Libration Point (L2). This is a point where the gravitational influences of the Sun and Earth combine with the centrifugal force to effectively cancel out, providing a comfortable point at which a spacecraft, for example, can sit and wait for an ISO to be discovered. For the Sun/Earth system the L2 point extends in a line outward from the Sun, at 1.5 million kilometres beyond Earth. Secondly there follows after launch an intercept and sample collection of material from 1I/’Oumuamua when 1I is crossing from below to above the ecliptic plane, ie at the ascending node. Thirdly there is an optional Deep Space Manoeuvre (DSM) at the spacecraft’s aphelion after the sample collection has taken place (this can be considered effectively as a minor course correction). Fourth and finally there is an Earth return on July 27th 2019, almost exactly 2 years after launch from L2, which happened on July 26th 2017 (so n = 2).

Figure 1



This is all very fine and dandy in theory, but is it practicable in reality? There are two reasons why not. Firstly, look at that launch date again: July 26th 2017. If we look back to when 1I/’Oumuamua was discovered, this was October 19th 2017. So immediately we have an issue in that the optimal launch date was actually before 1I/’Oumuamua was discovered! The second reason is slightly less evident and one needs to analyse the spacecraft’s trajectory in more detail for it to be revealed. It is this: as the spacecraft approaches 1I/’Oumuamua, its task is to collect a sample. To do this the spacecraft uses a very low density substance which has been tried and tested for sample return missions known as aerogel. This collection may be a complex procedure, possibly involving a subprobe to use as an impactor, but it is achievable with the right encounter conditions. What are these? The main condition is that, in order that the collected material does not undergo significant alteration or degradation, the relative velocity of the spacecraft with the target body, Vrel, must be less than 6 km/s. But we find for the trajectory to 1I/‘Oumuamua it is much higher - around 50 km/s.

The first of these issues, the launch date, may be resolved in the future for type 1 ISOs by the arrival on the scene of more powerful telescopes with higher data collection rates, such as the Vera C Rubin Telescope (also known as the LSST), and will allow earlier detection of ISOs. The second is a fundamental consequence of the orbit of a type 1 ISO (its high heliocentric speed and high inclination). This cannot therefore be realistically overcome.

However, let us not give up hope at this point. There are other categories of ISO, like for example type 2 & 4 ISOs in Table 1. How are these defined? In order to do this we must have some background knowledge.

What are Type 2 & 4 ISOs?

Most of us are aware of the particular type of celestial body known as a comet. Their tails can light up the night's sky and indeed often the sky in daytime also. Generally their orbits have e values less than one, meaning they have a finite orbital time period, and so they are bound to the Sun and originate in our solar system, as we have already discussed. In fact comets can be separated into two categories, these are short period comets and long period comets. Their key point of distinction however is that the long period ones are thought to originate in a cloud of proto-comets orbiting a huge distance from the Sun (somewhere between 2,000 AU-200,000 AU, where an AU is the distance between the Sun and Earth), the Oort Cloud, whereas short period comets may well have come from the Kuiper Belt, a disc extending beyond the orbit of the planet Neptune, but much closer to us than the Oort Cloud.

How does a proto-comet in the Oort cloud become a fully-fledged comet? It is generally believed this is caused by a gravitational perturbation, a nudge of encouragement, presumably as a result of some passing ISO grazing our solar system, at a great distance from the Sun. Essentially this nudge has the effect of dramatically reducing the Oort cloud Object's perihelion (the closest distance the comet gets to the Sun) so that it eventually encounters the inner solar system and is observed on Earth. Thus the consequence of this perturbation is to increase the e value from around zero (circular) to a value just less than one (highly elliptical). However there are some comets, known as weakly hyperbolic comets, which have e values slightly larger than one. As discussed above, this would seem to indicate the comet is an ISO, but in fact it has been found to be perfectly possible for a body in the Oort Cloud to be perturbed from its orbit with $e < 1$ into a weakly hyperbolic orbit with $e > 1$.

As a result of all this, we find that a type 2 ISO, defined as a weakly hyperbolic ISO (with V_∞ around 1 km/s), could easily be an object originating in the Oort Cloud, with obvious potential for confusion.

But there is another layer of complexity to this. There are very likely to be Oort Cloud objects which are actually ISOs, in other words they have journeyed from some far distant planetary system and upon arriving at our Oort Cloud have become resident, again through gravitational interactions. Thus we have the definition of type 4 objects. Furthermore to follow the logic and to add even further complexity, it is more than likely that some long period comets were originally type 4 ISOs.

Sample Return to Type 2 & 4 ISOs

The overall consequence of this complexity is that a mission to a weakly hyperbolic comet should be considered as they are quite possibly type 2 or type 4 ISOs. Indeed this is a far more fruitful line of research for a sample return mission because such ISOs have much lower heliocentric speeds than type 1 ISOs therefore potentially reducing the encounter velocity of a putative spacecraft. With this in mind I examined sample return trajectories to weakly hyperbolic comets and Table 2 (after References below) is the result.

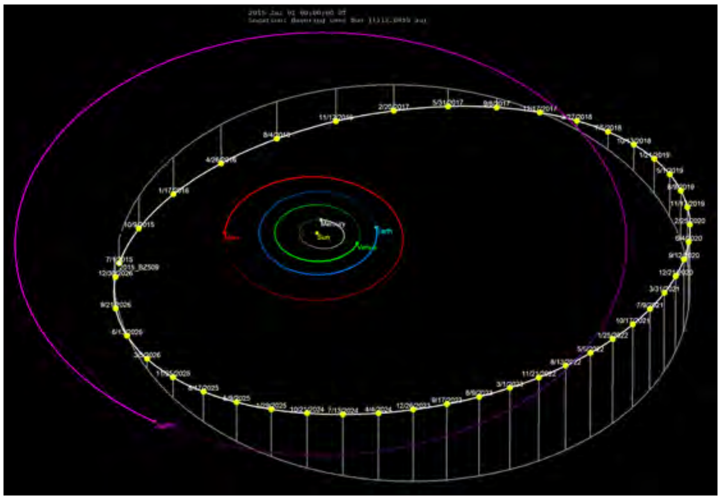
We find some comets are duplicated in order to take into account different values of n. It can be observed that three such weakly hyperbolic comets were contenders for sample return missions because the spacecraft's Vrel would have been less than 6 km/s. The total ΔV for these missions, the second column, were unfortunately large and as stated in the white paper, could be achieved by either Nuclear Thermal Propulsion (NTP) or by Solar Electric Propulsion (SEP) with arcjets. This is all very encouraging for the future and for possible missions loitering at L2, ready to be deployed for a sample return of a convenient weakly hyperbolic comet, possibly detected by the Vera C Rubin Telescope.

All this may be a long shot but the prize is enormous – a sample of material from somewhere outside our solar system – a fantastic reward for scientists and maybe worth the risk? And if the object turns out to be a bona fide Oort Cloud object and not an ISO, a sample return would still be a massive accomplishment and a valuable gift for scientists.

Rendezvous with Ka'epaoka'awela

Let us finish by examining a particular mission of type (B), a rendezvous, in fact one which is expounded in the white paper. The target in question is a celestial body called Ka'epaoka'awela (514107). What is it? It is an object co-orbital with Jupiter, so in other words having a very similar orbital period to Jupiter's and with a very similar mean distance from the Sun as Jupiter's. Clearly therefore, it has an e value less than one, so bound to the Sun and not a candidate for an ISO you might think. There is however an additional unusual feature of 514107 which needs to be explained: it is actually in a retrograde orbit around the Sun. Referring back to the beginning of this article the prograde nature of a body in the solar system was the second piece of evidence which allowed us to attribute a body as belonging to and originating in our solar system. What therefore is the consequence of 514107 being retrograde? Is the implication that it doesn't belong to our solar system? Is it in fact an ISO (a type 6 ISO)? It could well have entered our solar system in the dim and distant past, been pulled in by Jupiter's huge gravitational mass and become bound to the Sun, in an otherwise very unlikely retrograde motion. An animation produced by OITS of a rendezvous mission to find out whether 514107 is an ISO can be found here:

adamhibberd.com/interstellar-objects/



Retrograde orbit of Ka'epaoka'awela
Credit: Tomruen/Wikipedia

en.wikipedia.org/wiki/514107_Ka%CA%BBepaoka%CA%BBawela

Conclusion

So in conclusion, will there ever be a mission to an ISO? Well let's see what the Decadal Survey for Planetary Science and Astrobiology makes of it. The team at i4is has done their bit towards the endless pursuit of knowledge. It is so easy for this pursuit to be concerned only about the parochial, the now, the ephemeral. It is time humanity broadened its horizons a bit and Interstellar Objects are a convenient and timely stepping stone towards accomplishing this.

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About the Author

Adam Hibberd is a key member of the i4is Project Lyra team. Most recently he was also a major contributor to the i4is proposal for a near term missions to Venus (i4is.org/missions-to-venus/). See *News Feature: Hints of life on Venus* elsewhere in this issue.

Table 2

Object	Total ΔV km/s	n	Discovery	Launch from S/E L2	Encounter	Return	R encounter/ AU	Vrel encounter km/s	Vrel return/ km/s	Delta-V at L2/ km/s	Delta-V at Object /km/s	Flight D./ Days	Flight D. /yrs
C 2019 Y4 Atlas	16.1	n/a	28/12/2019	04/03/2020	31/05/2020	10/04/2021	0.25	**67**	25.7	12.5	3.6	402	1.1
C 2020 N1 P	6.7	n/a	03/07/2020	30/07/2020	04/03/2021	18/10/2021	1.32	**19.8**	11.6	3.4	3.3	445	1.22
C 2020 N1 P	5.7	n/a	03/07/2020	03/07/2020	04/03/2021	20/10/2021	1.33	**19.6**	11.6	2	3.6	474	1.3
C 2020 N1 P*	**20.4**	**10**	**03/07/2020**	**09/01/2021**	**01/03/2022**	**10/01/2031**	**4.55**	**5.9**	**20.6**	**20.4**	**0**	**3652**	**10**
C 2017 S6	18.4	14	30/09/2017	18/02/2018	31/10/2018	20/02/2032	3.45	**26.8**	17.4	18.4	0	5115	14
C 2018 U1	8.5	6	27/10/2018	27/12/2019	27/10/2021	25/12/2025	5	**23**	8.9	8.5	0	2190	6
C 2019 F1 Atlas	10.2	15	29/03/2019	07/05/2019	18/01/2025	07/05/2034	10.7	**10.2**	10.6	10.2	0	5479	15
C 2014 AA 52	9.1	3	04/01/2014	11/02/2014	27/08/2015	14/02/2017	2.9	**20.7**	7	6	3.1	1099	3.01
C 2014 Y1*	**17.2**	**17**	**16/12/2014**	**30/03/2015**	**27/01/2019**	**04/04/2032**	**10**	**6**	**16.8**	**16.4**	**0.8**	**6215**	**17**
C 2015 V2 Johnson	4.6	2	11/01/2015	30/01/2017	04/07/2017	31/01/2019	1.67	**25.1**	5	4.6	0	731	2
C 2015 H2*	23.9	16.5	20/05/2015	28/05/2017	29/11/2020	15/12/2033	11.7	**6**	35.2	17.4	6.5	6045	16.5
C 2013 V1 Boattini	**16.3**	**12**	**04/11/2013**	**19/01/2014**	**11/09/2015**	**19/01/2026**	**5.8**	**9.2**	**16.4**	**16.3**	**0**	**4383**	**12**
C 2013 V1 Boattini	11.5	30	04/11/2013	05/01/2014	19/09/2016	06/01/2044	8.8	**6.5**	11.8	11.5	0	10958	30
C 2018 C2 Lemmon	7.5	3	28/01/2018	01/02/2018	06/09/2018	29/01/2021	2.3	**15.2**	7.3	7.5	0	1093	2.99
C 2018 C2 Lemmon	18.7	6	28/01/2018	17/04/2018	01/03/2019	17/04/2024	3.67	**10**	18.6	18.6	0.1	2191	6
C 2018 C2 Lemmon *	**24.4**	**14**	**28/01/2018**	**08/05/2018**	**05/11/2019**	**08/05/2032**	**5.8**	**6**	**24.2**	**24.2**	**0.2**	**5114**	**14**
C 2020 K5 PanSTARRS	8.2	5	25/05/2020	30/06/2020	14/06/2022	30/06/2025	4.7	**17**	8.8	8.2	0	1826	5
2I Borisov	6.2	n/a	30/08/2020	12/07/2018	26/10/2019	18/09/2020	2.2	**33**	12.2	5	1.2	799	2.19
1I 'Oumuamua	4.7	2	19/10/2017	23/07/2017	24/10/2017	19/07/2019	1.35	**49.8**	5.2	4.7	0	726	1.99

Rows with * are missions with Encounter Vrel < 6 km/s. In addition yellow missions have Vrel < 6 km/s and no ΔV at the object, and so n is an integer number of years.

Book Review: Extraterrestrial Languages

Daniel Oberhaus

Reviewed by John I Davies

The search for extraterrestrial intelligence (SETI) and possible communication with extraterrestrial intelligence (CETI) are naturally of interest in wider interstellar studies - though i4is has not been involved in this field directly. If we are to understand ETI we must have a means of information interpretation. If the pulsar "beep" had contained some pattern it would have been necessary to interpret it. In this book Daniel Oberhaus demonstrates that a journalist can "do science". John Davies takes a look at a major addition to the subject.

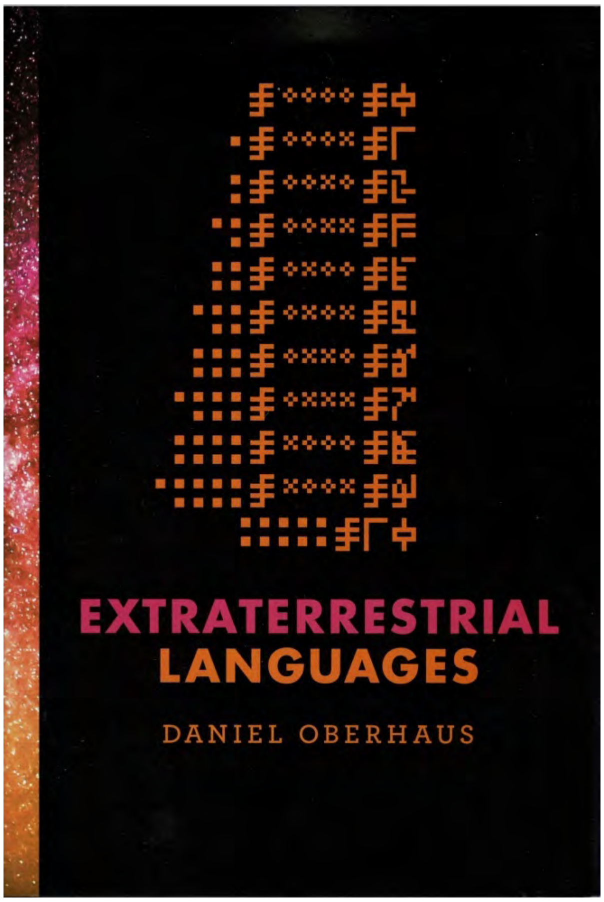
1 Introduction

Principium has featured SETI in major articles since *Retrospective: The Search for Extraterrestrial Intelligence*, in Issue 5, June/July 2013 but the topic of extraterrestrial languages has only been dealt with occasionally, for example in the review of the film, *Arrival*, by Patrick Mahon, in Issue 16, February 2017. Mr Oberhaus' presentation at IAC 2019 was summarised in *Chomsky in the cosmos: Lessons from neurolinguistics for the design of messages for extraterrestrial intelligence* in Issue 29, May 2020. So we largely enter uncharted waters in this review. Page references are to the MIT Press hardback edition, 2019 (mitpress.mit.edu/books/extraterrestrial-languages).

2 The Book

2.1 History

Oberhaus starts with a summary of the history of CETI. Humanity began to worry seriously about communicating with extraterrestrial intelligences (ETIs) in the 19th century. Oberhaus gives a quick tour of ideas from the false discovery of canals on Mars to the proposal by Gauss to demonstrate Pythagoras by planting crops in a triangle and squares in Siberia. Later Marconi sent radio messages to Mars. Perhaps the first serious attempt to devise a means of communication with ETI was by the British biological statistician Lancelot Hogben [1]. The next major work was Freudenthal's Lincos language in 1960, *Lincos, Design of a Language for Cosmic Intercourse*, and the early messages sent from the Arecibo dish by Carl Sagan and Frank Drake (of the famous equation) in 1978. The two Voyagers, of course, carried Sagan's message in 1977. A second language was devised by Ollongren and published in *Astrolinguistics* in 2013. Ollongren based this on Lincos and on Church's Lambda Calculus [2].



COVER ILLUSTRATION inspired by the numbers portion of a Cosmic Call message designed by Stephane Dumas and Yvan Dutil, sent from the Evpatoria radar in Ukraine on May 24, 1999.

Credit: MIT press

[1] See P29 May 2020 page 38, a review of *Chomsky in the cosmos: Lessons from neurolinguistics for the design of messages for extraterrestrial intelligence* by Oberhaus in IAC 2019 which memtioned Hogben's address to the British Interplanetary Society in 1952.

[2] The Calculi of Lambda-Conversion, Princeton University Press, 1941 archive.org/details/AnnalsOfMathematicalStudies6ChurchAlonzoTheCalculiOfLambdaConversionPrincetonUniversityPress1941.

2.2 From SETI to METI

Oberhaus suggests an analogy with Quine's thought experiment (page 26) about communicating with an uncontacted tribe (en.wikipedia.org/wiki/Indeterminacy_of_translation) though this demands a dialogue of some sort. This is likely to be a very slow one given that our nearest intelligent neighbours are multiple light years away (unless of course someone invents Ursula Le Guin's fictional ansible, an instantaneous communicator en.wikipedia.org/wiki/Ansible). It seems to this reviewer that we are much more likely to have a situation similar to the decipherment of early Egyptian texts, but without a handy Rosetta Stone (en.wikipedia.org/wiki/Rosetta_Stone). Oberhaus cites Chomsky and the concept of a universal, human, grammar and concludes that alien languages are unlikely to have that property (page 29). But suggests that John McCarthy and Marvin Minsky's ideas of universality of logic imply that it might not be so hard since all natural languages have hierarchical recursive syntax (page 31).

Minsky wrote extensively (pages 33-35) on this and was optimistic about communication with ETIs.

2.3 Aliens on Earth

Animal communication has been much studied and Oberhaus cites the early work of Lilly with dolphins [1]. The subject has not gone away - *Lessons from Studying Nonhuman Animal Communication*, Denise Herzing, report from IAC 2019, Principium 29, May 2020, page 36.

Oberhaus suggests, following Chomsky, that human language has the unique property of hierarchical structure, unlike animal communication (page 48).

He goes further "Although we can attempt to make up for our inability to naturally mimic dolphin whistles by artificial means like CHAT, at the end of the day we are still indoctrinating the dolphins into the symbolic regime rather than learning the meaning of dolphinese". This sounds close to the view embodied in John Searle's Chinese Room Argument (plato.stanford.edu/entries/chinese-room/) - that mere appearance of sentience is not sufficient to establish it; in the case of an apparent ETI we would never be able to establish that it was truly sentient. There have been many refutations of this view, see the Stanford article cited here but perhaps the strongest one was articulated by Alan Turing in 1950, 30 years before Searle, that this argument from "mere simulation" might apply to any of us, that it raises the perennial philosophical problem of Other Minds (plato.stanford.edu/entries/other-minds/) and given that "the only way by which one could be sure that machine thinks is to be the machine and to feel oneself thinking" and thus "it is usual to have the polite convention that everyone thinks" (A M Turing, *Computing Machinery and Intelligence*, Mind 49, 1950). Our apparent ETI may or may not be an automaton but we cannot assume we will ever determine this and thus, like Turing, we will have to be polite! Neither Turing nor Searle appear in the index to the book.

Oberhaus introduces information theory into discussion of animal communication via the work of McCowan, Doyle and Hanser [2] and the idea of a Zipf slope (word use frequencies in a text form a straight line when plotted from most frequent to least frequent).

Oberhaus (pages 49-50) applies Shannon entropy (en.wikipedia.org/wiki/Shannon's_source_coding_theorem) to possible ETI signals and suggests that Shannon and Zipf analysis would lead to opposite conclusions if applied to signals such as a bitmap image and a Fibonacci sequence. He quotes Weaver "To be sure, this word information in communication theory relates not so much to what you do say, as to what you could say" [3].

Monument to Claude Shannon at Murray Hill, New Jersey, with the Shannon–Hartley channel capacity equation and Shannon's signal entropy equation.

Credit: IEEE Spectrum

[1] The *Mind of the Dolphin; a nonhuman intelligence*, Doubleday, 1967.

Lilly became a cultish figure with some bizarre ideas about universal consciousness.

[2] McCowan, Doyle and Hanser have written extensively on this - scholar.google.co.uk/scholar?hl=en&as_sdt=0%2C5&q=mccowan+doyle+hanser.

[3] *The Mathematical Theory of Communication*, Claude E Shannon, Warren Weaver, The University of Illinois Press. 1964, *Recent Contributions to the Mathematical Theory of Communication*, Warren Weaver, 2.2. *Information* pure.mpg.de/rest/items/item_2383164/component/file_2383163/content.

2.4 Cosmic Computers and Interstellar Cats

Oberhaus introduces us to some early thinking on possible messages, some of which led to the 2003 "Cosmic Call" from the Arecibo radio telescope (page 57). Marvin Minsky suggested sending a computer (in practice a computer program) based on the AI received and, disastrously, implemented in Fred Hoyle's story *A for Andromeda* for BBC television.

Scene from *A For Andromeda* by Fred Hoyle.

credit: BBC Television

Julie Christie as Andromeda and Peter Halliday as John Fleming with the computer in the background.

The computer is constructed according to a message received from an ETI. The computer kills its operator, Christine, and creates Andromeda as its agent.

Note the flashing lights - those were the days!

The 2003 "Cosmic Call" message included an early "chatbot", Ella, which included the ability to play "Atlantic City blackjack".

Oberhaus describes a controversy between application of Markov processes (predictability of messages based on earlier messages) and Chomsky's linguistic ideas - going on to theorise that a civilisation significantly more advanced than humanity would almost certainly have developed artificial general intelligence, AGI (pages 58-59, for a discussion of this in the interstellar context see *Sending ourselves to the stars?* in Principium 12 and 13, February and May 2016).

One obvious approach to communicating with an ETI would be to send some existing text in a multiplicity of human languages. The high level of redundancy in human languages would allow the ETI to find some common interpretation (page 62).

A more recent attempt to produce a "self-bootstrapping" system like Hoyle's Andromeda is Cosmic OS by Paul Fitzpatrick of MIT. Oberhaus explains its ancestry stretching from Alonzo Church (of the Church-Turing theorem) and his Lambda Calculus and the early programming language LISP. Fitzpatrick's work is ongoing (people.csail.mit.edu/paulfitz/cosmicos.shtml). A more radical idea would be to send the code of human DNA (page 68, echoes of Hoyle again! The fate of the resulting "person" looks bleak to me.)

2.5 Is there a language of the universe?

Oberhaus returns to Hogben's ideas (page 72). The notion of pointing and speaking the noun for the thing pointed to (echoes of Hollywood's "Me Tarzan, you Jane") doesn't seem to work very well when the round trip time between conversationalists is at least eight years. Hogben was thinking of Mars, of course, where the delays are minutes, not years.

Science and, more especially, mathematics looks universal but Oberhaus cautions against mathematical Platonism, a controversial idea [1] (page 78-80). The book wanders a bit here - Oberhaus is clearly not a mathematical Platonist.

He gets back to ETs with Cockell's thought that, in a universe with consistent physics, aliens would be likely to look like us (*The Equations of Life: How Physics Shapes Evolution* (2018) Basic Books/Atlantic Books). The argument that DNA is almost as fundamental as physics did convince this reviewer.

[1] Platonism in the Philosophy of Mathematics /plato.stanford.edu/entries/platonism-mathematics/.

2.6 Towards a Lingua Cosmica

The problem of bootstrapping appears again (page 93). How can we explain our language without a language in which to explain it? Seen in these terms we would get an infinite regression. Oberhaus sees only two clear attempts to invent a "robust Lingua Cosmica": Freudenthal's Lincos and Ollongren's revision of it. Lincos was used in the first of the two Cosmic Call messages, in 1999 from Ukraine using "the most powerful planetary radar available on Earth at the time" (page 100) [1].

Oberhaus asserts that "it would be difficult to overstate the importance of the 1999 Cosmic Call message in reigniting interest in interstellar communication" (page 103).

Ollongren's second generation Lincos was a redesign using logic rather than mathematics as the foundation. Oberhaus includes a 21 page appendix explaining how Ollongren's work relates to Church's Lambda Calculus.

2.7 How to talk in space

Oberhaus considers the means by which messages may be transmitted (page 111) starting with the messages contained in the Pioneer and Voyager probes. Inevitably this is a case of "message in a bottle" - cast into an ocean far more vast than our own tiny Atlantic and Pacific. So we look to electromagnetic radiation as our means of message transport. He suggests that a narrowband signal should be sought, looking in a quiet part of the electromagnetic spectrum. Here we are heading into SETI, a vast subject and not Oberhaus' main focus.

Is it possible that an ETI is using some sort of spread-spectrum or even Ultra WideBand (UWB) transmission? There may be a limit (page 121) around 200 kHz pointed out by Seth Shostak. More about this in the sidebar: Wideband SETI.

Seth Shostak, Senior Astronomer, SETI Institute, https://www.seti.org/our-scientists/seth-shostak Credit: SETI Institute

Wideband SETI

SETI at Wider Bandwidths? Astronomical Society of the Pacific Conference Series, Volume 74. *Progress in the Search for Extraterrestrial Life*, 1995. David Messerschmitt makes the case in: *Interstellar communication: The case for spread spectrum*, Acta Astronautica, Volume 81, Issue 1, December 2012, Pages 227-238 (open access at arxiv.org/abs/1111.0547). Thus providing "robust immunity to radio-frequency interference (RFI) of technological origin in the vicinity of the receiver while preserving full detection sensitivity in the presence of natural sources of noise". But "This strategy requires the receiver to guess the specific noise-like signal, and it is contended that this is feasible if an appropriate pseudorandom signal is generated algorithmically." Messerschmitt earlier set out the engineering design principles upon which this judgement is based: *Design of interstellar digital communication links: Some insights from communication engineering*, David G Messerschmitt, Ian S Morrison, Acta Astronautica, Volume 78, September–October 2012 (open access at escholarship.org/content/qt4w59f2wk/qt4w59f2wk_noSplash_6d49b5b9b5ff6ca0aa0dd2454d8b10fe.pdf).

[1] Oberhaus describes Lincos as "intended to be encoded in unmodulated radio waves". This would be a neat trick if it wasn't a contradiction. If the waves are not modulated then they carry no message.

Oberhaus gives us a run through the (mostly well known) issues of what frequencies to expect - such as the "Waterhole" at 1.42 GHz (page 121, en.wikipedia.org/wiki/Water_hole_(radio)). He explains some basics of modulation including some more sophisticated concepts such as quadrature amplitude modulation (QAM) and frequency-shift keying (FSK) and the problem of a clock signal leading to use of Manchester encoding (en.wikipedia.org/wiki/Manchester_code). The transmit power requirements at galactic distances look daunting and Oberhaus cites (page 127) a 2009 Seth Shostak piece, *When Will We Find the Extraterrestrials?* [1]. He takes a look at optical SETI and briefly mentions Breakthrough Listen (but I assume he wrote this before the results began to arrive in volume).

2.8 Art as universal language

Oberhaus extends his range here. The problem of labelling nuclear waste disposal sites for generations who have lost the historical record of them leads to a discussion of universal graphics symbols. Cosmic iconography anyone?

He suggests that even music is not universal in human cultures (page 144) though he does describe the work of Alexander Zaitsev on the Cosmic Call message including his Teen Age Message (en.wikipedia.org/wiki/Teen_Age_Message). He cites Zaitsev in support of the idea that analogue signals are inherently more efficient than digital (page 147). This looks to this reviewer like a serious misunderstanding [2].

2.9 The many futures of METI

Oberhaus moves on to Messaging ETI. He recalls an early controversy following Frank Drake's 1974 Arecibo transmission. UK Astronomer Royal Sir Martin Ryle wrote to the president of the International Astronautical Union asking that the organisation formally ban the practice of interstellar messaging (page 155) [3]. Ryle later wrote directly to Drake saying it was "very hazardous to reveal our existence and location to the Galaxy; for all we know, any creatures out there might be malevolent—or hungry."

If anything, METI has become even more controversial since then. The metaphor is "shouting in a jungle" and Oberhaus cites a number of authorities on the adverse effects on technically primitive cultures on contact with more technically advanced ones. A recent and widely read fictional example is in the "Dark Forest" metaphor in *The Three Body Problem* and its two sequels by Liu Cixin. Oberhaus argues, with justifying citations, that the danger from unintentional messages (eg powerful radar) is minimal give the low probability of their reception (page 159). The inverse square law is our friend in this case; contrast the case of The Interstellar Downlink, discussed elsewhere in this issue.

Oberhaus cites Billingham and Benford in support of the idea that these unintentional signals would tend to cancel each other out [4] . Oberhaus uses the Square Kilometre Array as an example of the receiver which might be used by an ETI. This is surely short sighted? Once we have significant in-space manufacturing capability, perhaps in 50 or 100 years, the scale of radio telescopes would presumably be limited only by the ability to combine the signals received across the area covered.

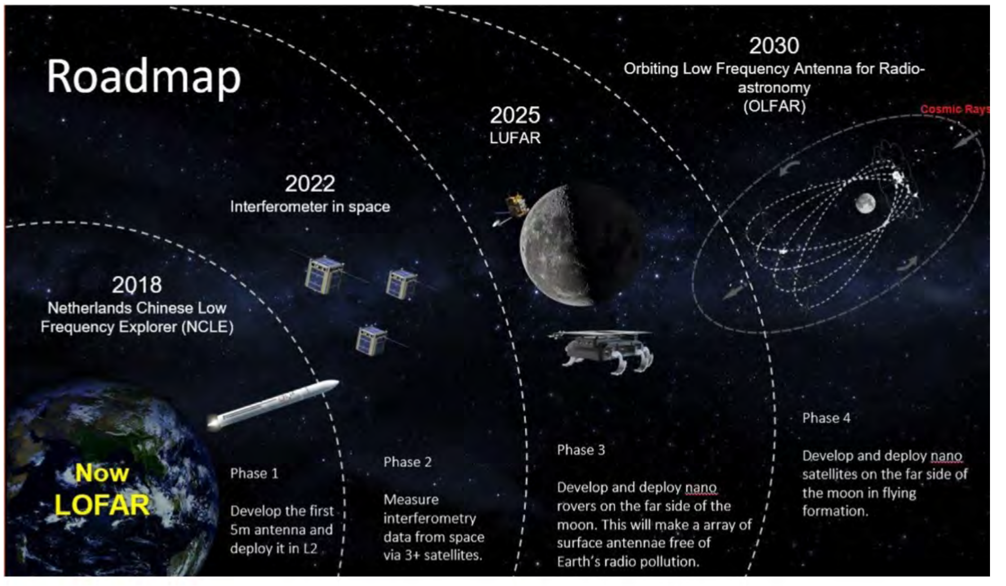
[1] In *Engineering & Science*, Spring 2009, calteches.library.caltech.edu/715/2/Extraterrestrials.pdf.

[2] Oberhaus pages 146-147 "A further benefit of an analog interstellar signal over digital methods can be seen in the drastically reduced transmission times." and "the theremin concert portion of the Teen Age message would take only fourteen minutes using analog encoding as opposed to nearly fifty hours of transmission time for the equivalent message encoded digitally (Zaitsev 2008)", The paper cited is *Sending and searching for interstellar messages*, Acta Astronautica, Volume 63, Issues 5–6, September 2008. The identically titled paper (citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.557.3564&rep=rep1&type=pdf) presented at 58th International Astronautical Congress, Hyderabad, India, 24 - 28 September 2007. IAC-07-A4.2.02 contains no reference to this.

[3] Citing Drake and Sobel's book *Is anyone out there? : The scientific search for extraterrestrial intelligence*. Delacorte Press 1992.

[4] *Costs and Difficulties of Large-Scale 'Messaging', and the Need for International Debate on Potential Risks*, John Billingham, James Benford, 2011, arxiv.org/abs/1102.1938: "Picking up signals from commercial radio and television broadcasts is difficult." and "What little detectable power reaches space is from many sources, not at the exact same frequencies, but in bands constrained by regulation by governments. Therefore, they are not coherent, so phase differences cause them to cancel each other out at great range."

In the relatively short term, for example, "...a swarm of hundreds to thousands of satellites, working together as a single aperture synthesis instrument deployed sufficiently far away from Earth to avoid terrestrial RFI" has already been proposed by Bentum et al of TU Delft, see their Roadmap below.



Four phase roadmap to Orbiting low Frequency Antennas for RadioAstronomy (OLFAR).

Credit: Bentum et al/TU Delft

From *A roadmap towards a space-based radio telescope for ultra-low frequency radio astronomy*, Bentum et al, article in press - Advances in Space Research (2019), [cas.tudelft.nl/pubs/bentum19asr.pdf.](cas.tudelft.nl/pubs/bentum19asr.pdf)

Oberhaus suggests that most critics have been concerned about intentional transmissions and describes the San Marino Index, a sort of rule of thumb to assess the risk of a transmission. Like the Drake equation these attempts to think systematically about ETI are still the best we can do in our present state of knowledge.

In all of this Sagan's question "Who speaks for Earth?" remains fundamental. Oberhaus discusses attempts to reduce cultural and even species bias in METI (page 167) and wraps up by doubting if we want to tell ETIs the truth about ourselves.

2.10 Appendices

Oberhaus includes appendices on The Arecibo Message (5 pages), The Cosmic Call Transmissions (13 pages), Lincos (10 pages) and The Lambda Calculus and its application to astrolinguistics (21 pages). I'll leave these, especially the latter, to specialists!

3 Conclusion

Overall this is a fine introduction to the subject, particularly for a comparative newcomer to the subject like this reviewer. Much of the detail is fascinating but if there is an overall fault it is that it is too wide ranging. Much of the discussion of SETI and METI is available elsewhere. And there are a couple of significant mistakes in communications technology. A narrower focus on the language problem specifically might have made a better book.

"It's extra-terrestrial - not like us"

Much has been discussed about first contact with ETI, if and when it happens. Poet John Cooper Clark has approached the subject from his usual dry point of view in *(I Married A) Monster From Outer Space*-

> We walked out – tentacle in hand
> You could sense that the earthlings would not understand
> They'd go.. nudge nudge …when we got off the bus
> Saying it's extra-terestial – not like us

johncooperclarke.com/poems/i-married-a-monster-from-outer-space

But we can't recruit him to the interstellar studies just yet. He loves allegory and he was no doubt commenting on a different sort of xenophobia.

4 Earlier reviews

The book was published one year ago, in October 2019, and has been widely reviewed.

4.1 Science magazine

(American Association for the Advancement of Science)

Andrea Ravignani, in *Efforts to communicate with extraterrestrials call into question the universality of language, math, and culture*, 4 November, 2019 (blogs.sciencemag.org/books/2019/11/04/extraterrestrial-languages/), suggests that Oberhaus has narrowed his view of language to Noam Chomsky's theory of generative linguistics. "Oberhaus is balanced in mathematics and computer science but anthropology, developmental psychology, and animal cognition are largely absent".

He recommends alternative views, notably Arik Kershenbaum (www.zoo.cam.ac.uk/directory/dr-arik-kershenbaum) to balance this.

Andrea Ravignani is at the Artificial Intelligence Lab, Vrije Universiteit Brussel, where he researches on vocal communication and rhythm in seals and humans.

4.2 The Economist

In *How to talk to aliens, The challenge says a lot about talk among people, too* (www.economist.com/books-and-arts/2019/11/28/how-to-talk-to-aliens), the Economist briefly summarises the book and ends with "the world's 7,000-odd tongues are vastly closer to one another than anything to be found out there". I did not spot this assertion in the book.

4.3 London Review of Books

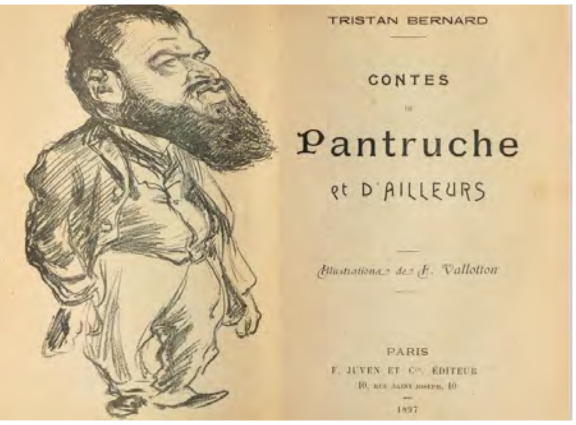
Nick Richardson, a former editor at the London Review of Books (LRB), and now a software engineer, reviewed *Extraterrestrial Languages* in LRB Vol. 42 No. 12, 18 June 2020 (www.lrb.co.uk/the-paper/v42/n12/nick-richardson/we-re-not-talking-to-you-we-re-talking-to-saturn#).

The review is titled *We're not talking to you, we're talking to Saturn* [1], a reference to a 19th century satire of SETI by the French humorist Tristan Bernard in which humanity, on receiving an unintelligible message from Mars, writes huge messages across the Sahara. The dialogue goes -

> 'I beg your pardon?'
> 'Nothing.'
> 'What are you making signs for then?'
> 'We're not talking to you, we're talking to the Saturnians.'

This sets the tone for the review by Richardson, which is tongue-in-cheek (or "pas sérieux" perhaps?) with occasional lapses into useful summaries of Oberhaus' book. The reviewer quotes the visible proof of Pythagoras in the book but does not credit it to Gauss. And he mentions 'Story of Your Life', by Ted Chiang (source of the film, *Arrival*, see above) and an interesting example of a fictional attempt to communicate with very alien aliens - but which is not mentioned by Oberhaus.

[1] The story is *Qu'est-ce qu'ils peuvent biennous dire? (What exactly can they tell us?)* see *The pioneers of interplanetary communication: From Gauss to Tesla*, Florence Raulin-Cerceau, Acta Astronautica 67 (2010) 1391–1398, citing Bernard in: *Contes de Pantruche et d'Ailleurs*, Paris, 1897,



Contes de Pantruche et d'Ailleurs, 1897 cover,

Credit: archive.org

Interstellar News

John I Davies reports on recent developments in interstellar studies

Outreach

i4is has been busy during the pandemic, delivering talks and symposia online-

- 15 September 2020 Uncle James' School, Ikot Ekpene, Nigeria - *First Steps to Interstellar Probes*, John Davies
- 26 September 2020 BIS West Midlands - *Interstellar Precursor Missions*, Rob Swinney
- 29 & 30 September - Barrow Arts & Sciences Academy, Winder GA, USA - *To the Stars in Two Equations*, John Davies
- 2 October 2020 - Herschel Society and Bath Royal Literary and Scientific Institute with BIS South West - *First Steps to Interstellar Probes*, John Davies
- 21 October 2020 - Industrial University of Hochiminh City, Vietnam - *Interstellar Probes: How can we do it?*, John Davies
- 22 October 2020 - Loughton Astronomical Society *Interstellar Objects – Oumuamua, Borisov & objects in between*, John Davies

All our talks are also available to members as videos and presentations via i4is.org/videos/ and i4is.org/members/member-events/.

We have more talks upcoming at Cardiff, Hibaldstow and York Astronomical Societies. But we can still do more. Contact us via info@i4is.org.

The i4is Talks Series

Rob Swinney, Director of Education at i4is, has initiated a series of detailed talks online. Some available to all and others exclusive to i4is members. The programme is -

- 27th Oct - Rob Swinney - 'Introduction to Interstellar Studies' - Members Only
- 3rd Nov - Marshall Eubanks - 'Missions to Interstellar Objects - An i4is Initiative' - Open
- 10th Nov - Andreas Hein - 'Worldship Design' - Members only
- 17th Nov - Dan Fries - 'Advanced Propulsion 1' - Members only
- 24th Nov - TBC - - Members only
- 1st Dec - Patrick Mahon - "Sci Fi" Interstellar Starships - Open

Next year, beginning in late January, we plan about six more talks, still being arranged, with some being open to non-members. Keep an eye out on i4is.org/events/ for more details and contact us via talks@i4is.org for details and to register.

The Interstellar Research Group (IRG, formerly TVIW) 7th Interstellar Symposium will be on September 25-27, 2021 (irg.space/irg-2021/) at the Tucson Marriott University Park, Arizona, following the NASA Innovative Advanced Concepts (NIAC) symposium at the same venue. i4is is working with colleagues in IRG to deliver this event. See page 71 for a full-size poster.

All the latest from the Interstellar Research Group in its October 2020 Newsletter, *Have Starship, Will Travel*, issue 21. This includes their 2020 Scholarship Winners (and the winning essay), their Vlog, TVIW reorganizing to IRG and *A Dialogue on SETI* between Keith Cooper (see our review of his book, *The Contact Paradox*, in P30) and Paul Gilster (Centauri Dreams) irg.space/wp-content/uploads/2020/10/IRG_Newsletter_N20_v02.pdf.

Potential For Liquid Water Biochemistry Deep under the Surfaces of the Moon, Mars and Beyond

Professors Manasvi Lingam (Florida Tech & Harvard - see also *Hints of life on Venus* elsewhere in this issue) and Abraham Loeb (Harvard and Breakthrough Starshot) suggest the past or current existence of habitable conditions deep underneath the surfaces of the Moon and Mars as well as bound and free-floating extrasolar rocky objects. They model conditions and derive possible biomass. They suggest methods for detecting biosignatures in such deep biospheres. The paper is *Potential For Liquid Water Biochemistry Deep Under The Surfaces Of The Moon, Mars And Beyond* arxiv.org/abs/2008.08709.

i4is Masters Thesis in collaboration with ESA and Technical University of Munich

Johannes Lebert, a MSc student of the Technical University of Munich has started his work on a thesis with the title *Optimal Strategies for Exploring Near-by Stars*, in collaboration with the ESA Advanced Concepts Team and the Institute of Astronautics of the Technical University of Munich.

1I/'Oumuamua: The dust bunny hypothesis

A paper posted just as our last issue "went to press", *'Oumuamua as a Cometary Fractal Aggregate: the "Dust Bunny" Model*, Luu et al[1] (arxiv.org/abs/2008.10083), suggests that the interstellar object (ISO), 'Oumuamua -

> "...displayed such unusual properties that its origin remains a subject of much debate. We propose that 'Oumuamua's properties could be explained as those of a fractal dust aggregate (a "dust bunny") formed in the inner coma of a fragmenting exo-Oort cloud comet. Such fragments could serve as accretion sites by accumulating dust particles, resulting in the formation of a fractal aggregate. The fractal aggregate eventually breaks off from the fragment due to hydrodynamic stress. With their low density and tenuously bound orbits, most of these cometary fractal aggregates are then ejected into interstellar space by radiation pressure."

Andy Tomaswick made some interesting observations on this in Science X, *Okay, new idea: 'Oumuamua is an interstellar 'dust bunny'* (phys.org/news/2020-09-idea-oumuamua-interstellar-bunny.html). Tomaswick suggests that the only other ISO found so far, 2I/Borisov, may represent a phase of the process described by Luu et al - although this idea does not appear in their paper.

An interesting omission in the Luu et al paper is any mention of the anomalous acceleration of this ISO beyond their introduction. Since this observation provides much of the motivation for radical hypotheses about the structure and ontogeny of 'Oumuamua this seems strange. However, since it also fails to mention other ideas such as the Loeb-Bialy idea of a thin reflective sheet [2] and the Seligman and Laughlin idea of a molecular hydrogen "iceberg" [3], the authors may simply be being conservative in their scope - perhaps to steer clear of trashy press LGM stories.

[1] *'Oumuamua as a Cometary Fractal Aggregate: the "Dust Bunny" Model*, Jane X Luu (University of Oslo), Eirik G Flekkøy (University of Oslo) and Renaud Toussaint (University of Strasbourg / University of Oslo)

[2] Principium 23 November 2018 page 8, *NEWS FEATURE - What is Oumuamua? The Loeb/Bialy Conjecture and i4is Project Lyra.*

[3] Principium 30 August 2020 page 55, *Was 'Oumuamua made of molecular hydrogen ice?*

The Interplanetary Internet

There is a nice piece from Susan D'Agostino, Contributing Writer with Quanta magazine, including a video of Vint Cerf explaining where we are and where we are going in interplanetary communications, *To Boldly Go Where No Internet Protocol Has Gone Before* (www.quantamagazine.org/vint-cerfs-plan-for-building-an-internet-in-space-20201021). As McCoy might have put it "It's the Internet Jim, but not as we know it!"

Dr Cerf is a board member of the InterPlanetary Networking Special Interest Group (IPNSIG) - ipnsig.org. More about Delay & Disruption Tolerant Networking (DTN) at ipnsig.org/introducing-delay-disruption-tolerant-networking-dtn.

The interstellar downlink is even more challenging than interplanetary network but Vint Cerf has, of course, taken an interest.

ESA on Space-based solar power

The European Space Agency is seeking ideas to realise the long-discussed idea of power from space, both for terrestrial and space purposes, *Space-based solar power: seeking ideas to make it a reality* (www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Space-based_solar_power_seeking_ideas_to_make_it_a_reality). By comparison with Earth-based generation it overcomes the inconvenient phenomenon of the Earth's rotation which means other sources - or energy storage - are needed. ESA Engineer Advenit Makaya says "Of interest could be ideas that make use of in-orbit construction, or in-space resources. If, for example, we could build solar power satellites using materials we find on the Moon or asteroids, it could make the concept cheaper, and therefore more viable."

ESA envisages beaming power down to the Earth, the Moon and Mars, but the in-space applications may be at least as interesting. Makaya mentions using in-situ materials for construction but In-Situ Resource Utilisation (ISRU) will require processing of raw materials, comminution and beneficiation, and this first stage is likely to require substantial amounts of power.

And, of course, the demands of laser propulsion for interstellar probes are a natural use for in-space power, as envisaged in the i4is Project Andromeda study (i4is.org/what-we-do/technical/andromeda-probe/).

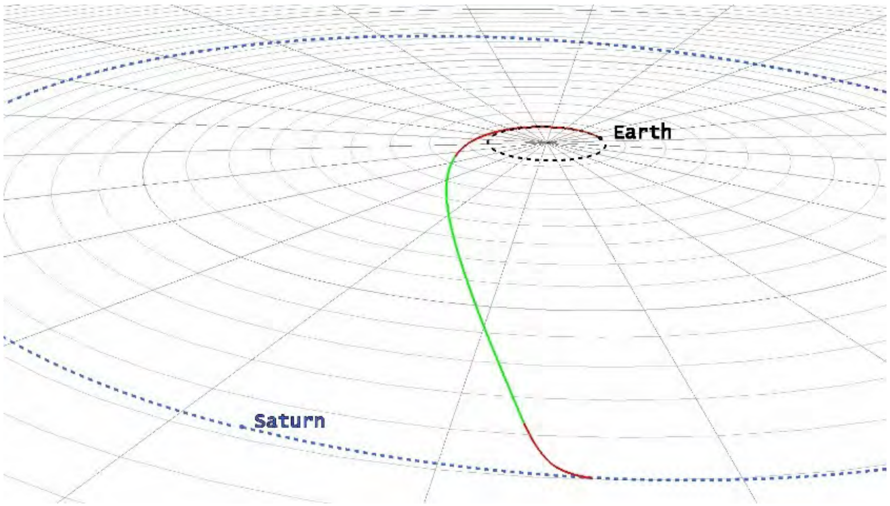
A Titan mission using the Direct Fusion Drive (DFD)

A paper by Marco Gajeri, Paolo Aime and Roman Ya Kezerashvili parallels the IAC 2020 paper reported by Olivia Borgue elsewhere in this issue (*Exploration of trans-Neptunian objects using the Direct Fusion Drive*, IAC-20,C4,9,7,x56172). *A Titan mission using the Direct Fusion Drive* [1] presents new trajectories for a robotic mission to Titan to demonstrate the advantages of the DFD, a D-^{3}He fuelled, aneutronic, thermonuclear fusion propulsion system, related to the ongoing fusion research at Princeton Plasma Physics Laboratory (PPPL). Major advantages include increased payload mass, reduced transit time (assisted by powered deceleration) and by-product power generation.

Titan is the largest moon of Jupiter and the predicted transit times of 2 to 2.6 years are less than half of that required for the latest Jupiter probe, Cassini, which deployed a lander, Huygens, to Titan. The proposed propulsion system is based on PPPL-developed Princeton field-reversed configuration (en.wikipedia.org/wiki/Princeton_field-reversed_configuration#Spacecraft_propulsion and www.psatellite.com/technology/fusion/). The proposals show how the propulsion system supports both continuous thrust and thrust-coast-thrust profiles enroute - and, on arrival, Titan orbit insertion. The substantial amount of by-product electrical power means that demands like downlink bandwidth would be much more easily satisfied.

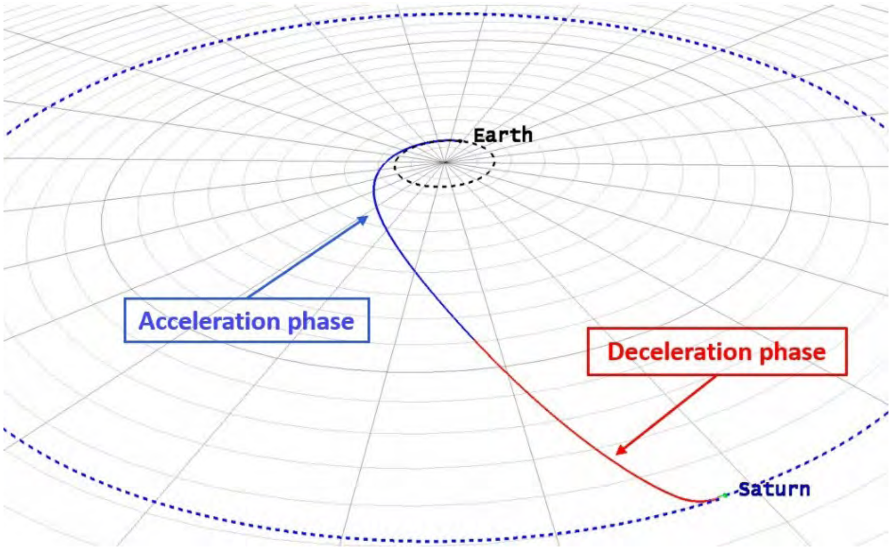
The paper touches on interstellar applications of the DFD. Naturally i4is will be keeping an eye on this work.

More about the DFD propulsion idea in JBIS Vol 72 No.2 February 2019, *Direct Fusion Drive for interstellar exploration*, S A Cohen et al.



Thrust-coast-thrust profile for the Titan mission. It is possible to observe three segments of the trajectory, the red solid curves suggest that the spacecraft thrust is active and the green line represents the coasting phase without active thrust.

Credit: Gajeri et al - Figure 1 in the paper (both caption & image)

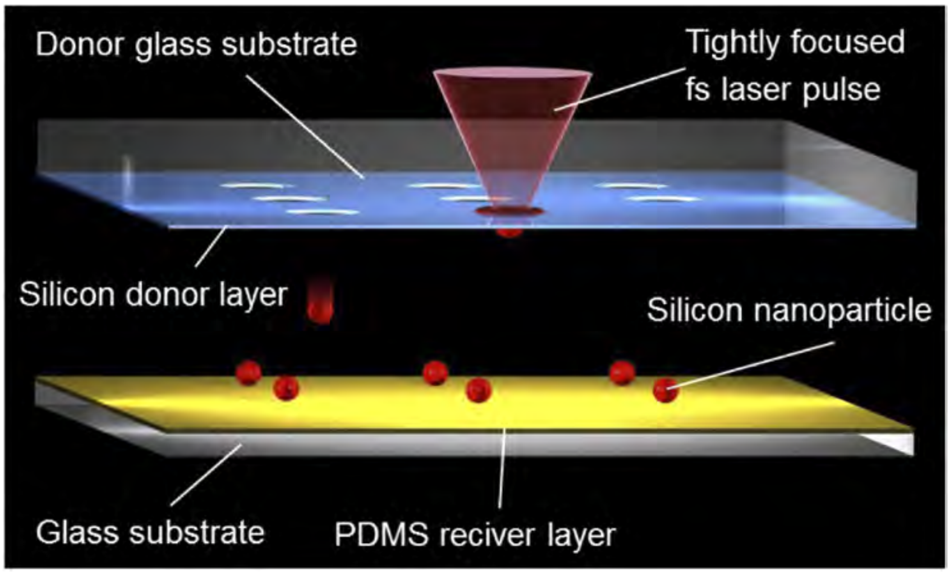


Planar trajectory for the continuous thrust profile mission. At the end of the blue curve there is the change in direction of the thrust (switch time). The trajectory follows Earth's orbit for some time before a nearly straight trajectory to Saturn.

Credit: Gajeri et al Figure 7 (caption and image)

[1] *A Titan mission using the Direct Fusion Drive, arxiv.org/abs/2009.12621* Marco Gajeri (Politecnico di Torino, City University of New York), Paolo Aimea (Politecnico di Torino), Roman Ya. Kezerashvili (City University of New York, Samara National Research University, Samara, Russian Federation)

Applying laser printing technology to metasurface mirrors made of Si nanospheres.



Schematic illustration of femtosecond laser printing of Si nanoparticles. A 50 nm crystalline Si layer on donor glass substrate wafer is used as a target (irradiated by single laser pulses) to generate and transfer spherical Si nanoparticles onto the PDMS layer.

Credit (image and caption); Evlyukhin et al - their Fig. 8.

Better mirrors for better laser propulsion?

A recent paper, *Lightweight metasurface mirror of silicon nanospheres*, Evlyukhin et al, [1] presents numerical results and theoretical analysis of a metasurface mirror consisting of periodically arranged silicon nanospheres embedded in a polymer. The authors claim absolute 100% reflection at a single wavelength, which can be tuned by changing nanosphere dimensions or periodicity (for example, by mechanical stretching). They propose practical realisation of extremely lightweight metasurface mirrors made of silicon (Si) nanospheres using laser printing technology with possible application to solar or laser-driven light sails for acceleration of ultra-light space craft to relativistic velocities.

We look forward to more on this idea. Very highly efficient mirroring sails are vital if lightsail craft are to be our first probes to the stars.

[1] Lightweight metasurface mirror of silicon nanospheres, Andrey B Evlyukhin, Mariia Matiushechkina, Vladimir A Zenin, Michèle Heurs, and Boris N Chichkov (all Leibniz Universität Hannover, except Heurs: University of Southern Denmark), Optical Materials Express Vol. 10, Issue 10, pp.2706-2716 (2020) https://doi.org/10.1364/OME.40931. open access:

www.osapublishing.org/ome/fulltext.cfm?uri=ome-10-10-2706&id=440175

[2] *Materials challenges for the Starshot lightsail*, Atwater, H A, Davoyan, A R, Ilic, O et al (all Caltech). Nature Materials 17, 861–867 (2018). open access: daedalus.caltech.edu/files/2018/05/Materials-challneges-for-Starshot-lightsail.pdf

Starshot contractor has jobs available

Metamaterial Inc announced that it is recruiting scientists to support Starshot "Lightsail" research. See *META Looks to Recruit Top Scientists for the Development of Materials Suitable for Interstellar Exploration*, Financial Times, 18 August 2020. The story references a 2018 paper - Atwater et al, *Materials challenges for the Starshot lightsail* [2]. The specific requirement may have already been filled but Metamaterial Inc are still recruiting at metamaterial.com/careers/.

Possible snags in lightsail engineering?

It has been said that the challenge of sending a lightsail probe to the nearest stars is largely engineering rather than science. However some issues are at the very challenging end of applied science. A possible example is *Sailing towards the stars close to the speed of light*, Fűzfa et al [3]. The issues they raise for the principal Starshot mission scenario include - misalignment between the driving light beam and the direction of sail leads to a deviation of about 80 AU in the case of an initial misalignment of 1 arc sec at a velocity of 0.2c toward Alpha Centauri and the tremendous energy required is used at only about 3% efficiency. They also discuss the effect of the sail reflectivity on trip duration, sail temperature and time dilation.

[3] Sailing towards the stars close to the speed of light, André Fűzfa, Williams Dhelonga-Biarufu, and Olivier Welcomme (all University of Namur, Belgium). Phys. Rev. Research 2, 043186, 5 November 2020, open access: journals.aps.org/prresearch/pdf/10.1103/PhysRevResearch.2.043186

Places like home - "Hab zone" exoplanets

The paper, *The Occurrence of Rocky Habitable Zone Planets Around Solar-Like Stars from Kepler Data*, Steve Bryson et al [1] (arxiv.org/abs/2010.14812) presents occurrence rates for rocky planets in the habitable zones of main-sequence dwarf stars based on the Kepler telescope (retired 2018 but data still being analysed) exoplanet candidate catalogue and stellar properties from ESA Gaia astrometry (positions, distances and motions) data. Looking at exoplanets between 0.5 and 1.5 times Earth diameter and based on instellation flux (how bright is the local Sun!) they found large uncertainties in the results. This arose from the low frequency of small planets in the relevant Kepler data set. They suggest obtaining more complete and reliable catalogues, either through improved analysis of existing data or through obtaining more data with quality comparable to Kepler. However their conservative conclusion is that the average number of habitable zone exoplanets per star (planets with radii between 0.5 and 1.5 times Earth and host star effective temperatures between 4800 K and 6300 K) they suggest a frequency between 0.37 and 0.88 such planets per star. This translates to between 4 and 10 such planets within 10 parsecs (33 light years) of the Sun.

It's great to see such effort going into exoplanet research. Visiting our neighbouring solar systems looks much more interesting if it include places we might live ourselves!

TVIW Updates from IRG

As always there has been much of interest in TVIW-updates from the newly-renamed Interstellar Research Group (IRG). A small selection of recent examples -

- November 2 update: *Curvature Invariants for the Alcubierre and Natário Warp Drives*, arxiv.org/abs/2010.13693 The paper is - *Warp drive with zero expansion*, Jose Natario, IoP Class. Quantum Grav.19(2002) 1157–1165 - www.if.ufrj.br/~mbr/warp/etc/CQG19.1157.2002.pdf.
- November 2 update: *In-Space Fabrication and Growth of Affordable Large Interior Rotating Habitats*, arc.aiaa.org/doi/10.2514/6.2020-4193, and several others from AIAA 2020.
- October 21 update: *Which stars can see Earth as a transiting exoplanet?* academic.oup.com/mnrasl/article/499/1/L111/5931805.
- October 19 update: *Traversable wormholes supported by non-exotic matter in general relativity* www.sciencedirect.com/science/article/abs/pii/S1384107620302499
- September 30 update: *The Sun Diver: Combining solar sails with the Oberth effect*, Coryn A L Bailer-Jones (Max Planck Institute for Astronomy, Heidelberg) arxiv.org/abs/2009.12659

More at tviw.us/interstellar-updates/.

Recent Acta Astronautica papers

Acta Astronautica is one of the two principal peer-reviewed journals in astronautics. The other is its older relative, the Journal of the British Interplanetary Society (JBIS). We can't claim to catch all papers relevant to interstellar studies but here are a few from recent issues -

- Vol 175, October 2020, *Future interstellar rockets may use laser-induced annihilation reactions for relativistic drive*, Leif Holmlid (University of Gothenburg), Sindre Zeiner-Gundersen (University of Iceland).
- Vol 176, November 2020, *Feasibility study of a laser launch system for picosatellites and nanosatellites in low-earth orbits*, Tomoki Kamei & Makoto Matsui (Shizuoka University), Koichi Mori (Nagoya University).
- Vol 174, September 2020, *Design considerations for relativistic laser sails*, Brice N Cassenti (University of Connecticut), Laura J Cassenti (ET Solutions).

And, of course, numerous i4is team pieces by Hein, Hibberd, Eubanks, Perakis and others. And others featured elsewhere in this and other issues of Principium.

[1] *The Occurrence of Rocky Habitable Zone Planets Around Solar-Like Stars from Kepler Data*, (authors.library.caltech.edu/106381/), October 2020, submitted to The Astronomical Journal, authored by Steve Bryson (NASA Ames) and 86 others with affilitions (alphabetical order) Aarhus University Denmark, Ball Aerospace and Technologies Corp., Bay Area Environmental Research Institute, Brigham Young University, Caltech/IPAC-NASA Exoplanet Science Institute, Carnegie Institution for Science, Carnegie Observatories, Center for Astrophysics|Harvard & Smithsonian, Cross-Entropy Consulting, Instituto de Astrofísica de Canarias, Instituto Federal de Educacao Cincia e Tecnologia do Rio de Janeiro, Jacobs Engineering, Jet Propulsion Laboratory, Lawrence Livermore National Laboratory, Lowell Observatory, Millennium Engineering & Integration Services, MIT, NASA/Marshall Space Flight Center, National Science Foundation, Orbital Sciences Corporation, Orbital Sciences Corporation, Pennsylvania State University, Rincon Research Corporation, San Diego State University, SETI Institute, Smithsonian Astrophysical Observatory, Space Telescope Science Institute, Technical University of Denmark, The University of Texas at Austin, University of Birmingham, University of California Santa Cruz, University of Hawaii, University of Nevada, University of Southern California, Villanova University.

Recent Interstellar Papers in JBIS

Our older sibling, the British Interplanetary Society, pays close to attention to interstellar studies via JBIS, its academic journal-

V73 #10 October 2020

From Earth-Orbit Space Colonies to Deep-Space and Interstellar Habitats and Worldships: Solving the Economics, Stephen Ashworth

V73 #7 July 2020: General Interstellar Issue

Protocols for Encounter with Extraterrestrials: lessons from the Covid-19 Pandemic, John W Traphagan & Ken Wisian

Water and Air Consumption aboard Interstellar Arks, Frédéric Marin & Camille Beluffi

Habitability of M Dwarfs: a problem for the traditional SETI, Milan M Cirkovic & Branislav Vukotic

On a Spectral Pattern of the Von Neumann Probes, Z Osmanov

Reworking the SETI Paradox: METI's Place on the Continuum of Astrobiological Signaling, Thomas Cortellesi

Dynamic Vacuum Model and Casimir Cavity Experiments, Harold White, Paul Bailey, James Lawrence, Jeff George & Jerry Vera

V73 #7 May 2020

Thermal Thorium Rocket (THOR) – a new concept for a radioactive decay heated thermal rocket engine, Gábor Bihari

And the June issue, cover opposite, had more about the BIS SPACE habitat project, as featured in our last issue, P30, *Implications for an Interstellar Worldship in findings from the BIS SPACE Project*, Richard Soilleux.

JBIS
Journal of the British Interplanetary Society
VOLUME 73 NO.7 JULY 2020
General Interstellar Issue
PROTOCOLS FOR ENCOUNTER WITH EXTRATERRESTRIALS: lessons from the Covid-19 Pandemic
John W. Traphagan & Ken Wisian
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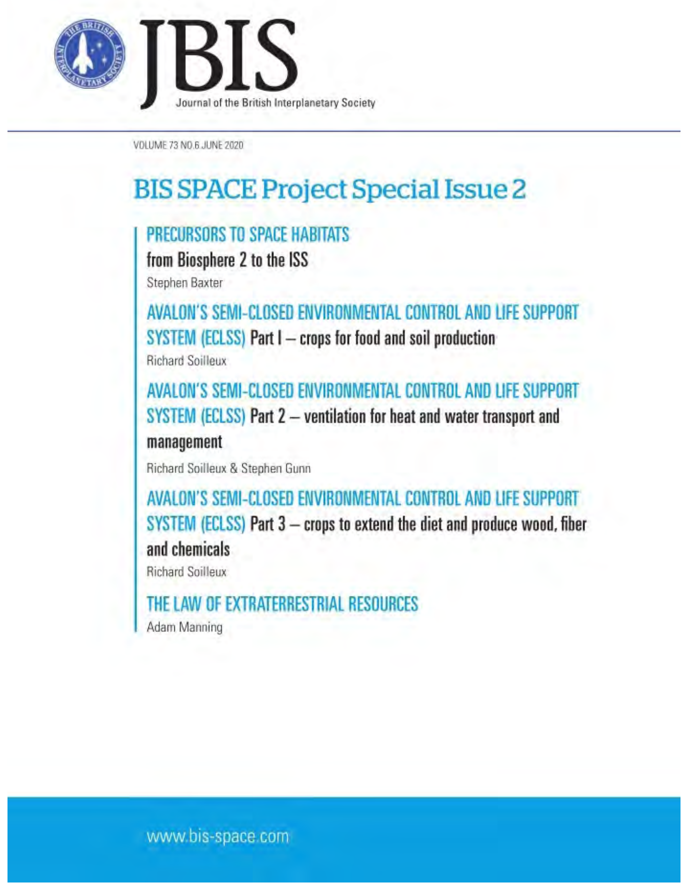
Harold White, Paul Bailey, James Lawrence, Jeff George & Jerry Vera
www.bis-space.com



JBIS
Journal of the British Interplanetary Society
VOLUME 73 NO.6 JUNE 2020
BIS SPACE Project Special Issue 2
PRECURSORS TO SPACE HABITATS from Biosphere 2 to the ISS
Stephen Baxter
AVALON'S SEMI-CLOSED ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS) Part I – crops for food and soil production
Richard Soilleux
AVALON'S SEMI-CLOSED ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS) Part 2 – ventilation for heat and water transport and management
Richard Soilleux & Stephen Gunn
AVALON'S SEMI-CLOSED ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS) Part 3 – crops to extend the diet and produce wood, fiber and chemicals
Richard Soilleux
THE LAW OF EXTRATERRESTRIAL RESOURCES
Adam Manning
www.bis-space.com

KEEP AN EYE ON OUR WEBSITE

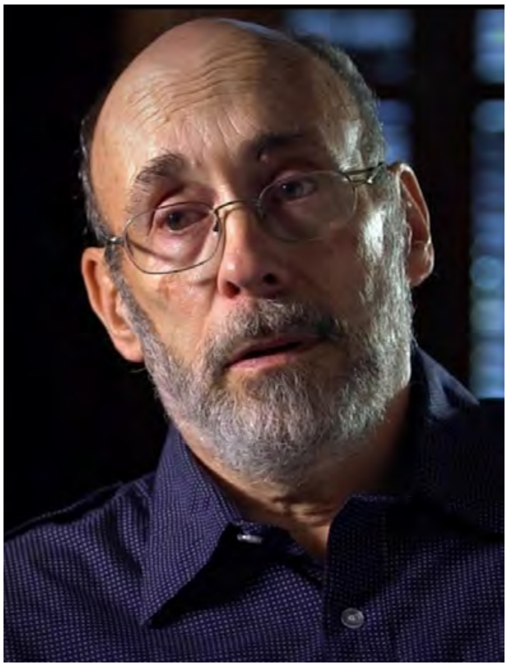
Our website is the place to find up to date announcements of our work. Here are some recent examples -

- i4is Article published in Astrophysical Journal Letters
- Newsletter: i4is online talk this Tuesday plus more member content! 8 November
- Talk Series: Missions to Interstellar Objects
- Talk Series: Worldship Design
- Talk Series: Introduction to Interstellar Studies
- i4is Venus balloon concept featured in Forbes
- Project Lyra on Universe Today

Letter to the Editor

In-Space Self-Sufficient Habitats - A Possible Superconducting Alternative to Passive Shielding

From: Dr Gregory L Matloff



As demonstrated in articles published in JBIS, Principium and elsewhere, in-space self-sufficient habitats, interstellar arks and worldships will be massive beasts. The reason for this is the potentially life-threatening effects of high-Z galactic cosmic rays (GCR). Massive passive shields meters thick around the spacecraft were selected for this application in Ref 1. This material increased the mass of a 10,000 person habitat at an Earth-Moon Lagrange point by a factor of about 10X over the original 1974-vintage O'Neill Model 1 10,000-person habitat.

But there is a possible alternative to passive shielding. As presented in Chap 4 Appendix D of Ref 1, electromagnetic shielding is not impossible. Such "active" shields to protect astronauts engaged in near-term interplanetary travel have been presented and reviewed in the literature [2]. In some cases, for crew protection during a 1.5-3 year Mars voyage, such active shields might somewhat reduce required shielding mass.

An interstellar voyage might take ~1,000 years. So at first glance, passive shielding for arks and worldships seems essential. However, the ambient temperature of interstellar space is near absolute zero. So many materials will be superconducting, obviating the need for coolant coils necessary in the inner solar system.

Solar-sail launched arks will depart the inner solar system at around 1,000 km/s [3]. Such craft will cross the orbit of Neptune about one month after sail unfurlment near the Sun. So the exposure duration to GCR before a superconducting shield can be initiated will be only ~2X that of some Apollo astronauts.

It is a very worthwhile research effort to consider active electromagnetic GCR shields using superconductivity in the interstellar environment.

References

1. NASA SP-413 Space Settlements: A Design Study, ed. R D Johnson and C Holbrow (1977).

2. L W Townsend, "Critical Analysis of Active Shielding Methods for Space Radiation Protection", IEEAC paper #1094, Version 6, Updated 1 Dec. 2004.

3. G L Matloff, "Graphene Solar Photon Sails and Interstellar Arks", JBIS, Vol. 67, pp. 237-248 (2014).

The Interstellar Downlink

Principles and Current Work

John I Davies

Inevitably the problem of reaching the universe beyond the solar system has been dominated by the propulsion challenges inherent in distances measured in light-years. However sending a probe to the stars is essentially pointless from the human point of view unless that probe can communicate its findings to us. This is the problem of the Interstellar Downlink.

Recent work supported by Breakthrough Starshot and others has begun to advance this technology. In May this year several i4is technical team members were invited to contribute to a workshop organised by Breakthrough Initiatives as part of its Starshot programme. The workshop addressed this major challenge for any interstellar probe - communication with Earth - and specifically the downlink, from the probe to Earth.

Here John Davies introduces the problem and reviews the current status of the subject. See elsewhere in this issue for a report by Robert Kennedy on the i4is contribution to the Breakthrough Starshot Communications Workshop

1 Introduction

This article will introduce the fundamentals of Interstellar Communication, especially the distance and the inverse square law - "The Douglas Adams Problem squared!" It will introduce some Communications Basics, how communications engineers analyse their problems, and early work including the BIS Daedalus project and internet pioneer Vint Cerf's work on an interplanetary internet.

And finally current work, summarising some founding papers by the Breakthrough Starshot team.

2 Basics of Interstellar Communication

2.1 The Douglas Adams Problem squared!

The root of the problem of Interstellar Communication is distance. All known communications technologies rely on electromagnetic transmission. Short of stringing telephone wires from here to Alpha Centauri, electromagnetic transmission is subject to the inverse square law and four light years is a lot of metres to be squared!

The order of magnitude of the loss of signal power this implies are best illustrated by some familiar examples -

- Distance to your local mobile base station: The base technology for wide area mobile communications is GSM and the original maximum distance assumed between your mobile and your serving base station was 35 km (en.wikipedia.org/wiki/GSM#Base-station_subsystem).
- Distance to a LEO communications satellite: The Iridium system uses satellites in medium Earth orbit at about 800 km altitude (en.wikipedia.org/wiki/Iridium_satellite_constellation#Overview).
- Distance from Pluto for the New Horizons probe: Pluto is about 40 astronomical units from Earth (www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-pluto-58.html). Since the Earth-Sun distance is about 150 million km that's 150*40 = 6,000 million km.
- Distance to Alpha Centauri system: Perhaps the number best known to all interested in matters interstellar - about 4 light years.

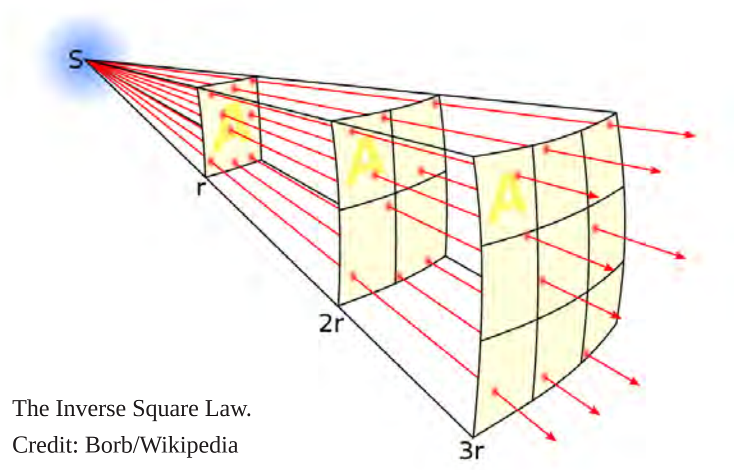
Light speed is about 300 million (300,000,000) metres per second and there are about 32 million (32,000,000) seconds (=$3.2*10^7$) in a year so 4 light years is about 4*300*32 million million metres or 40 thousand million million metres. Written out that's 40,000,000,000,000,000 metres. In handier floating point form that's $4*10^{16}$ metres.

The Inverse Square Law

How does the inverse square law work?

Think about the Sun. It's a sphere, roughly speaking. What is the surface area of a sphere? It's $4\pi r^2$ so the surface area is proportional to the square of the radius. Now think about where you are sitting, basking in the Sun I hope! All the light emitted from the Sun's surface (at radius about 430,000 miles or 700,000 kilometres) has to pass through a sphere of radius one astronomical unit (AU) where you are sitting. That's a much bigger sphere than the Sun.

So how much less frazzled are you going to be than if you were at the Sun's surface? It's the same amount of radiation spread, pretty evenly, over that larger sphere. That's an area of $4\pi r^2$ where the r is the astronomical unit, 93 million miles or 150 million kilometres. So it's going to be weaker in proportion to the square of the difference in radius. The same applies to your signal from Alpha Centauri. Your antenna allows you to concentrate your signal beam in the right direction but once the radiation is on its way it diverges just like the light from the Sun.



The Inverse Square Law.
Credit: Borb/Wikipedia

The very approximate numbers above give you the scale. As the great English humorist said "Space is big. Really big. You just won't believe how vastly hugely mind-bogglingly big it is. I mean, you may think it's a long way down the road to the post office, but that's just peanuts to space."* If he was still around and engaged with matters interstellar - as I am sure he would be - he might also remark that your signal is very handicapped. Your paraplegic mate Dave is Superman by comparison; Your signal takes four times the effort to go twice as far as him and a hundred times the effort to go only ten times as far.

Looking at the distances in metres using our trusty spreadsheet we find -

Downlink from -	Distance (approx)	Unit	Conversion factor to metres	Distance in metres
Terrestrial Mobile (GSM)	35	km	1,000	35,000
sci	4.E+01	km	1.E+03	4.E+04
LEO (Iridium satellite)	800	km	1,000	800,000
sci	8.E+02	km	1.E+03	8.E+05
Pluto (New Horizons probe)	40	AU	149,597,870,700	5,983,914,828,000
sci	4.E+01	AU	1.E+11	6.E+12
Alpha Centauri	4	ly	9,460,730,472,580,800	37,842,921,890,323,200
sci	4.E+00	ly	9.E+15	4.E+16

The rows labelled **sci** are the same numbers in scientific notation, spreadsheet style - and, looking at that 17 digit number for the distance in metres to Alpha Cent. you can see why engineers and scientists prefer that exponent notation.

*Douglas Adams, The Hitchikers Guide to the Galaxy en.wikipedia.org/wiki/The_Hitchhiker's_Guide_to_the_Galaxy

My infallible (I hope) spreadsheet also tells me -

Downlink from -	Distance (approx)	Unit	Conversion factor to metres	Distance in metres	Order of magnitude (distance in metres squared)	Ratio* of signal to Terrestrial Mobile (GSM)	Ratio* of signal to LEO (Iridium satellite)	Ratio* of signal to Pluto (New Horizons probe)	Ratio* of signal to Alpha Centauri
Terrestrial Mobile (GSM)	35	km	1,000	35,000	1,225,000, 000	1	0	3.42E-17	8.55E-25
sci	4.E+01	km	1.E+03	4.E+04	1.E+09	1.E+00	2.E-03	3.E-17	9.E-25
LEO (Iridium satellite)	800	km	1,000	800,000	640,000,000, 000	522	1	0.00000 00000 00018	4.469E-22
sci	8.E+02	km	1.E+03	8.E+05	6.E+11	5.E+02	1.E+00	2.E-14	4.E-22
Pluto (New Horizons probe)	40	AU	149,597, 870,700	5,983,914, 828,000	35,807,236,6 68,758,300,0 00,000,000	29,230,397, 280,619,000	55,948,807, 294,935	1.00	0.0000000250
sci	4.E+01	AU	1.E+11	6.E+12	4.E+25	3.E+16	6.E+13	1.E+00	3.E-08
Alpha Centauri	4	ly	9,460,730, 472,580,800	37,842,921, 890,323,200	1,432,086,73 7,197,100,00 0,000,000,00 0,000,000	1,169,050,39 7,711,920,00 0,000,000	2,237,635, 526,870, 470,000,000	39,994,338	1.00
sci	4.E+00	ly	9.E+15	4.E+16	1.E+33	1.E+24	2.E+21	4.E+07	1.E+00

* the ratios are multipliers eg the signal from Alpha Centauri is 39,994,338 times weaker than from Pluto.

Again the rows labelled **sci** are the same numbers in scientific notation, spreadsheet style

Distance to your local mobile base station: The base technology for wide area mobile communications is GSM and the original maximum distance assumed between your mobile and your serving base station was 35 km (en.wikipedia.org/wiki/GSM#Base-station_subsystem).

35 km = 3.5 * 10^4 metres.

Squared this is 12.25 * 10^8 or 1.225 * 10^9

Order of magnitude = 10^9

Distance to a LEO communications satellite: The Iridium system uses satellites in medium Earth orbit at about 800 km altitude (en.wikipedia.org/wiki/Iridium_satellite_constellation#Overview).

800 km = 8*10^5 metres.

Squared this is 64*10^{10} or 6.4*10^{11}

Order of magnitude = 10^{11} - the signal is 10^3 weaker - or 1000 times weaker than for your terrestrial mobile phone

Distance to Pluto for the New Horizons probe: Pluto is about 40 astronomical units from Earth (www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-pluto-58.html). Since the Earth-Sun distance is about 150 million km that's 150*40 =

6000 million km or 6*10^9 km.

Squared this is 36*10^{18} or 3.6*10^{19}

Order of magnitude = 10^{19}- the signal is -

$10^{(19-11)} = 10^8$

- or 100 million times weaker than the Iridium signal and

$10^{(19-9)} = 10^{10}$

- or 10 billion times weaker than for your terrestrial mobile phone

Distance to Alpha Centauri system: Perhaps the number best known to all interested in matters interstellar - about 4 light years.

Light speed is about 300,000 km/sec and there are about 32 million seconds (=3.2*10^7) in a year so

4 light years is about 4*3.2*^{7} km or 12.8*10^{10} metres.

Squared this is about 164*10^{20} or 1.64*10^{22}

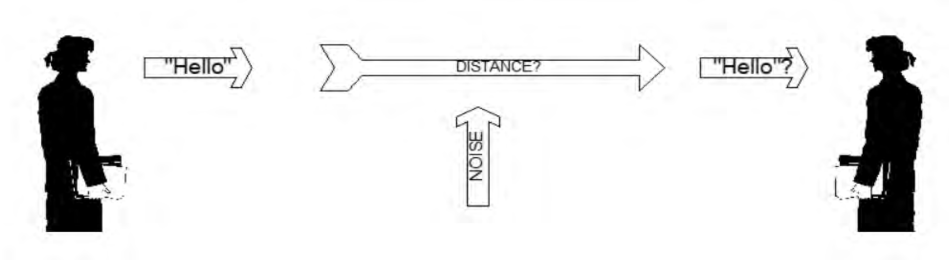
Order of magnitude = 10^{22} is $10^{(22-19)} = 10^3$

- or one thousand times weaker than for Pluto

2.2 The Communications Basics

Any communication can only take place if the sender and the receiver understand one another and their means of communication works. If you don't speak my language or you speak too quietly in the circumstances then I will not understand you. Communications engineers characterise this as a "link budget". Here's a crude example of Alice on the left speaking to Jane on the right.

Am I loud enough? Are you near enough? Is the room quiet enough? Is your hearing OK? Do you speak English?



The received signal (which we hope is "Hello") is the sum of an equation - Received signal = transmitted signal (which really <u>**is**</u> "Hello"!) * clarity of speech * distance loss * noise loss * misunderstanding.

In the real world all those multiplying factors are less than one so what arrives is less than what is sent.

In the same way your satellite TV reception depends upon -

- Quality of signal - especially extra information to correct errors
- Satellite transmit power
- Satellite transmit dish size
- Distance to your receiving dish - mainly as input to the inverse square law, which is simple geometry as in the 2.1 *Douglas Adams Problem squared* above.
- Noise - which can be artificial (another satellite perhaps) or natural (from the Sun, the rest of the universe and even the famous cosmic microwave background)
- Your receiver dish size
- Sensitivity of your receiver electronics
- Ability of your receiver to correct errors

The same sort of calculation applies to the signals to and from your mobile phone, how well your wifi works and even how well your old fashioned medium wave "steam radio" works.

Communications engineers adopt an accountancy term for this calculation - they discuss "link budgets".

2.3 Link Budget

Now the link budget for a distant probe such as New Horizons out at Pluto is a calculation with some very small multipliers in it. Communications engineers use a logarithmic measure in link budgets, decibels (dB), so link budget can use addition and subtraction rather than multiplication. These are logarithms to base 10, as in those "log tables" the older ones amongst us had to use in school.

Decibels are tenths of a bel so imagine a decimal point in any value of dB you see. The distance loss from Voyager is around 308 dB, so that's 10 to the power 30.8, $10^{30.8}$ which means that the transmitted signal power is reduced by about 6,300,000,000,000,000,000,000,000,000,000 times between the Voyagers and Earth. This may not be too much of a problem for the big transmitters and dishes on earth (the uplink) but getting information from a Voyager (the downlink) is a considerable challenge.

Now consider a probe at Alpha Centauri, four light years away rather than the 15-20 light hours of the Voyagers. And recall that the inverse square law applies so a difference of distance 4*365*24 hours versus 15 hours 35,040/15 = 2336 means a loss of 2336 squared = 5,456,896. So the signal from Alpha Centauri is 5 million times weaker than from the Kuiper Belt where the Voyagers are.

Again, it all depends upon the size of your hardware. The Daedalus probe specifies a 450 ton payload and the later Icarus Firefly study aims for a 150 ton payload and a small nuclear reactor. The downlink challenge is much more severe for the gram scale probes envisaged by Breakthrough Starshot or even the kilogram scale probe envisaged the i4is Andromeda study*.

* The Andromeda Study: A Femto-Spacecraft Mission to Alpha Centauri, Hein et al 2017, https://arxiv.org/abs/1708.03556

2.4 "Say again?"

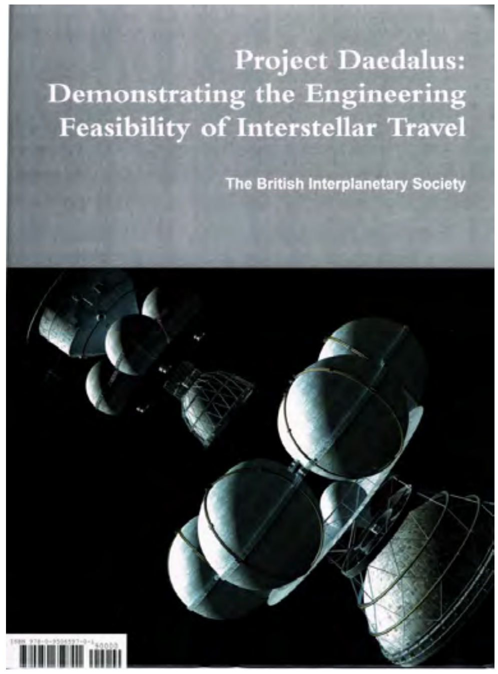
In both military and amateur radio communications there is a standard response when you can't understand what the other person has just said. The phrase is "Say again" - asking the speaker to repeat what they just said. In data communications protocols there are equivalent mechanisms called ARQ, Automatic Repeat reQuest. But users of mobile telephones don't expect to have to do this - or at least not often! So the protocols for this include mechanisms described as Forward Error Correction (FEC).

The interstellar downlink cannot tolerate "Say again" or ARQ. The delay would be the entire roundtrip, at least 8 years, and probe would need a very sensitive receiver to hear the "Say again".

FEC has limitations set by Claude Shannon's noisy-channel coding theorem (en.wikipedia.org/wiki/Noisy-channel_coding_theorem) and the proportion of errors which can be corrected depends upon how many additional data bits are added to the transmission to provide the correcting information. Mobile phone protocols protect against errors in digitised speech as part of the analogue/digital conversion process by defining codecs (coder/decoder - see www.etsi.org/technologies/codecs for examples). The Breakthrough Starshot studies are investigating FEC - as you will find in the final section of this article- 4 *Current Work* below.

3 Earlier Work

3.1 Daedalus



As in almost all things related to interstellar probes let's refer first to the relevant paper published as part of the BIS Daedalus study in the 1970s, *Project Daedalus: the vehicle communications system* in the *Project Daedalus Final Report* (PDFR)*. For an introduction to the whole Daedalus study see *Project Daedalus –A Beginners' Guide*, Patrick J Mahon, in Principium | Issue 24 | February 2019, page 30.

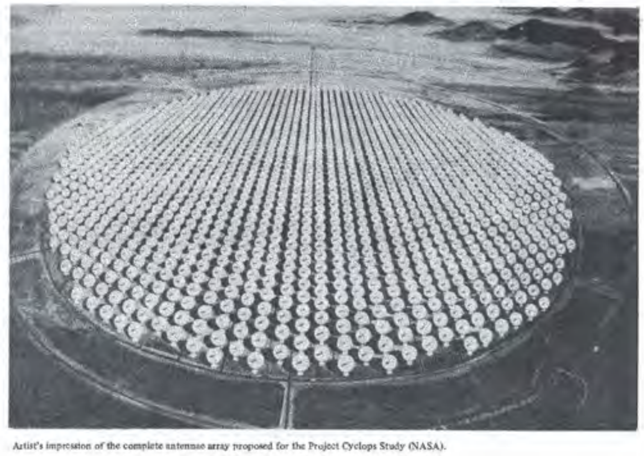
The Daedalus communications paper was written by Tony Lawton and Penny Wright, both of EMI Electronics. The paper deals with two principal communication requirements, the downlink from the main vehicle to earth and the link between the main vehicle and 18 sub-probes to be deployed on approaching the target star system. Recall that Daedalus is a "flyby" mission at 12% of the speed of light and transit time through the system is short. This means that the observation challenges have similarities to those for the Breakthrough Starshot study, which envisages a flyby at 20% of light speed. There are major differences in the flyby. Daedalus would be a single probe with a 450 ton payload (including the 18 sub-probes) using the electronic technology known in the mid 1970s while Starshot would be a very much large number of gram scale probes using the technology of the 2030s or later.

The Daedalus downlink during and after the encounter would be microwave transmission at 11.4 cm or 2.6 GHz, "A radio link is far more efficient than a laser system for long distance communication due to the much lower background photon noise" (Lawton/Wright, PDFR page s145). But laser signalling is envisaged for boost phase telemetry when radio frequency interference (RFI) from the fusion drive would be a problem and for the links between sub-probes and the main vehicle during the encounter phase. The radio frequency power would be one MW (PDFR page s166, table 6) using the second stage fusion reaction chamber as a dish antenna to deliver at downlink data rate of 864 kbps over an RF bandwidth of 432 kHz using "bi-tonal frequency shift keying" or binary frequency shift keying (FSK) mentioning that this "is superior to a simple pulsed system in terms of signal to noise ratio. This is because there is a continuous carrier wave for the receiving system to detect and lock onto." Contrast the techniques suggested by the Starshot researchers in section 4 *Current Work* below.

* Lawton, A T and P P Wright. "Project Daedalus: the vehicle communications system." JBIS 31 (1978): S163-S171. This and all the Daedalus papers are collected in the BIS book. Project Daedalus: Demonstrating the Engineering Feasibility of Interstellar Travel, www.bis-space.com/eshop/products-page-3/merchandise/books/project-daedalus-demonstrating-the-engineering-feasibility-of-interstellar-travel/

The technology available at the time led to the choice of High Powered Klystrons (HPK). Klystrons were an invention of the radar engineers of the second world war and are still in use for applications demanding higher power levels than available from semiconductors (for example the Cloudsat radar - earth.esa.int/web/eoportal/satellite-missions/c-missions/cloudsat - uses an Extended Interaction Klystron (EIK)). Again the contrast with the Starshot downlink transmitter is clear and a natural consequence of the relative scale of the probes as well as the 45 year technology gap.

The receiving end is labelled the Solar System Receiving Station (SSRS). This could be Earth or space based and built during the coast phase of several decades. The paper does not specify a size but quotes the Project Cyclops study which proposed a "bogey system of 3.16 km clear aperture".*



Antennae array proposed for the Project Cyclops Study (NASA) from the JBIS paper.

Credit: Lawton/Wright/NASA

3.2 Cerf's interplanetary internet

If present thinking in interstellar studies leads to a near-term launch of chipsat-scale probes within a few decades then the vision of Internet veteran Vinton G Cerf of a mature interplanetary internet** is unlikely to have been achieved by that time.

But delay-tolerant protocols developed to help fulfil that vision have already been defined and used. The Bundle Protocol Specification is an Internet Engineering Task Force Experimental Protocol, RFC 5050 (tools.ietf.org/html/rfc5050) which has already been the basis for some implementations.

RFC 5050 includes a timestamp measuring seconds from the year 2000 and is a Self-Delimiting Numeric Value - meaning that it can be arbitrary long (lesson learned from the original 32 bit IP address and the major software engineering effort required to overcome it!). There are 32 megaseconds in a year so 25 bits required and 32 bits is therefore enough to specify 128 years. An interstellar internet would be a strange beast but we should not rule it out in the long term.

Vint Cerf addressing the Royal Institution London, 9 March 2020. Credit: RIGB

* Page 74 of *Project Cyclops: A design study of a system for detecting extraterrestrial intelligent life*, NASA/Stanford 1971

See also *Project Cyclops: The Greatest Radio Telescope Never Built*, Robert Dixon - in - *Searching for Extraterrestrial Intelligence: SETI Past, Present, and Future*, Springer, 2011.

** *The Interplanetary Internet: A Communications Infrastructure for Mars Exploration*, 53rd International Astronautical Congress 2002 https://trs.jpl.nasa.gov/bitstream/handle/2014/9399/02-1611.pdf

See also - *Google's Chief Internet Evangelist on Creating the Interplanetary Internet*, Wired 2013 - www.wired.com/2013/05/vint-cerf-interplanetary-internet/.

4 Current Work

A useful starting place in understanding the thinking of the Breakthrough Starshot team is their published papers. This section includes references to them, a brief analysis of the implications of each and a discussion of them including some comments on the possible advantages of a space based infrastructure. It is by no means a thorough analysis of the work. The papers themselves are available as open publications and are largely comprehensible even by your reporter, who has not worked in this field professionally for almost 50 years!

4.1 The Breakthrough Starshot System Model

The Breakthrough Starshot System Model, Kevin L G Parkin, Acta Astronautica, Volume 152, 18 pages. November 2018, open publication - arxiv.org/abs/1805.01306

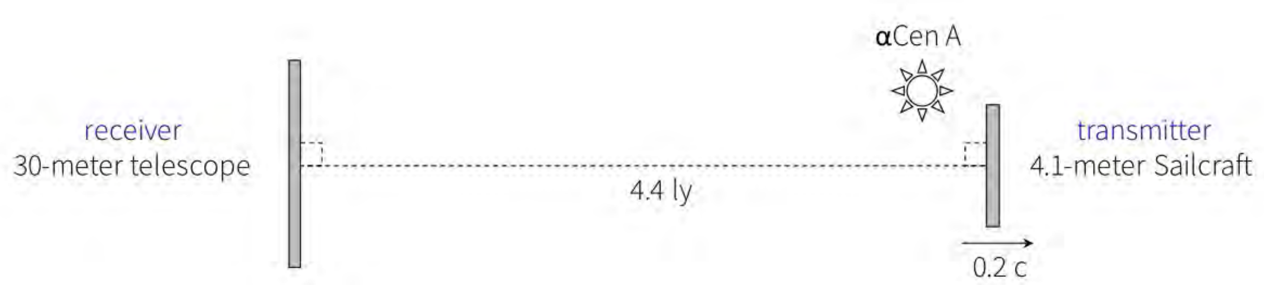
Part of the Starshot systems engineering work, Parkin's paper presents a system model and describes how it computes cost-optimal point designs including interstellar mission, a precursor to the outer solar system and a ground based test facility. The results for the interstellar case show costs of $0.01/W lasers, $500/m² optics, and $50/kWh energy storage resulting in an $8 billion capital cost for the ground-based beam source but a challenging $6 million energy cost to accelerate each sail. However it also shows that Starshot could scale to achieve double the planned 20% c at an extra cost of $29 billion and ultimately 90% of light speed - given a beamer the size of Greater London! Parkin looks in detail at the robustness of the systems engineering conclusions.

This system model thinking sets the scene for the detail work on downlink communications. There are three papers focussed on this so far and a further one looking at methods of relaying the downlink through a number of probes which will be the subject of a later Principium article.

4.2 A Starshot Communication Downlink

A Starshot Communication Downlink, Kevin L G Parkin, May 2020, arxiv.org/abs/2005.08940 (6 pages)

In this paper Parkin derives a raw data rate of 260 bits per second assuming a 1.02 μm wavelength 100 Watt laser using 4.1 m diameter "antenna" on the probe received at 1.25 μm by a 30-meter telescope on Earth. The telescope would receive 288 signal photons per second.



Arrangement of the transmitter relative to the receiver for data downlink following transit of αCentauri A. Credit (image and caption): Parkin

For comparison the New Horizons probe data rate from Pluto was about 1,000 bits per second. (pluto.jhuapl.edu/Mission/Spacecraft.php).

Parkin uses a link budget (as explained in section 2.3 *Link Budget* above) - Parkin's table cells **bold** -

<table>
<tr><td>Link Budget item</td><td>In dB terms</td><td>Equivalent to -</td></tr>
<tr><td>Transmitter input power (P_T)</td><td>+50 dBm 100 W at 1.02 µm</td><td>100 W</td></tr>
<tr><td colspan="3">A dBm is a decibel milliwatt, as explained in 2.3 above. Imagine a decimal point, one to the left, in any value of dB you see, so 50 dBm in milliwatts is $10^{5.0}$ milliwatts which is 100,000 milliwatts or 100 watts - about the same as an old-fashioned incandescent light bulb.</td></tr>
<tr><td>Transmitter gain (G_T)</td><td>+140 dBi 4.1 m diameter circular primary, 70% aperture efficiency</td><td>100,000 billion</td></tr>
<tr><td colspan="3">dBi is the ratio of gain of an antenna compared to one which radiates equal power in all directions, so the 4.1 m antenna on the probe concentrates the signal in the required direction, back to the Solar System, so that the laser light appears to be $10^{14.0}$ times brighter.</td></tr>
<tr><td>Receiver gain G<subscript R</td><td>+156 dBi 30 m diameter circular primary, 70% aperture efficiency</td><td>400,000 billion</td></tr>
<tr><td colspan="3">Again dBi is the ratio of gain of an antenna. In this case compared to one which receives from all directions equally. So the 30 m antenna concentrates the signal from the direction of Alpha Cent so that the light received appears $10^{15.6}$ times brighter.</td></tr>
<tr><td>Path loss</td><td>-476 dB free-space path loss over 4.367 ly, 80% atmospheric transmittance, 3 dB link margin</td><td>About 10 followed by 46 zeros - too big to fit!</td></tr>
<tr><td colspan="3">Path loss is conventional losses, including path loss, atmospheric transmission losses and link margin, but not relativistic loss.
Note how the inverse square law loss over 4 light years makes the rest of the losses look trivial!</td></tr>
<tr><td>Relativistic loss L_β</td><td>-3.5 dB transmitter recedes from receiver at 0.2 c; Doppler effect, headlight effect</td><td>about 2.</td></tr>
<tr><td colspan="3">The probe is travelling at 20% of light speed, c. The effect is small $10^{0.35}$ is about 2</td></tr>
<tr><td>Received signal power, S</td><td>-133 dBm 288 photons/second at 1.25 µm</td><td>1/20,000,000,000,000 of a milliwatt</td></tr>
<tr><td colspan="3">Again dBm is decibel milliwatts. -133 dBm is $10^{-13.3}$ milliwatts. In more practical terms the signal from New Horizons, out beyond Pluto, is -220 dBm ($10^{-22.0}$ milliwatts) at the NASA Deep Space Network dishes in Goldstone (California), Madrid and Canberra (Australia). But the signal from Alpha Cent would be at a much shorter wavelength, 1.25 µm infrared light, than the microwave signal from New Horizons.</td></tr>
</table>

Parkin uses numbers derived in his System Model paper (see 4.3 above). The transmit antenna aperture is set by using the laser sail. The sail diameter is 4.1 m - minimising capital expenditure on the Earth-based "beamer" (200 GW laser array). Based on this the assumption is that "cruising at 0.2c, the interstellar medium manifests as a 0.7 kW monoenergetic hydrogen beam" (see Parkin's System model paper, section 7. *Conclusions*, as referenced in 4.3 above). So the "battering" that all probes travelling at these high speeds is used as a power source and his earlier paper asks "A key question for future research is, what fraction of this power can be harvested?". His communication paper assumes 100 W will be available at the transmitter, which is 14% of the 700 W raw energy from the ISM "beam", which looks like a reasonable round figure starting point at this early stage of thinking. The major factors degrading the signal on its long journey are noise, including radiation from the Earth's sky, from the dust disc around Alpha Cent and light scatter within the receiving telescope. Radiation from Alpha Cent itself could be minimised by use of a coronagraph (en.wikipedia.org/wiki/Coronagraph).

Parkin concludes that since each Starshot sailcraft is generating 8-50 Gbit per year this is "more than enough to look for signs of life by imaging planets and gathering other scientific data". With a flyby rate of one sailcraft per week "the cumulative pipeline of data will be vast indeed". Finally he suggests briefly that a mesh network of cooperating sailcraft would allow later craft to be re-targeted to objects of interest, given sufficient cross-range capability*.

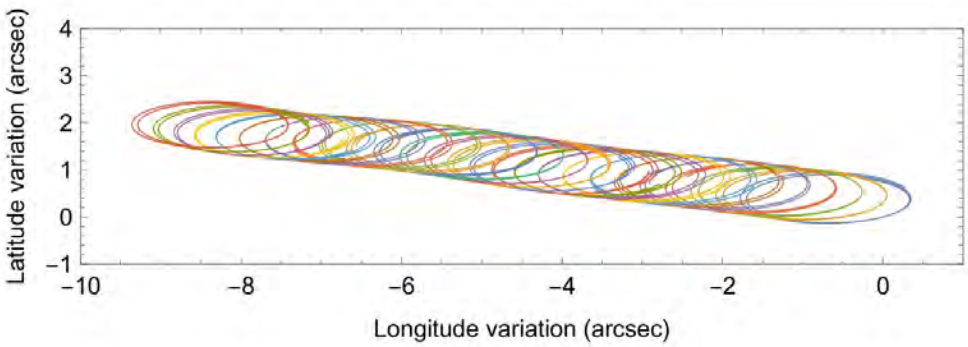
4.3 Technological Challenges in Low-mass Interstellar Probe Communication

Messerschmitt D G, Lubin P and Morrison I, *Technological Challenges in Low-mass Interstellar Probe Communication*, accepted by the Journal of the British Interplanetary Society, June 2020, arxiv.org/abs/2001.09987 (10 pages).

In this paper Messerschmitt, Lubin and Morrison examine the effect of swarm of probes, contrasting single probe performance. In this context, swarming does not imply cooperative or additive effects but is simply the effect of the large number of probes implied by the scale economics of the Starshot proposal. The single probe case is not intended for implementation. The scale economies offered by the relatively low cost of each sailcraft make this attractive - though the beam power cost "per shot" quoted in Parkin's System Model reduces this advantage (see 4.1 *The Breakthrough Starshot System Model* above - and 4.5 *Observations* below). Some of the assumed parameters, such as the transmit antenna aperture, differ from those in the Parkin paper above but this is foundation work - and engineers may not even agree with themselves in this sort of early scenario study!

Much of the paper is concerned with the difficulties arising from receiving signals from multiple probes - as illustrated by the diagram from the paper - Longitude variation (arcsec) versus Latitude variation (arcsec).

Longitude variation versus Latitude variation - relative effects of Earth motion and target star motion on reception of transmissions



Relative angle of probe trajectories as seen from a terrestrial receiver. Shown in different colors are the trajectories over 2.12 years of downlink operation for each of 26 probes launched at 30 day intervals. The oval shape for each probe's trajectory is due to the parallax effect as the probe as viewed from different locations on the earth's orbit. The general drift in the trajectories is due to the proper motion of the target star Proxima Centauri, which requires the launch angle of the probes to change so as to track the target.

Credit (image and caption): Messerschmitt et al

The effect of the motion of the Earth around the Sun in each year produces about two elliptical shapes in roughly two years of receiving data from each probe. The motion of the target star Proxima Centauri has a larger effect and is secular, meaning it does not repeat, and is the result of the different trajectories of the star and our Solar System through the galaxy. Messerschmitt et al suggest that the optimum transmit time would be 10% of the transit time to Proxima Centauri. It takes 20 years at 0.2c to transit 4 light years. Launching probes 30 days apart with each transmitting for 2.1 years means that 26 of them of them will be transmitting at any one time (2.1*365/30= about 26).

In addition to the single versus swarm comparison Messerschmitt et al consider a number of difficulties to be encountered in receiving the very weak signals arriving on Earth. Among these are -

- Impracticability of receiving during terrestrial daylight due to atmospheric scattering of sunlight - the blue sky!
- "Dark counts" caused by thermal and quantum events in both receiving "antennas" (since this is optical these will likely be mirrors).

Data storage and Transmission Rate implications

The time to cross the Proxima Centauri system would be much less than 2.1 years. Taking the example of the Solar System and delay of signals from New Horizons at Pluto of about 5 hours that's 5/0.2=25 hours for a Starshot probe from Pluto to Earth. Taking this as a rough order of magnitude means that about 25 hours of real-time data would be transmitted over about 2 years.

* A quick calculation based on 1 astronomical unit being about 8 light-minutes shows that the sailcraft would transit the Earth-Sun distance, one astronomical unit (AU), in 8/0.2=40 minutes and that in one day (24*60=1,440 minutes) the sailcraft would travel 1,440/40=36 AU about the distance to Pluto. So a week would leave successive sailcraft about 3.5 solar system diameters apart.

- Practical issues concerned with gathering incoming to a very large number of receivers.
- Very high data reliability requirement - the paper suggests no more than one error in 1-10 megabits with 83% of transmitted data being redundant information providing error-correction coding (ECC).

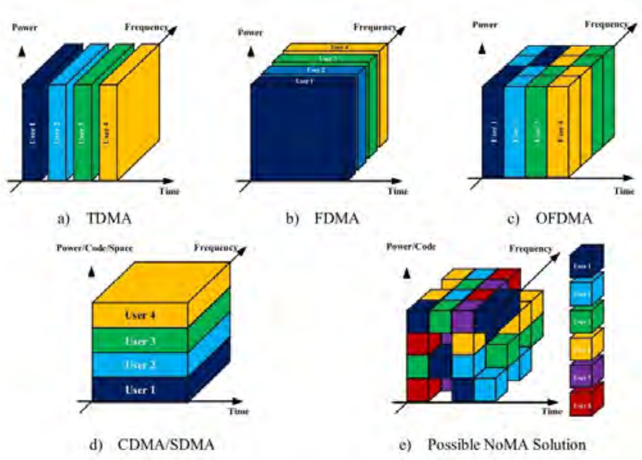
One issue which is raised but left largely for future study is the inevitable multiplexing of simultaneous signals from multiple probes - 26 of them at any one time in the example scenario above. The study identifies four possible approaches "separation of signals by angle, by frequency, by time, or by code". Respectively, these are

- space-division multiple access (SDMA)
- frequency-division multiple access (FDMA)
- time-division multiple access (TDMA)
- code-division multiple access (CDMA)

All are used in mobile telecommunications systems but your mobile phone has an easy job by comparison with a Starshot sailcraft at Alpha Centauri!

In the Conclusions the authors say "There are a considerable number of obstacles to achieving the downlink objectives with a focus on a large multiple probe swarm. We have outlined the most troublesome ones identified to date, suggesting considerable need and opportunity for R&D efforts directed at overcoming these obstacles. Readers with relevant expertise are encouraged to tackle these challenges."

There is a lot of engineering talent in commercial areas such as satellite communications and mobile telecommunications. The interstellar downlink could benefit greatly from their attention.



Illustrative example of different multiple access schemes - from *Toward the Standardization of Non-Orthogonal Multiple Access for Next Generation Wireless Networks*, Chen et al, IEEE Communications Magazine • February 2018, (www.researchgate.net/profile/Xiaolin_Hou4/publication/323141497_Toward_the_Standardization_of_Non-Orthogonal_Multiple_Access_for_Next_Generation_Wireless_Networks/links/5c947420a6fdccd460312299/Toward-the-Standardization-of-Non-Orthogonal-Multiple-Access-for-Next-Generation-Wireless-Networks.pdf) Credit: Chen et al / IEEE

4.4 Challenges in Scientific Data Communication from Low-Mass Interstellar Probes

Messerschmitt D G, Lubin P and Morrison I, *Challenges in Scientific Data Communication from Low-Mass Interstellar Probes*, accepted by The Astrophysical Journal, Jan 2018 - May 2020, arxiv.org/abs/1801.07778 (arxiv 43 pages), published in The Astrophysical Journal Supplement Series, Volume 249, Number 2, August 2020, (ApJS 39 pages). The arxiv version differs significantly from the definitive ApJS version but it is available as an open publication and has the merit of verbose rather than terse references.

This is an earlier and much more detailed paper by the same authors as discussed in 4.3 *Technological Challenges* above. Nevertheless these are early days in the design process and the authors emphasise this in 1.1. *Goals*, "The goal of this paper is not to propose a concrete and fully specified design for such a communication downlink, as there are too many uncertainties, interactions between launch and downlink communication, and questions about the technologies that may be available in the timeframe of the first operational downlink" (both arxiv and ApJS versions).

The paper remarks that first launch is unlikely for at least two decades and the first reception of data adds the transit time of 20 years.

The paper devotes four pages to the receiver (ApJS page 4) and about two thirds of a page to the transmitter (ApJS 3). There are clearly many more unknowns for the probe. This brief review concentrates on the probe end and inevitably simply gives a flavour of the paper, which has about 130 numbered sections.

Where both versions of the paper are referenced, for example (arxiv 2.5.2, ApJS 4.2) this is abbreviated to (2.5.2/4.2).

4.4.1 Power sources

The entire link budget is obviously constrained by the power available to the probe transmitter. The paper is cautious about this, making "... no prior assumption about transmit power, but rather characterize the minimum transmit power necessary subject to the other constraints" (arxiv 2.5.2, ApJS 4.2).

Three power sources are suggested - a radio-isotope thermoelectric generator (RTG), photovoltaic power (PV) from the target star during the encounter and forward-edge ISM proton-impact conversion during the cruise phase (before and after encounter). Contrast the Parkin paper discussed in 4.2 A Starshot Communication Downlink above which suggests the ISM source "0.7 kW monoenergetic hydrogen beam" delivering 100 W to the transmitter.

An RTG is the "traditional" power source for deep space probes - from the Pioneers and Voyagers to New Horizons and most if not all future proposals. For a twenty year mission the exponential decay of the standard Plutonium 238 (see *Assessment of Plutonium-238 Production Alternatives*, www.energy.gov/sites/prod/files/NEGTN0NEAC_PU-238_042108.pdf) may be not be a problem given the 40 year duration of the still-functioning Voyagers.

The 2016 i4is Andromeda study by i4is for Breakthrough Starshot, *The Andromeda Study: A Femto-Spacecraft Mission to Alpha Centauri* (arxiv.org/abs/1708.03556) in 2.10 *Power Supply for the Probe* also considered Americium-241 which has a much longer radioactive half-life but with a reduced power density. The same study examined and rejected RTG (too heavy), Alphavoltaics (too heavy) Betavoltaics (too heavy), Microbal battery (stability, temperature) and suggested a CubeSat Nuclear D-cell battery, a thermophotovoltaic source. But the assumed probe mass for Andromeda was much greater, with the beamer in space and a total mission duration of 50 years travelling at a cruise speed of 10% c.

4.4.2 Burst pulse-position modulation (BPPM)

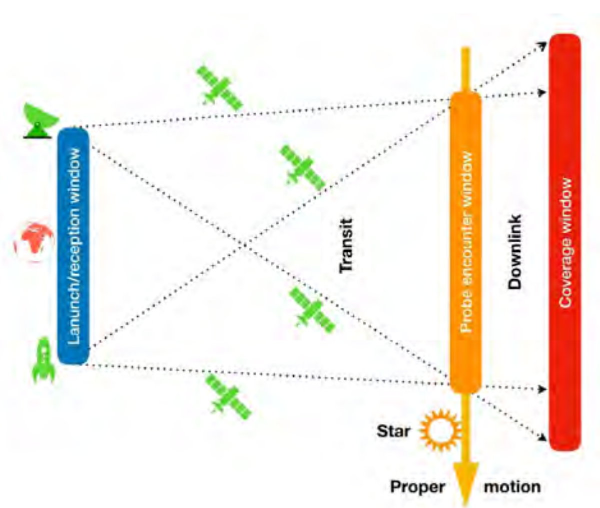
The paper proposes a "novel burst pulse-position modulation (BPPM) [which] beneficially expands the optical bandwidth and ameliorates receiver dark counts". The paper suggests a semiconductor laser generating pulses with duration of the order of 0.1–1 μs, with a repetition rate of about 1–2 Hz. This is a duty cycle of 0.00001 to 0.0000005 so average powers of 1-100 mW become peak powers in kilowatts. The paper points out, however, that this scaling of peak power is difficult to achieve in practice. Good conversion efficiency is also hard to achieve and compromising on that very short duty cycle in turn means that parameters like receiver aperture (telescope mirror size) have to increase and that interference from moonlight for the terrestrial receivers becomes more significant.

4.4.3 Receiver Aperture

Messerschmitt et al calculate the coverage required to receive the signal from concurrently transmitting probes and the antenna gain required to pick up the tiny, single photon, signals. These are in conflict if a single receive antenna is used. This is similar to the situation for your modern TV satellite dish versus the backyard monsters, yards across, that were common in more rural areas when I first visited the USA in the late 1980s. Big antennas need to point very accurately, usually at just one satellite, small antennas are much less directional but not as good with weak signals.

The scope of the problem is well illustrated by Figure 1 in the paper. So the paper proposes an array of smaller receivers (telescopes) with signals combined to achieve the necessary photon detection rate and a sophisticated mixture of combining optical paths with combining the electronic signals produced by the photon detectors.

The four most extreme probe trajectories as viewed from Earth



"Figure 1. 2D schematic representation of the four most extreme probe trajectories as viewed from Earth. The launch/reception window captures the seasonal variation in Earth's position, and the probe encounter window captures the proper motion of the target star. As shown, all encounters are assumed to fall on the same side of the target star, which moves away from the encounter positions. Downlink operation follows encounter. Receiver coverage is assumed to cover all concurrently transmitting probes, and a coronagraph function takes advantage of spatial separation to reject a portion of the target star's radiation."

Credit: Messerschmitt et al

4.4.4 Choice of optical frequency

The paper considers only optical frequencies for the downlink. It does not rule out the option of radio but suggests that optical link has an advantage of 10^4 to 10^5 in the link budget.

For the chosen optical bearer, the effects of the Earth atmosphere are substantial (7/11). The paper concludes that communication with low-mass probes at optical wavelengths is not feasible given the current state of technology (4.3/8.3). The key technology advances required include -

- Daytime Sky Irradiance - ruling our reception during daylight (note that ApJ version section 11 refers to a section 11.9 which does not exist. This should probably be a reference to 10.9 *Parameter-metric Sensitivity).*
- Nighttime Sky Radiance - with the phase of the Moon having a substantial effect.
- Atmospheric turbulence - here the multiple receivers required by multi-probe coverage and single photon direction also help to mitigate turbulence effects.
- Outages - mainly from weather including water vapour, clouds, and storms (there is no mention of outages from aircraft and satellites).

4.4.5 Error correction

The interstellar downlink will test the limits of error control in communications engineering. Since the roundtrip time is around four years ARQ, as described in 2.4 *Say again?* above, is clearly ruled out and Forward Error Correction (FEC) will be required. The paper addresses error correction in the optical layer in *ECC Layer* (10.3/14.3) and FEC encoding in *Role of redundancy* (10.3.3/14.3.3) which suggests that "we have to fall back on best practices" and identifies Reed-Solomon coding as an appropriate choice.

The paper suggests a 2008 tutorial by Messerschmitt, *Some Digital Communication Fundamentals for Physicists and Others*, www2.eecs.berkeley.edu/Pubs/TechRpts/2008/EECS-2008-78.pdf.

4.4.6 Other Challenging Design Issues and Critical Technologies

The paper identifies some *Other Challenging Design Issues*(8/12) and *Critical Technologies* (9/13) notably -

- *Probe Motion Effect* (8.1/12.1) on Doppler shift of signal (Uncertainty in Probe Velocity, Earth Motion)
- *Gravitational Redshift* (8.1.3/12.1.3) produced by the target star
- *Multiplexing options* (8.2/12.2)
- *Probe Attitude Control* (8.5/12.6) especially for downlink Pointing Accuracy
- *Coronagraph Function* (8.6/12.7)
- *Transmit Light Source* (9.1/13.1) including Pulse Compression,
- *Optical Bandpass Filtering* (9.2/13.2) and *Single-photon Detection* (9.3/13.3)

* In-Situ Resource Utilisation (ISRU) and in-space assembly are very live topics. Examples: *Adaptive In-Situ Resource Utilisation (ISRU) Systems For Long Term Space Development*, Shergill & Kingston, IAC 2019 and *In-orbit Spacecraft Manufacturing: Near-term Business Cases*, Skomorohov et al, IAC 2019, www.researchgate.net/profile/Andreas_M_Hein/publication/309358565_In-orbit_Spacecraft_Manufacturing_Near-term_Business_Cases/links/580b1d6908ae74852b5401fc/In-orbit-Spacecraft-Manufacturing-Near-term-Business-Cases.pdf .

4.5 Observations

The following observations occur to this reporter. Some of them may be misunderstandings or errors - it is many decades since this was my professional area.

As explained above, the longer Messerschmitt et al paper [1] exists in two editions the open access early version on arxiv.org and the final Astrophysical Journal version. Section numbers are given in that order, for example 10.3/14.3.

4.5.1 Why not have the receiving telescope(s) in space?

The longer Messerschmitt et al paper [1] only very briefly considers a *Space-based Receiver* (4.4/8.4). Use of Earth based telescopes would require at least three instruments, like the NASA Deep Space Network [9]. Weather outages could be minimised by site selection but not eliminated. A space telescope could operate continuously by avoiding sunlight or moonlight scattering into the aperture. A ground based telescope can only be used at night and, even then, is affected by scattered moonlight.

The growing constellations of low Earth orbit (LEO) satellites are already a serious concern for terrestrial astronomers. They may be predictable but would still result in outages which could have significant effects on the link budget averaged over time.

A space telescope array might also be scalable at lower cost if most materials were provided using ISRU*.

As Messerschmitt et al [1] remark, the timescale to first data is nearly half a century and if we have not achieved this sort of capability by then there must have been significant stalls on the way to ISRU and in-space fabrication.

The James Webb Space Telescope (JWST) at 6.5 m aperture is less than an order of magnitude smaller than Parkin's assumed Starshot receiver [4] and terrestrial telescopes larger than the Starshot receiver are already under construction so 30 m terrestrial is conservative for such an otherwise ambitious project.

Digressing a little from downlink issues - but why not have beamer in space too, as in the i4is Andromeda study, see 2.3 *Link Budget* above? This would allow longer beaming, less demanding acceleration, free power (noting high cost of power per sailcraft noted by Parkin). It would allow scaling of both power gathering and beamers without gravitational constraints. And it would minimise dangers from a mis-directed beam. There would probably be a higher initial cost. An ISRU-based study is perhaps needed to reveal some idea of the lifetime cost.

4.5.2 Error Correcting Code

Error Correcting Code (ECC) is covered in detail, especially in the longer Messerschmitt et al paper [1] 10.3/14.3. *ECC layer* - but no application-specific error correction is discussed. In the same paper 2.2. *Scientific Objective* - an image of 1000 by 1000 is assumed compressed to one bit per pixel but "After compression, even a single bit in error often propagates across the image and thus has serious consequences". An implemented system would almost certainly compress images at source so that each pixel, after analogue to digital conversion, would have selective error correction applied so that more significant bits received greater error protection, as in typical mobile communications codec standards [10]. This achieves compression with graceful degradation as error rates increase and, for applications such as imaging, is preferable to error correction which treats all bits as equal. Adjacency of samples in space is also relevant in image data, as is time adjacency in voice, and the challenges faced in delivering images from a tiny probe at four light years are far greater even than the technology which delivered those stunning images of Pluto from the New Horizons probe.

5 Heavier Metal

Another recent study - *Project Icarus: Communications Data Link Designs between Icarus and Earth and between Icarus spacecraft*, Peter Milne, Michel Lamontagne and Robert M Freeland II (JBIS, Vol. 69, pp.278-288, 2016) is based on the massive fusion powered successor to the Daedalus design (see *Reaching the Stars in a Century using Fusion Propulsion, A Review Paper based on the 'Firefly Icarus' Design* by Patrick J Mahon in P22, August 2018).

It aims to deploy a large antenna composed of self-assembling swarms or built by "Spiderfabs" allowing for high bandwidth communication, including an uplink, to a probe orbiting the target system rather than a flyby.

The target 20 Gbps data rate between the Icarus probe and Earth, is the equivalent of 13 high definition TV channels (at 1.5 Gbps each).

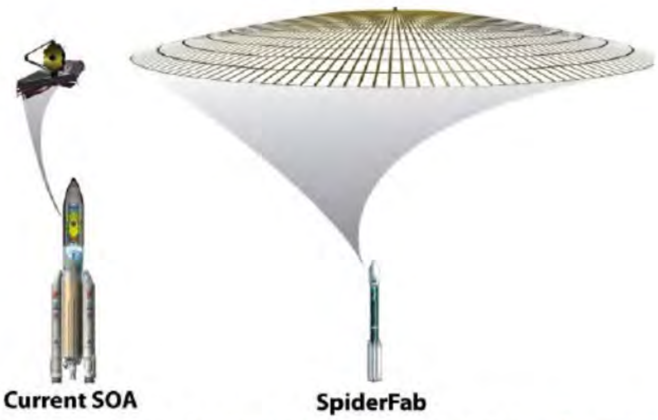


Figure 1. SpiderFab Value Proposition. *On-orbit fabrication of spacecraft components enables higher gain, sensitivity, power, and bandwidth at lower life-cycle cost*

The Spiderfab value proposition (from the report cited in Milne et al above, SpiderFab™: *Process for On-Orbit Construction of Kilometer-Scale Apertures*, Robert Hoyt, Jesse Cushing, Jeffrey Slostad, Tethers Unlimited Inc, 2013 - https://core.ac.uk/download/pdf/189598541.pdf)

But tiny sailcraft which might be launched within 20 years cannot be easily compared with a vehicle of 25,000 tons which might be launched sometime in the next century. The Milne et al paper will be the subject of an article in a later issue of Principium.

6 References: Starshot and other related sources

1. Messerschmitt D G , Lubin P and Morrison I, "Challenges in Scientific Data Communication from Low-Mass Interstellar Probes", accepted by The Astrophysical Journal, Jan 2018 - May 2020 http://arxiv.org/abs/1801.07778).

2. Messerschmitt D G , Lubin P and Morrison I, "Technological Challenges in Low-mass Interstellar Probe Communication", accepted by the British Jour. of the Interplanetary Society, June 2020 (https://arxiv.org/abs/2001.09987).

3. The Breakthrough Starshot System Model, Kevin L G Parkin, 2018 arxiv.org/abs/1805.01306

4. A Starshot Communication Downlink. Kevin L G Parkin May 2020, arxiv.org/ftp/arxiv/papers/2005/2005.08940.pdf

5. Technological Challenges in Low-mass Interstellar Probe Communication. Messerschmitt (UC Berkeley), Strauch (UC Berkeley), Lubin (UC Santa Barbara), Morrison (Curtin University, Australia) January 2020 arxiv.org/pdf/2001.09987.pdf

6. Interstellar Communication Network. I. Overview and Assumptions. Michael Hippke (Sonneberg Observatory, Germany), The Astronomical Journal, 2020 dec1.sinp.msu.ru/~panov/News/Texts/1912.02616.pdf

7. Interstellar communication network.II. Deep space nodes with gravitational lensing. Michael Hippke (Sonneberg Observatory, Germany), https://arxiv.org/pdf/2009.01866.pdf

8. Messerschmitt D G, Lubin P and Morrison I, "Relaying Swarms of Low-Mass Interstellar Probes" - https://arxiv.org/pdf/2007.11554.pdf (see also Principium 30 page 51)

9. NASA Deep Space Network - "DSN Telecommunications Link Design Handbook" 2.5 Forward Error Correcting Codes, pages 10-30. May 03, 2017 Jet Propulsion Laboratory https://deepspace.jpl.nasa.gov/dsndocs/810-005/Binder/810-005_Binder_Change42.pdf- see also - http://deepspace.jpl.nasa.gov/dsndocs/810-005/

10. ETSI TS 126 346 V12.3.0 (2014-10) Universal Mobile Telecommunications System (UMTS);LTE; Multimedia Broadcast/Multicast Service (MBMS); Protocols and codecs {footnote: 3GPP TS 26.346 version 12.3.0 Release 12) https://www.etsi.org/deliver/etsi_ts/126300_126399/126346/12.03.00_60/ts_126346v120300p.pdf}

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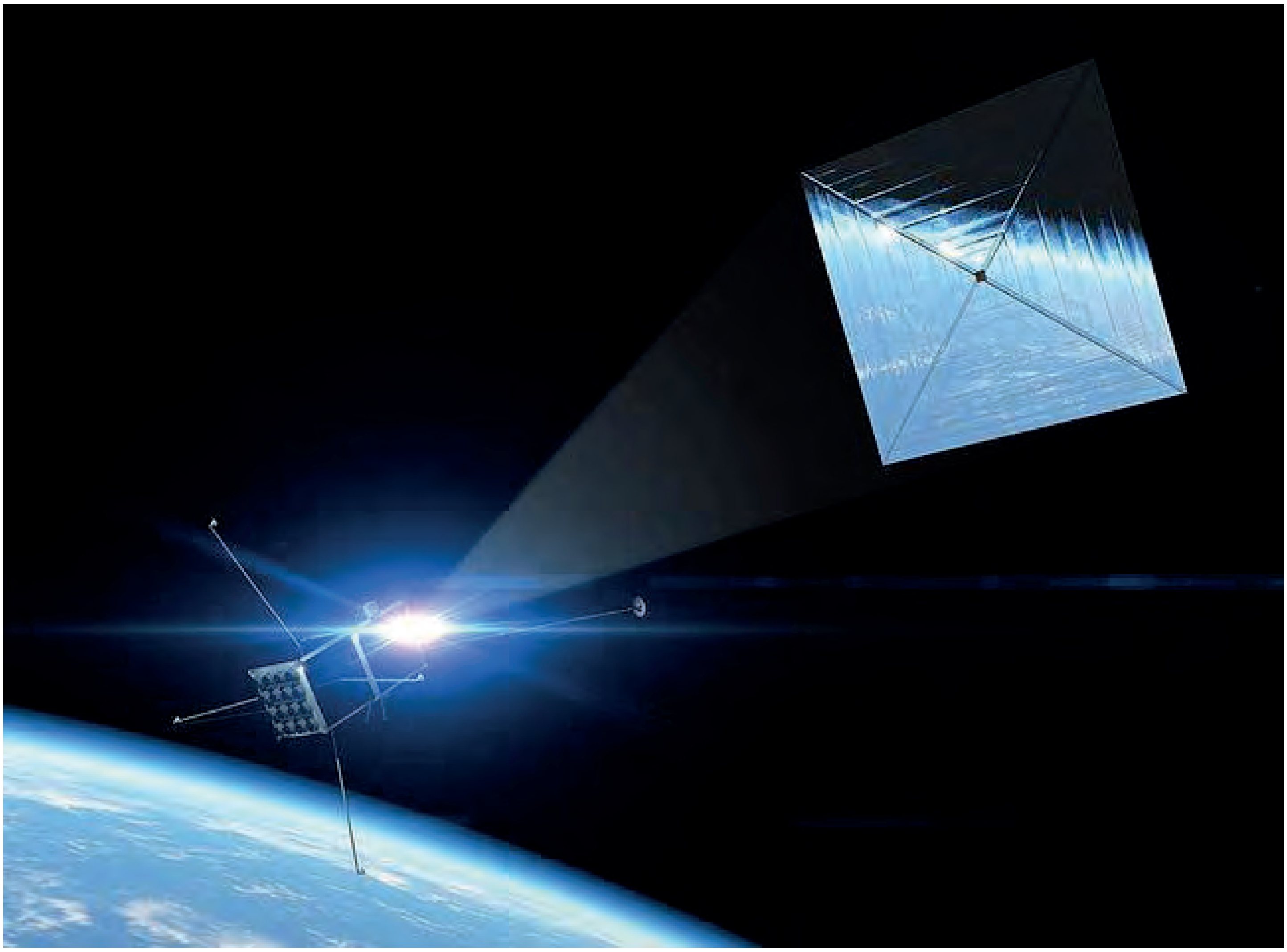

The Initiative for Interstellar Studies (i4is) has launched a membership scheme intended to build an active community of space enthusiasts whose sights are set firmly on the stars. We are an interstellar advocacy organisation which:

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71st International Astronautical Congress 2020

The Interstellar Report - Part 1 of 2

This year's Congress was a ***Cyberspace Edition*** offered without registration fee, free of charge for a global community. Principium readers, and especially i4is members could therefore access the whole programme. This was a possibly unique opportunity to engage with this global event without the substantial entry fee normally charged and, of course, without travel expenses.

The catalogue of all technical sessions is at -

iafastro.directory/iac/browse/IAC-20/catalog-technical-programme

In this report and in part two in our next issue we aim to report all the items likely to be of special interest to Principium readers. Many were explicitly interstellar in topic but others are important in contributing to our interstellar goal including innovations in propulsion, exploitation of resources in space, deep space communication and control, enhanced and more economical access to space, etc.

Our reporters are -

- Dr Al Jackson (AJ)
- Angelo Genovese (AG)
- Adam Hibberd (AH)
- Olivia Borgue (OB)

- Our thanks to all of them. We also have reports from John Davies (JID)

On this occasion access to both papers and presentations has been granted, to all who register by the International Astronautical Federation (IAF).

Registration is available at -

https://iac2020.vfairs.com/en/registration

However we have also sought out open publication without registration and cited links where we have found them.

Page	Item	Title	Author	Report
44	IAC-20,C4,9,7,x56172	Exploration of trans-Neptunian objects using the Direct FusionDrive	Mr Paolo Aime	OB
45	IAC-20.C4.9.4	A High Inclination Solar Mission enabled by Near-Term Solar Sail Propulsion	Mr Les Johnson	OB
46	IAC-20,D4,4,2,x60132	Rapid Access to the Interstellar Medium: A Feasibility Study	Dr Leon Alkalai	AG & AH
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51	IAC-20,D4,4,4,x59255	System Engineering a Solar Thermal Propulsion Mission Concept for Rapid Interstellar Medium Access	Dr Jonathan Sauder	AH
52	IAC- 20,A3,4B,3,x56468	Comet Interceptor: An ESA mission to a Dynamically New Solar System Object	Dr Joan Pau Sanchez Cuartielles	AH
53	IAC-20,A5,4- D2.8,4,x58230	Optimal Spacecraft Trajectories under Uncertainties	Mr Deepak Gaur	AH
54	IAC-20,D4,4,11,x58592	A Feasibility Analysis of Interstellar Ramjet Concepts	Ms Taavishe Gupta	AJ
55	IAC-20,A5,4-D2.8,3,x59291	Assessment of On-Orbit Cryogenic Refueling: Optimal Deport Orbits, Launch Vehicle Mass Savings, and Deep Space Mission Opportunities	Mr Justin Clark	JID
56	IAC-20,A5,4- D2.8,9,x59363	Nuclear Thermal Propulsion (NTP) Post-Burn Transient: Cool-Down Propellant Consumption and its Effect on Total Delta-v	Mr Jack Plank	JID

IAC-20,C4,9,7,x56172	Exploration of trans-Neptunian objects using the Direct FusionDrive	Mr. Paolo Aime	Politecnico di Torino	Italy

IAF cited paper:

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Open paper: https://webthesis.biblio.polito.it/14755/

Reported by: Olivia Borgue

The study presents exploration possibilities enabled by a direct fusion drive (DFD) nuclear propulsion system [1]. The DFD is half-way between a conventional NTP and an electromagnetic thruster. The propellant is deuterium plasma heated by fusion products, magnetic fields contain and heat up the fuel. The expected performance is illustrated in Figure 1.

	Low power		High power		Our choice
Fusion power, [MW]	1		10		2
Specific impulse, [s]	8500	8000	12000	9900	10000
Thrust, [N]	4	5	35	55	8
Thrust power, [MW]	0.46		5.6		1
Specific power, [kW/kg]	0.75		1.25		1

Figure 1. Expected performance of direct fusion drives (from Aime, Table 1)

The targets addressed in this study are trans-Neptunian objects (TNOs) such as Pluto, Eris, Haumea or Makemake. More specifically, they targeted Haumea with the objective of delivering at least 1500 kg of payload within 10 years of flight, maintaining a constant engine performance.

The trajectory is designed to have a spiral departure phase, an interplanetary phase and a rendezvous phase (Figure 2). The thrust of the DFD is expected to be comparable to that of the most efficient electromagnetic high-power thrusters, but the specific impulse would be higher.

They expect that the DFD will enable an entirely new class of interstellar missions.

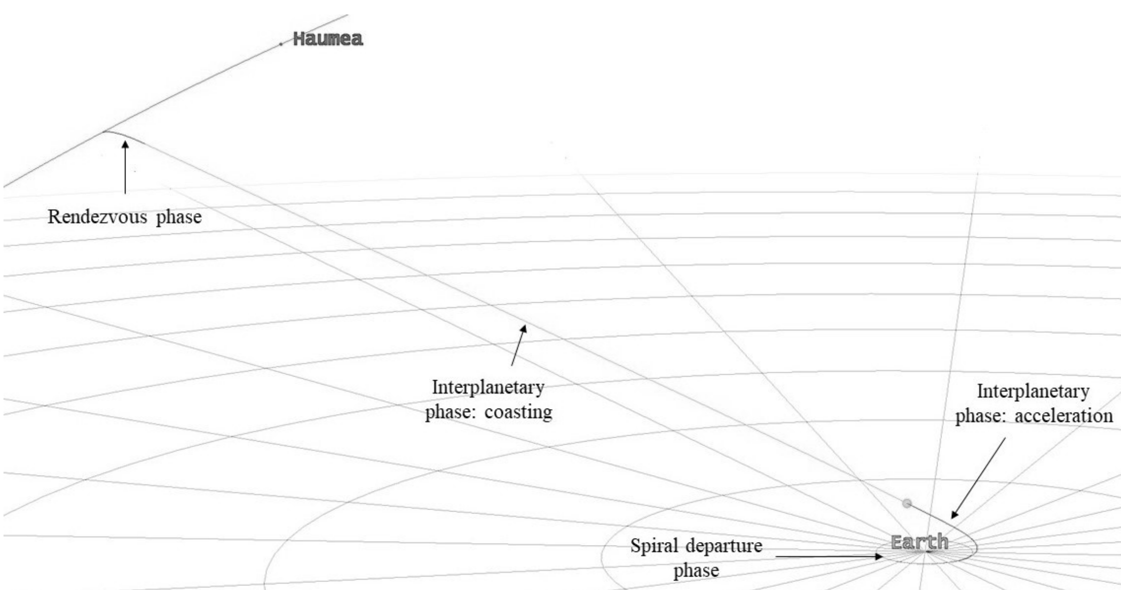

Figure 2. Trajectory to reach Haumea with a DFD (from Aime Figure 1)

[1] See also *A Titan mission using the Direct Fusion Drive* in *Interstellar News* in this issue.

IAC-20.C4.9.4	A High Inclination Solar Mission enabled by Near-Term Solar Sail Propulsion	Mr. Les Johnson	NASA, Marshall Space Flight Center	USA

IAF cited paper:

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Open paper: none found

Reported by: Olivia Borgue

Why study the sun from its poles (high inclination solar mission)? Because it provides information that we cannot obtain from other angles. It is like expecting to understand Earth weather without knowing what happens in the polar regions.

A high inclination solar mission would gather information about the Sun´s magnetic fields, solar winds and space weather. The problem is how to get to high inclination solar orbits and how to get the data.

Conventional alternatives to reach high orbits have many drawbacks:

- rockets are impractical,
- gravity assist maneuvers have very long period orbits and not much time is spent gathering data,
- electric propulsion takes a lot of mass and volume in propellant and would interfere with measurements.

The ideal solution is to use solar sails (photon pressure to produce thrust), they don´t require propellant and provide a large delta V. However, they are underdeveloped. Few missions have implemented solar sails (Figure 1). Nevertheless, other missions are currently ongoing or planned for the near future (Figure 2)

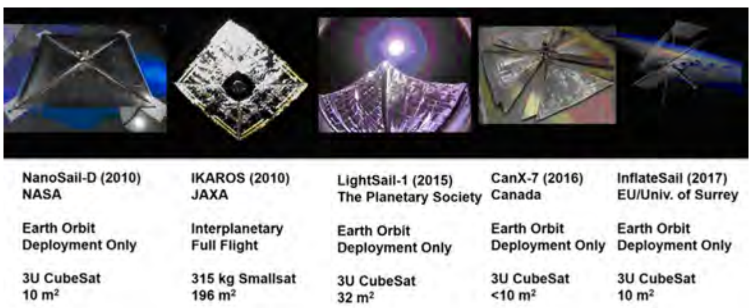
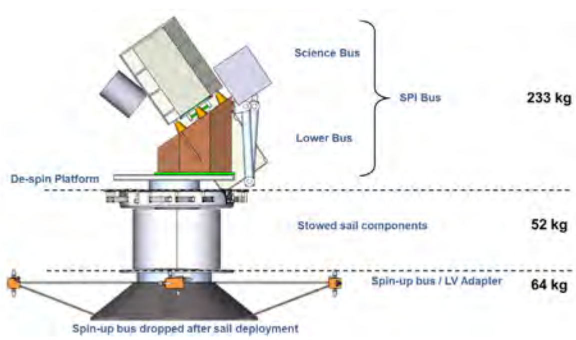


Figure 1. Missions that implemented solar sails.

Figure 2. Current and planned solar sails missions.



The HISM sailcraft mission concept showing the science bus and the separate, separable spin-up bus.

Credit: Johnson (Figure 2)

This study presents a solar sail based on a scaled Solar cruiser design, proposed to be launched by NASA in 2024. The solar sail in this study is scaled up to 7000 m² and would take science observation moving towards and from the target orbit. It aims at implementing remote sensing and in SITU science observation mission to study the suns behavior at high inclinations. It is estimated that the space craft can be built with existing capabilities with a total mission time of 9-12 years depending on the weight.

IAC-20,D4,4,2,x60132			
Rapid Access to the Interstellar Medium: A Feasibility Study	Dr. Leon Alkalai	NASA/JPL	USA

IAF cited paper:

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Open paper: None found

Reported by: Angelo Genovese & Adam Hibberd

Angelo Genovese

This paper is about the results of a JPL feasibility study on the rapid access to the interstellar space beyond the Solar System. Using current technologies (New Horizons) at least two centuries are required to reach the solar-gravity lens focus area (SGLF 550 AU). The goal of this study was to explore mission and flight system concepts that will reach the solar-lens focus in less than 50 years.

The launch system considered is the SLS Block 2B + EUS (Extended Upper Stage) + Advanced Boosters option as it offers the highest performance of this new heavy-lift expendable launch vehicle family.

The authors propose two different mission design philosophies: 1) low launch characteristic energy[1] C3 (~20 km^2/s^2) with a big launch mass (~38,000 kg) carrying a large amount of propellant to a solar perihelion point where a big burn (Oberth maneuver) would cause the spacecraft to have a fast solar system escape velocity, 2) very high C3 (~120 km^2/s^2) and a much smaller probe (~6,000 kg) performing just a Jupiter-powered flyby.

Two propulsion technologies are considered for the solar Oberth maneuver, namely Solar Thermal Propulsion (STP) and conventional Solid Rocket Motors (SRM). This study shows that SRM outperforms conventional STP, as can be seen in Table 2 (STPc Only vs SRM Only); the SRM final escape velocity is 12.4 AU/yr versus the STPc final escape velocity of 10.3 AU/yr.

Table 2 Mission Architectures Performance Comparison (credit: Alkalai/ JPL)

	50 AU (KBO's) (yr)	125 AU (ISM) (yr)	550AU (SGLF) (yr)	Final Vesc (AU/yr)	Mission
STPc Only	12.8	20.2	62.6	10.3	Solar
STPc NEP	13.3	20.1	51.6	13.6	Solar
STPi Only	11.0	15.5	41.2	16.6	Solar
STPi NEP	11 .4	16.1	38.5	19.5	Solar
SRM Only	12.0	18.1	52.7	12.4	Solar
SRM NEP	12.3	18.1	44.6	16.2	Solar
SRM Only	7.9	18.1	75.9	7.4	Jupiter
SRM NEP	8.8	16.9	55.5	11.0	Jupiter
NEP Only	10.7	20.6	53.5	14.2	Jupiter

Furthermore, even higher escape velocities can be reached combining a SRM or STP system with a low thrust propulsion system, as the new Nuclear Electric Propulsion (NEP) system developed by NASA's Glenn Research Center using the 10 kWe[2] Kilopower reactor and the NEXIS ion thruster.

The NEP system is utilized after the solar perihelion burn performed by either STP or SRM; for missions far deep in interstellar space (SGLF) NEP will show its performance, while for missions to closer Kuiper Belt Objects (KBO) having NEP is a sort of burden as NEP will add acceleration gradually to the spacecraft and it will take a long time for the spacecraft to reach high speed. So, if the goal is to reach KBO's fast using the first mission architecture, NEP should be absolutely off the table.

[1] https://en.wikipedia.org/wiki/Characteristic_energy

[2] kWe - kiloWatt electric - as distinct from the thermal power of the reactor

Figure 8 illustrates the above conclusions: the dark green (SRM ONLY) remains a rather flat line (constant escape velocity) for the entire mission, whereas the light green (SRM+NEP), although has a lower performance at the beginning, will pick up to a much higher escape velocity after 15 years from the solar perihelion. The escape velocities of both light and dark green become equal after about five years from the perihelion burn.

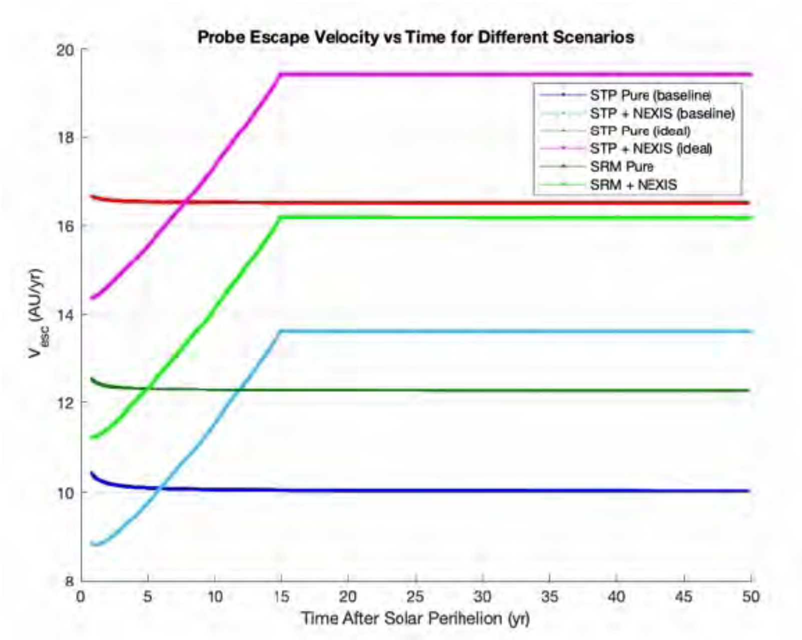

Fig 8 The Effect of NEP on Escape Velocity
Credit: Alkalai / JPL

The main drawbacks of the first mission design architecture are the technical thermal issues that result in a very high dry-mass/wet-mass ratio. An alternative mission architecture eliminates the need for a solar perihelion dive using a Jupiter powered flyby at low altitude (3,000 km). In this new scenario, the spacecraft is launched with a very high C3 (120 km^2/s^2) directly from Earth to a Jupiter powered flyby. Table 2 shows that for short distances (reach a KBO), a Jupiter-powered flyby seems appropriate; for distances to the ISM, a Jupiter-powered flyby followed by a NEP system could provide a good enough solution; and to reach far towards the solar-gravity lens focus and beyond, an SRM at solar perihelion followed by NEP seems to be the best option with an escape velocity of 16.2 AU/yr (4.5 times faster than Voyager 1).

If the technology of the STP system is further improved, the study shows that it can outperform an SRM due to its higher ISP (1350s). With a fully developed STP technology, an escape velocity of 19.5 AU/yr (5.4 times faster than Voyager 1) seems within reach. This could allow reaching the solar-gravity lens focus at 550 AU in less than 40 years; therefore, it is important to have continued investments into STP technology.

Adam Hibberd

In 2013/2014 the KISS study into rapid spacecraft missions to the Interstellar Medium was instigated as a result of firstly Voyager 1 detecting the Heliopause and secondly the detection by the Kepler Space Telescope of exoplanets. Two main ways of doing this, using current or near-future propulsion schemes were found to be:

1) travel to Jupiter followed by a Jupiter Oberth,

2) travel to Jupiter, then a passage close to the Sun and a Solar Oberth.

The research undertaken simulates using solar thermal propulsion for (2) exploiting the solar flux from the Sun and a heat-exchanger to vaporise propellant, in this case LH2. An Isp of approximately 1350s is achievable. The research found a 3 stage system for the Solar Oberth was a good solution. This could be installed into a SLS Block 2B.

As far as perihelion distance from the Sun is concerned it was found that there is a sweet spot at around 3 Solar Radii. Thus the closer to the Sun and the mass of the heat shield becomes too great, whereas further away the effectiveness of the SO reduces. Also currently, STP is not as good as Solid Rocket Motors (SRM) because an SRM has a comparatively low dry to wet mass ratio which gives a greater velocity increment (from the Tsiolkovsky equation). This may change with future development of STP.

Also low thrust Nuclear Electric Propulsion (NEXIS, 10 kW, Isp=7000s) was considered for the outbound phase after the Solar Oberth (1) or Jupiter Oberth (2). This is mainly worthwhile (in terms of high heliocentric excess velocities) for missions deep into the ISM (like to the solar gravity lens distance of 550 AU), rather than for example KBO (Kuiper Belt Objects).

Authors: Leon Alkalai, Reza R Karimi, Jonathan Sauder, Michael Preudhomme, Juergen Mueller, Dean Cheikh, Eric Sunada, Abby Couto, Nitin Arora, and Jacqueline Rapinchuk IAC-20,D4,4,6,x61030

IAC-20,D4,4,6,x61030	Feasibility assessment of deceleration technologies for interstellar probes	Mr. Kush Kumar Sharma	International Space University (ISU)	France

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Open paper: None found

Reported by: Al Jackson & Adam Hibberd

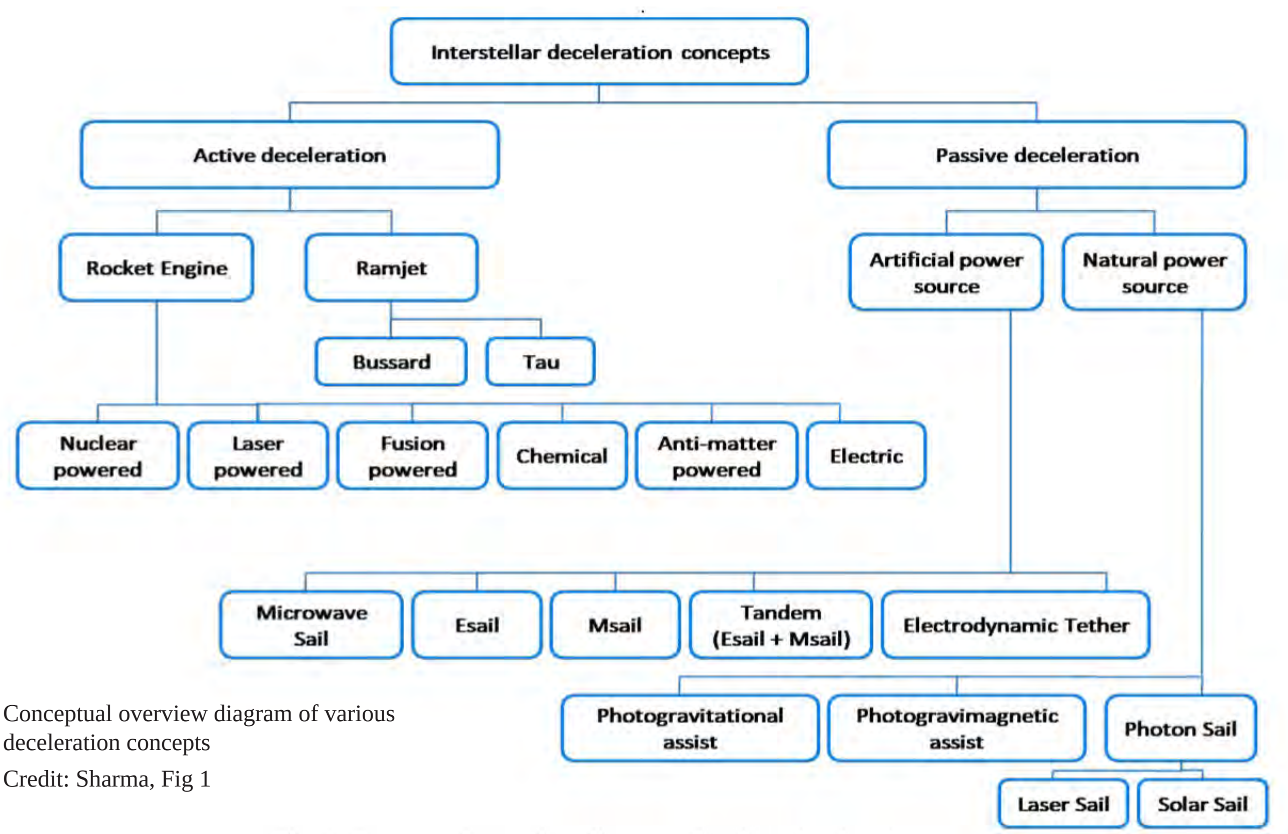
Al Jackson

An important element of interstellar flight is slowing or stopping at target destination. Massive spacecraft would require active deceleration mechanisms; lightweight spacecraft can use passive processes. This paper examines many in the chart given below. Active deceleration of a massive ship requires very large amounts of reaction mass or large power systems. Passive deceleration for small masses might use the medium, radiation or particles, near the target star. It may be possible to make use of the 'stellar sphere' of the target star to stop or slow down. Of interest is the interaction of an interceptor with the stellar sphere radiation forces and magnetic field of a target star. Of particular consideration is the interaction of a spacecraft with radiation pressure, Poynting-Robertson drag, Lorentz forces, stellar wind drag and Coulomb drag. A Technology Readiness Level assessment is made of the various systems that can be deployed.

Deceleration concepts	TRL
Electric sail	3 - 4
Magnetic sail	2 - 3
Tandem (esail + msail)	2
Solar sail	4 – 5
Photogravitational assist	2
Photogravimagnetic assist	2
Electrodynamic Tether	4

Technology Readiness Level assessment

Credit: Sharma Table 2:



Conceptual overview diagram of various deceleration concepts

Credit: Sharma, Fig 1

Adam Hibberd

Interstellar probe missions are high risk, high costs, but high scientific return. This return includes: Planetological + Astrobiological data, study of planets and satellites within the largest system, study of the Interstellar Medium. The nearest star is Alpha Centauri. An exoplanet, has been discovered around Alpha Proxima C, lying in the in the habitable zone. There are four mission types:

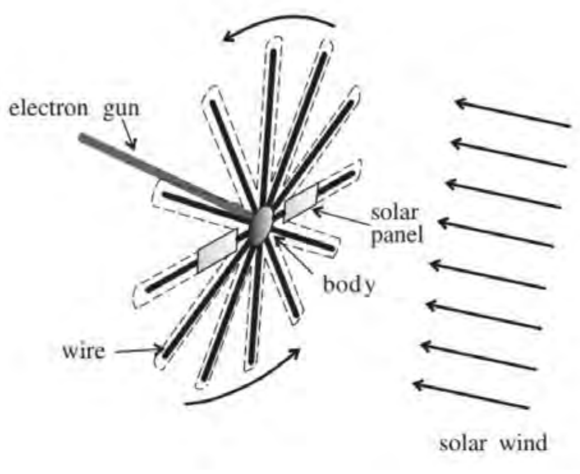
1) Flyby
2) Orbit Insertion
3) Landing (with or without rover)
4) Sample Return

The Mission phases are: acceleration, cruise, deceleration. There are two types of IS deceleration concepts, Active and Passive deceleration. Passive exploits natural astrophysical sources such as stellar radiation pressure, gravity, photons, interstellar ions, etc whereas active requires more mass in the form of fuel. Five passive deceleration schemes were assessed, Electric Sail, Magnetic Sail, Tandem Electric/Magnetic Sail, photogravitational assist, photogravimagnetic assist. The TR, Technical Readiness Level of all passive types are in the region 2-4, apart from the solar sail.

It was found that use of the tandem electric/magnetic sail reduced the deceleration time from 50 years for photogravitational assist to 28.8 years for tandem.

It was found that there is no common baseline which can be used to establish the relative efficacy of these different sorts of passive propulsion schemes. Recommendations are:

1) Develop mathematical model for using photogravimagnetic assist to decelerate a spacecraft.
2) Conduct preliminary design study with subsystem specifications for interstellar mission.
3) Explore the possibility of using laser- or microwave beamed energy derived from spacecraft's on board power for deceleration of small probes.
4) Study the effect of mass ejections of the star on the deceleration force and duration.
5) Perform a specific interstellar mission design study using the different deceleration concepts.
6) Explore potential deceleration methods by combining existing concepts.



Conceptual diagram of electric sail

Credit; Sharma, Fig 2

P. Janhunen, Electric Sail for Spacecraft Propulsion, Journal of Propulsion and Power , 20(4), 2004, 763-764.

space.fmi.fi/~pjanhune/Esail/paper1.pdf

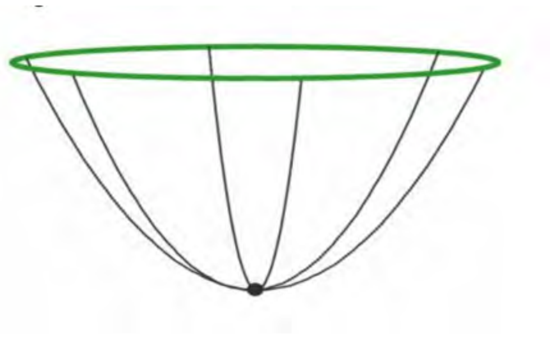


Illustration of magnetic sail in the form of superconducting Biot Savart loop (green)

Credit; Sharma, Fig 3

C. Gros, Universal scaling relation for magnetic sails: momentum braking in the limit of dilute interstellar media, Journal of Physics Communications (2018)

iopscience.iop.org/article/10.1088/2399-6528/aa927e/pdf

Authors: Kush Kumar Sharma, Prof Chris Welch (ISU), Dr Andreas Makoto Hein (Ecole Centrale de Paris and i4is)

IAC-20,D4,4,5,x58922			
Vaporization of interplanetary dust during the acceleration phase of a laser-driven lightsail	Ms. Monika Azmanska	McGill University	Canada

IAF cited paper:Mitigation of Interplanetary Media Impacts for Laser-Driven Interstellar Travel (new title)

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/IAC-20,D4,4,5,x58922.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/presentations/IAC-20,D4,4,5,x58922.show.mp4

Open paper: None found

Reported by: Al Jackson

Light sails pushed by laser beams to velocities around 0.2 c have been proposed as propulsion systems for interstellar travel. These light sails will undergo high-energy collisions with small dust grains in the solar system environment. This paper proposes the plausibility of using the irradiance of the driver laser array to mitigate the damage to the sail during the acceleration phase of the mission. Displacement of dust via the laser light transmitted through the sail, as would be the case with thin dielectric sails, may be feasible. Charged particle re-direction via graded materials is an established technology that has been demonstrated experimentally in the particle accelerator community. The driver laser may have the ability to ablate the dust grains prior to impacting the sail. This study also concerned other grain materials (alumina, iron, etc) likely to be present in dust grains in the solar system. Issues of beam profile and laser interaction are addressed. There is some discussion of sail protection during the interstellar cruise phase.

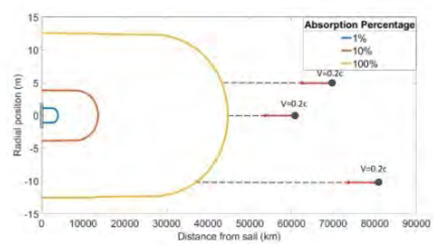


Fig. 1: a) Graphite Grain

ablation analysis:

numerical results for the vaporization of dust grains travelling at 0.2c towards a lightsail positioned at 0.1 AU for a) graphite grain b) alumina grain c) iron grain

Credit (image and caption): Azmanska et al

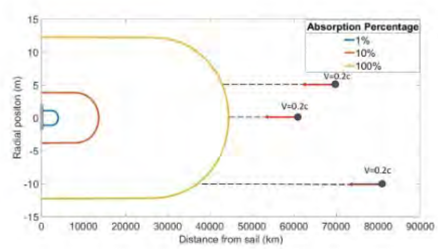


Fig. 2: b) Alumina Grain

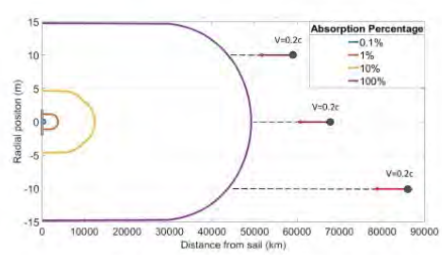


Fig. 3: c) Iron Grain

Authors: John Kokkalis, Monika Azmanska, Andrew Higgins (all McGill University)

IAC-20,D4,4,4,x59255			
System Engineering a Solar Thermal Propulsion Mission Concept for Rapid Interstellar Medium Access	Dr. Jonathan Sauder	JPL-Caltech	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/IAC-20,D4,4,4,x59255.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/presentations/IAC-20,D4,4,4,x59255.show.mp4

Open paper: None found

Reported by: Adam Hibberd

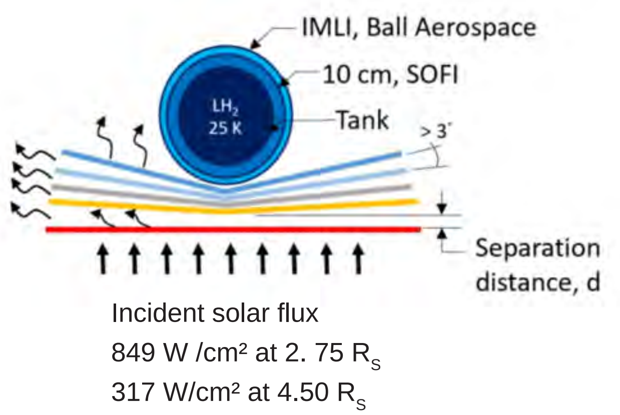
The goal is to gain access to ISM, six times faster than Voyager. In order to do this, two technologies were leveraged:

1) Solar Oberth Manoeuvre after travel to Jupiter, the E-J leg achieved by a combination of Earth/Venus gravity assists

2) Solar Thermal Propulsion to exploit the high solar flux close to the Sun

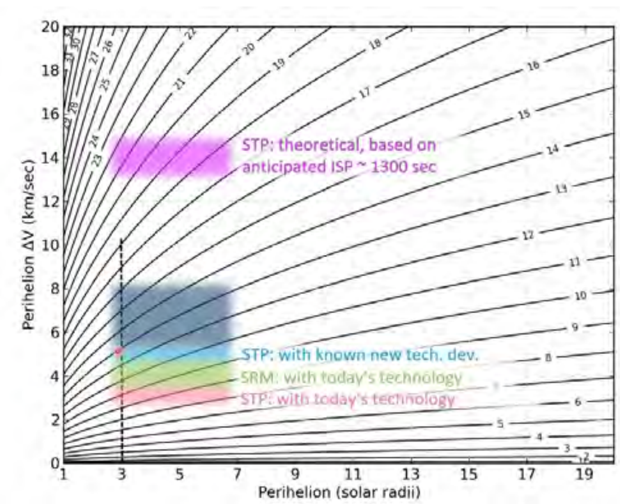
The spacecraft is assumed to use cryocoolers with LH2 propellant with a Barium Fluoride heat shield (size 17 m x 14 m) which is deployable so it can be stored in a SLS Block 2B Launcher. A numerical model for the spacecraft and the Solar Oberth was constructed with these assumptions and a Monte Carlo Simulation was performed. It was found that there is an optimal distance of the Solar Oberth of 3 Solar Radii, closer than this and the heat shield weight begins to detrimentally impact on the spacecraft's performance, further than this, the effectiveness of the SO reduces. Three stages were considered with optimal mass ratios 37:19:44.

Current Solid Rocket Booster (SRB) technology would allow Hyperbolic Excesses of 12 AU/yr whereas with Solar Thermal Propulsion, at its theoretical capability of Isp=1300s, 20 AU/yr can be achieved [1].



The heat shield assembly consists of a high-temperature panel exposed to the sun in addition to a set of radiation shields to further reduce the backloading onto the propellant tanks.

Credit(including captions): Sauder Fig. 4.



Performance of a Perihelion Oberth Maneuver

Credit: Sauder

Authors: Jonathan Sauder, Michael Preudhomme, Juergen Mueller, Dean Cheikh, Eric Sunada, Reza Karimi, Abby Couto, Nitin Arora, Jacqueline Rapinchuk, Leon Alkalai

[1] 1 AU per year = 4.7 km/sec

IAC- 20,A3,4B,3,x56468			
Comet Interceptor: An ESA mission to a Dynamically New Solar System Object	Dr. Joan Pau Sanchez Cuartielles	Cranfield University	UK

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/4B/manuscripts/IAC-20,A3,4B,3,x56468.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/4B/presentations/IAC-20,A3,4B,3,x56468.show.mp4

Open paper: dspace.lib.cranfield.ac.uk/handle/1826/15881

Reported by: Adam Hibberd

Comet-I is the first f-class (fast class) mission by ESA, awarded in 2019 (www.cometinterceptor.space/). Other classes are l, s & m (large, small and medium). It will launch on an Ariane with the Ariel Exoplanet Telescope, both spacecraft being delivered to the Sun/Earth Lagrange 2 point. As far as budget, it has a €150M budget, equivalent to m-class.

The mission is to intercept a ‘dynamically new’ comet with surface ices laid down at the formation of the solar system, as opposed to those which have encountered the inner solar system many times with surfaces eroded as a result.

The comet must first be discovered by the Vera C Rubin Telescope. Current telescopes can pick comets up at distances between Jupiter and Saturn but there is the potential with the VCR to spot them much deeper in the Solar System, so much earlier, giving 2-3 years warning. The comet must have an intercept point reachable by the Comet-I stationed at its L2 point.

3000 long period comets have been discovered altogether, with 300 in the last 10 years. It has been calculated 21 of these would have had intercept points achievable by Comet-I. The sort of ΔV’s required are 0.5-2.0 km/s but with a Gravity Assist at Earth, this can be reduced to 0.1 km/s.

Comet-I consists of three craft, the mothercraft A which gets no nearer than 1000 km from the target comet whereas two subprobes B1 and B2 will get close and do the hard work [1].

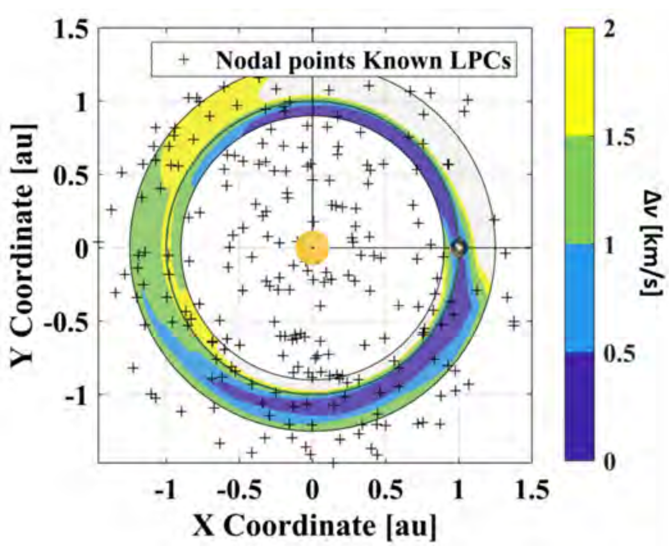
Summary of scientific instruments in Comet-I.

SPACECRAFT	INSTRUMENT	DESCRIPTION
ESA S/C A	CoCa	Visible Camera
	MANIaC	Mass Spectrometer
	MIRMIS	NIR/Thermal IR Imager
	DFP	Dust, Field & Plasma
ESA S/C B2	EnVisS	All-sky multispectral imager
	OPIC	Visible imager
	DFP	Dust, Field & Plasma
JAXA S/C B1	HI	Hydrogen Imager
	PS	Plasma Suite
	WAC & NAC	Wide and Narrow FOV cameras

Credit: Cuartielles et al, Table 1.

Accessible regions in the ecliptic plane as a function of different spacecraft’s Δv capabilities.

Credit (image and caption): Cuartielles et al Figure 4.



Authors: J P Sáncheza, G H Jones, C Snodgrass for the Comet Interceptor Science Team

[1] More about Comet-I in *News Feature: All Comets Great and Small*, Principium. Principium 25, May 2019 page 34. An account of the inaugural lecture delivered by Professor G H Jones at University College, London, 20 February 2019. Prof Jones is Mission Principal Investigator for this mission,

IAC-20,A5,4- D2.8,4,x58230			
Optimal Spacecraft Trajectories under Uncertainties	Mr. Deepak Gaur	Amity School of Engineering	India

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/manuscripts/IAC-20,A5,4-D2.8,4,x58230.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/presentations/IAC-20,A5,4-D2.8,4,x58230.show.mp4

Open paper: None found

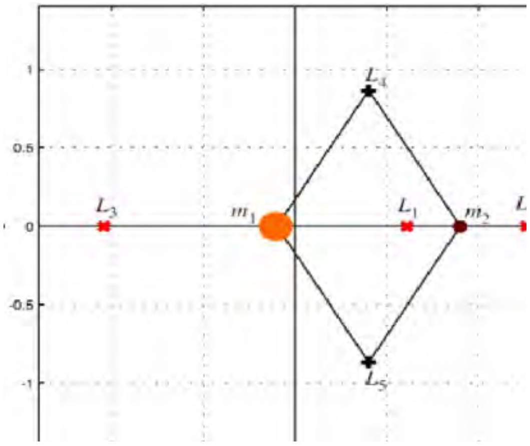
Reported by: Adam Hibberd

This paper was all about the Circular Restricted Three Body Problem (CRTBP) which is the scenario where there are two main bodies each orbiting in a circle around their common Centre of Gravity (these circles are coplanar) and a third object with zero or negligible mass. There is no known general solution to such a problem, however one constant of motion is known to be the Jacobi Constant, symbol ‘C’ as follows

$$C = 2U - V^2$$

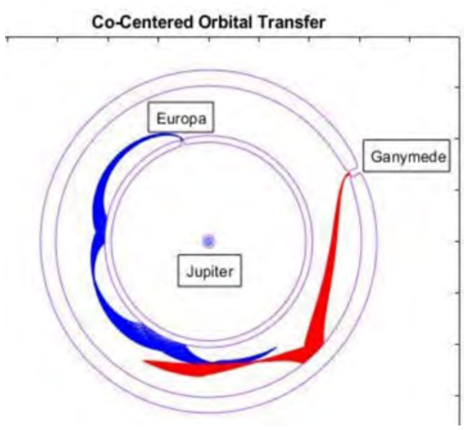
Where U is the potential and V is the speed. If we set V=0, ie find the trajectories which have zero velocity then we get C = 2U. This defines the ZVS (zero velocity surfaces) for different values of C. If we further set the gradient of the potential $\partial U/\partial x = \partial U/\partial y = \partial U/\partial z = 0$, this gives the particular values of (x, y, z) where the ZVS are stable, ie the Lagrange Points, L1, L2, L3, L4, L5. 3D Halo orbits are periodic orbits around Lagrange points. Other kinds of periodic orbit around Lagrange Points are Lyapunov orbits which have no z component and also vertical orbits.

Study of Low Energy Transfer (LET) orbit methodologies can be divided into 2 classes: Weak Stability Boundaries (WSB) & Dynamical Systems Theory (DST). WSB solutions tend to have long duration missions. The paper concentrates on DST.



Lagrange points for CRTBP[1]

Credit: Gaur Fig. 4.



Co-Centered Orbital transfer for Jupiter-Ganymede-Europa

Credit: Gaur Fig. 13.

Authors: Deepak Gaur, Mani Shankar Prasad

[1] Circular Restricted Three Body Problem.

Lagrange point typical cases -

System	m1(major mass)	m2(minor mass)	Example occupants of Lagrange point			
			L1	L2	L3	L4 and L5
Earth-Moon	Earth	Moon	possible station?	possible Moon farside relay	?	Kordylewski dust clouds
Sun-Earth	Sun	Earth	Solar and Heliospheric Observatory (SOHO)	ESA Gaia, NASA JWST	?	Unstable asteroids?
Sun-Jupiter	Sun	Jupiter	?	?	?	Trojan asteroids

IAC-20,D4,4,11,x58592	A Feasibility Analysis of Interstellar Ramjet Concepts	Ms. Taavishe Gupta	International Space University (ISU)	France

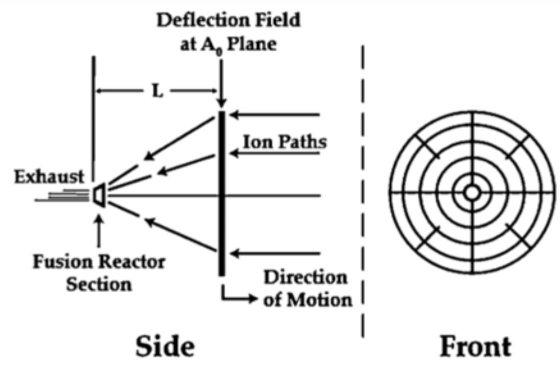
IAF cited paper:
iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/IAC-20,D4,4,11,x58592.pdf
IAF cited presentation video:
iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/presentations/IAC-20,D4,4,11,x58592.show.mp4

Open paper: None found

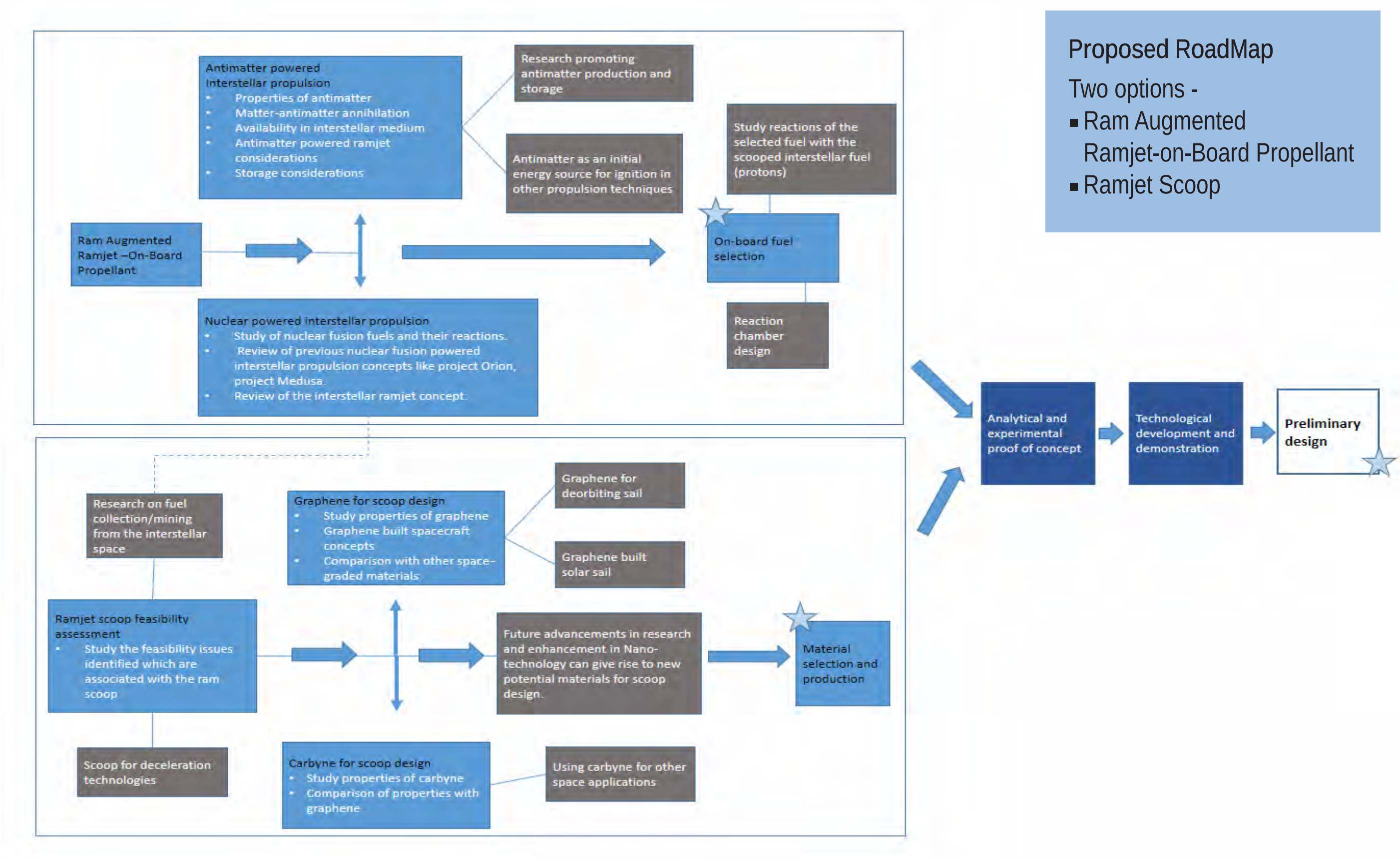
Reported by: Al Jackson

This paper is a comprehensive review of the interstellar ramjet. Robert Bussard's fundamental paper is reviewed. John Ford Fishback's extended analysis of the Bussard ramjet and Daniel Whitmire's solution to the difficult p-p fusion chain with the catalytic ramjet is covered. Variations on the interstellar ramjet are reviewed, the laser powered ramjet and the augmented ramjet. Conditions and properties of the interstellar medium are discussed. A feasibility study of interstellar ramjet concepts is outlined marking out areas of research, identifying capabilities and supporting technologies. A matrix of concept potential vs engineering physics is presented. A roadmap is presented with recommendations for further research. IAC-20,A5,4- D2.8,3,x59291

See also: *The Interstellar Ram Jet at 60*, A A Jackson, Principium | Issue 29 | May 2020 page 42



Schematic diagram of Bussard's ramjet concept
Credit: Gupta Fig. 2 [1]



Authors: Taavishe Guptaa, Andreas M Hein, Chris Welch

[1] Gupta refers to - B.W. Robert, Galactic Matter and Interstellar Flight, Astronautica Acta, Volume 6, 1960, (accessed 10.12.19).
The Bussard paper is available at - large.stanford.edu/courses/2013/ph241/micks1/docs/bussard.pdf

[IAC-20,A5,4-D2.8,3,x59291](https://iafastro.directory/iac/paper/id/59291)			
Assessment of On-Orbit Cryogenic Refueling: Optimal Deport Orbits, Launch Vehicle Mass Savings, and Deep Space Mission Opportunities	Mr. Justin Clark	Ohio State University College of Engineering	USA

IAF cited paper:
iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/manuscripts/IAC-20,A5,4-D2.8,3,x59291.pdf

IAF cited presentation video:
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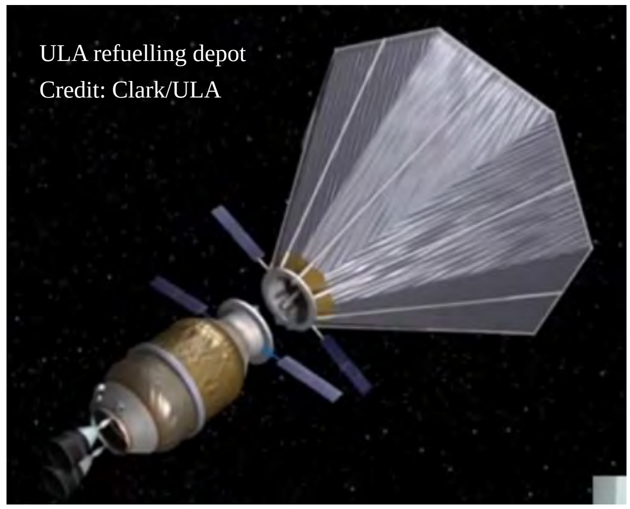
Open paper: None found

Reported by: John Davies

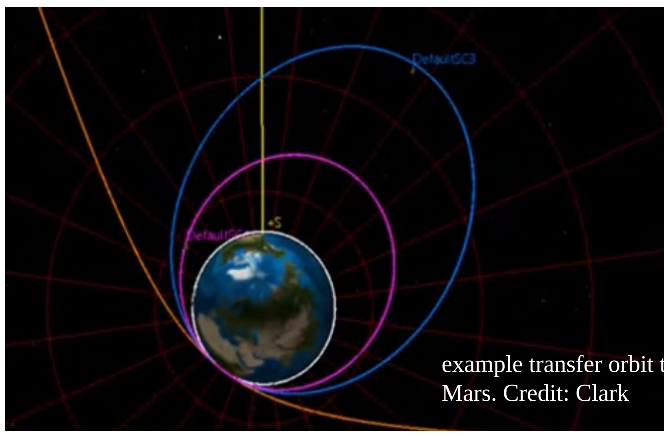
Mr Clark opened his justification for an orbital "gas station" (petrol station in UK) with an appeal to the Tsiolkovsky rocket equation, using the specific impulse formulation [1]-

$$\Delta V = g_0 * I_{sp} * \ln\left(\frac{m_0}{m_f}\right)$$


ULA refuelling depot
Credit: Clark/ULA

Proposals already exist for both - the ULA refuelling depot which is a semi-permanent depot [2] and the SpaceX "Starship" refuelling proposal.

SpaceX "Starship" refuelling proposal. Credit: Clark/SpaceX


example transfer orbit t
Mars. Credit: Clark

Clark introduces some recent developments in technologies to enable refuelling including the NASA Robotic Refuelling Mission 3 (RRM3) to the ISS which demonstrated propellant transfer and a proposed 2023 NASA mission - a semi-permanent depot to explore techniques in transferring propellants (low-G transfer, vented chill & no-vent Fill) and to mitigate boil-off (insulation, cryocoolers). The Ohio State team have a method of optimising the orbit at which refuelling takes place. These allow missions to visit a refuelling station with no DeltaV penalty - these are gas stations on the freeway! They look at all elliptical orbits between an initial low earth orbit (LEO) and the target orbit for the mission, An example is a hyperbolic transfer orbit to Mars. Here the white initial orbit, two possible ellipses and the final Mars transfer orbit shown in orange. The method takes a destination, rocket stage mass ratios, and specific impulses and produces comparisons between optimal refuelling mission masses and a no-refuelling scenario with just one vehicle. The team modelled several scenarios varying launch vehicle stage specific impulses and mass ratios, one vs two stage launch vehicles and utilization of both lunar refuelling with locally produced fuels and of Orbital Transfer Vehicles (OTVs) with electric propulsion. Some examples studied included the NASA Artemis 1 to the Moon (with mass improvement factors around 2), the SpaceX Mars mission (with a wide range of results)

[1] Exhaust velocity, ve=g_o*I_{sp} hence the substitution, Quick dimensional analysis check g_o is the acceleration due to gravity so the dimensions are velocity=acceleration*time so m/sec = m/sec²*sec = m/sec

[2] example www.ulalaunch.com/docs/default-source/exploration/evolving-to-a-depot-based-space-transportation-architecture.pdf

IAC-20,A5,4-D2.8,9,x59363	Nuclear Thermal Propulsion (NTP) Post-Burn Transient: Cool-Down Propellant Consumption and its Effect on Total Delta-v	Mr. Jack Plank	The Ohio State University College of Engineering	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/manuscripts/IAC-20,A5,4-D2.8,9,x59363.pdf

IAF cited presentation video:

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Open paper: None found

Reported by: John Davies

Mr Plank began with the specific impulse equation -

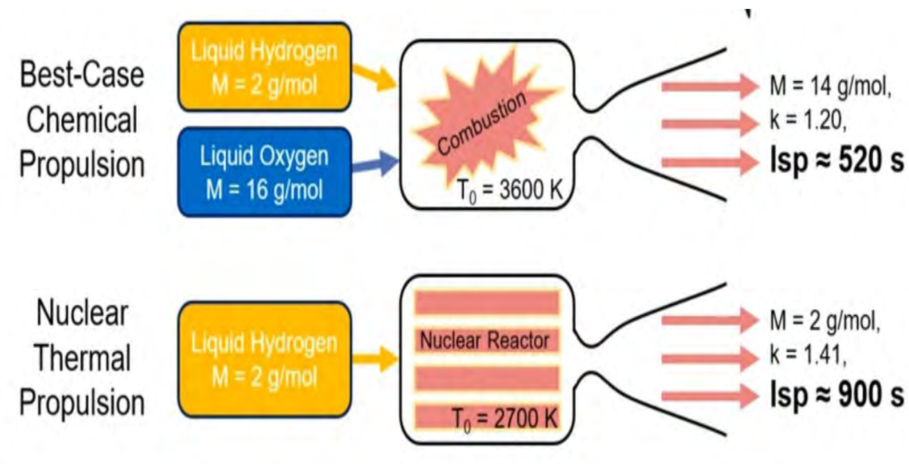
$$I_{sp} = \frac{1}{g_0}\sqrt{\frac{2kR_UT_0}{(k-1)M}}$$

He pointed out that "NTP has much higher Isp than CP without sacrificing thrust, permitting larger, faster deep space missions". In the equation To is chamber temperature, M is molecular weight, properly molecular mass, of the exhaust. For high efficiency we need high To and low M.

Best case chemical propulsion (LOX, LH2) which yields Isp = 520 seconds. The numbers here are about the same as the Space Shuttle main engine[1].

Contrasting specific impulse (Isp) for best case chemical propulsion (LOX, LH2) with Nuclear Thermal Propulsion (NTP)

Credit: Plank



Contrast NTP where the propellant is simply heated by a nuclear reactor [as in the primary coolant in a conventional nuclear power station] so the single propellant is liquid hydrogen, with molecular mass which is 7 times less. So despite the lower chamber temperature the specific impulse, shown by the equation, is much higher [note that specific impulse is directly proportional to exhaust velocity].

Plank is particularly concerned here with decay heat in NTP. The main chain reaction in the reactor produces "daughter" elements. Some of these decay to further elements after reactor shut-down [the same decay heat is what powers the radioisotope thermal generators (RTG) providing electrical power on deep space missions like Voyager and New Horizons]. This typically yields kilowatts and even megawatts of heat for hours after reactor shutdown but the falling chamber temperature results in a lower specific impulse. But the reactor will overheat without the flow through it.

The decay heat problem (credit: Plank) -

- Unstable daughter nuclei continue to decay after shutdown
- Venting LH2 during cool-down stops overheating, generates some thrust
- About 9% of the total LH2 spent during the whole maneuver
- Only 4% of the maneuver's total delta-V (58 m/s out of 1400 m/s)
- Inefficient. T_o drops during cool-down) reducing Isp.

- and in this example the cool down phase is about 10 hours. This uses propellant less efficiently.

[1] www.nasa.gov/returntoflight/system/system_SSME.html, more detail at en.wikipedia.org/wiki/RS-25

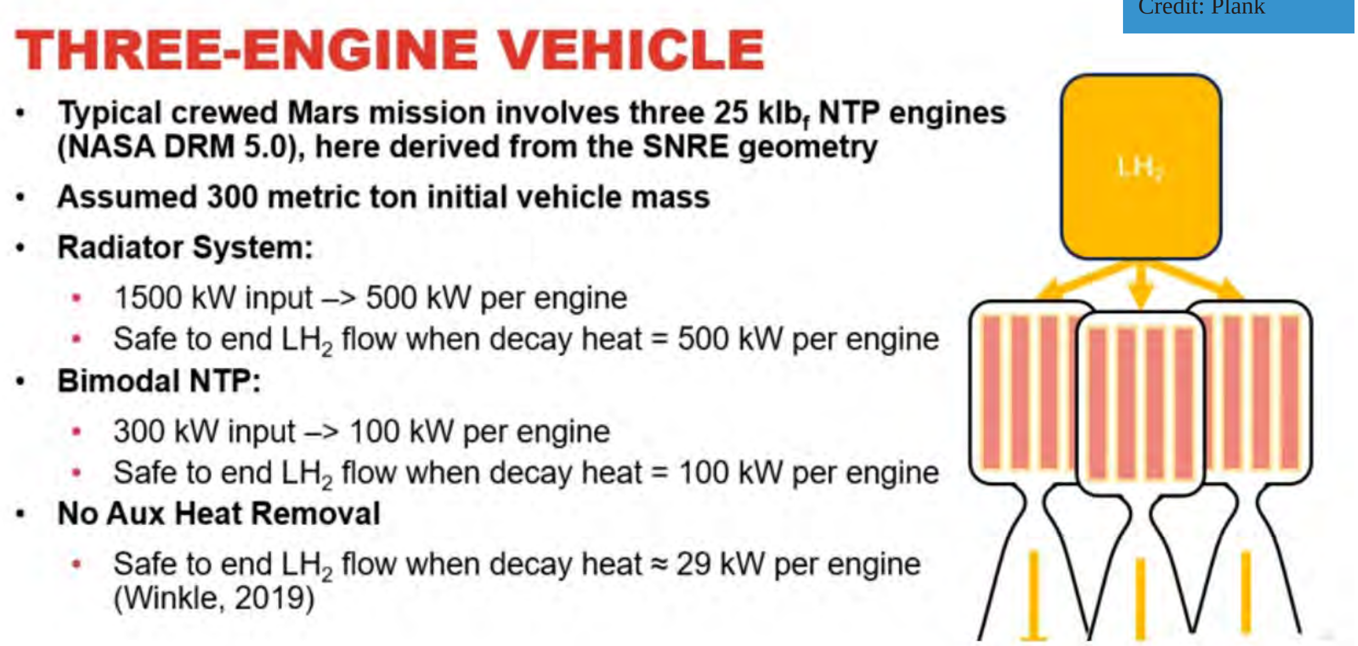
Plank lists some more efficient approaches from the literature on the subject -

- "Bimodal" Nuclear Thermal Propulsion (BNTP) - using, for example, the Brayton cycle to generate electrical power by dropping [throttling down] the reactor to a lower power level. In this case yielding 300 kW thermal and thus 40 kW electrical.
- Using radiator panels, as used by the International Space Station (ISS), to dump 1500 kW into space

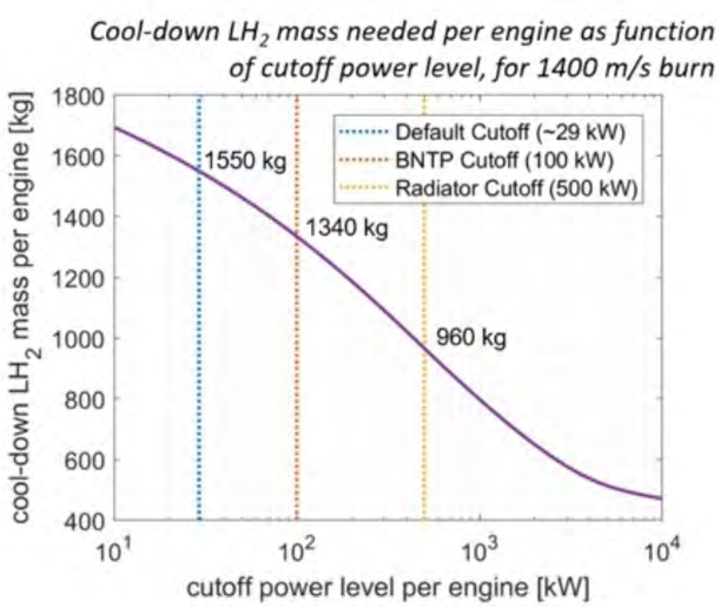
But some LH2 flow to the reactor is still required.

Plank uses a reference vehicle based on the NASA Mars Design Reference Mission (en.wikipedia.org/wiki/Mars_Design_Reference_Mission).

Reference vehicle
Credit: Plank



Plank's detailed calculations are in his paper. They are based on work by Emrich and Durham [2]. These result in the mass of hydrogen required per engine versus the heat being removed (cut-off power) in the three cases - no additional cooling, BNTP and radiators. He shows savings around 1000 kg of propellant mass for this reference case. And he notes that these savings apply every time the reactor is closed down. But there is a tradeoff of course - the heat removal system itself costs mass! He also analyses the benefits of heat removal in terms of propulsion. He suggests that more detailed studies are required, also adding in factors such as system complexity (bad!) and use of radiators for wider thermal control purposes (good!).



Cooldown LH2 mass required
Credit: Plank

[2] W Emrich, Jr., "Principles of Nuclear Rocket Propulsion," Butterworth-Heinemann (2016) and F P Durham, "Nuclear Engine Definition Study Preliminary Report, Volume 11 - Supporting Studies," Los Alamos National Laboratory (1972)

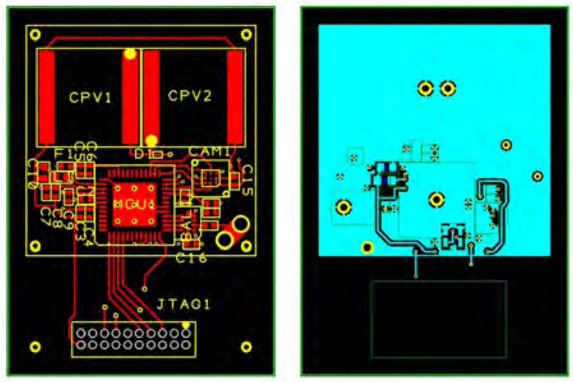
News Feature: i4is Project Glowworm update

Dan Fries and John Davies

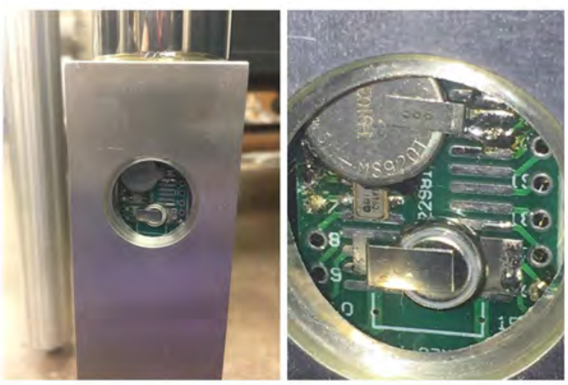
i4is Project Glowworm is a demonstrator of laser-push propulsion in low Earth orbit (LEO). Dan Fries, i4is Deputy Technical Director, and John Davies, Principium editor, report on recent work and related publications.

The i4is Technical Team (see article by Dan Fries elsewhere in this issue) are working towards the target of a LEO demonstrator mission with the objective of raising the orbit (semi-major axis) of a laser sail-equipped chipsat by 10 km. The team has shown that the parent cubesat will need to follow the chipsat to achieve this. Using this technique, simulations show that the laser in the parent cube sat will be sufficient to achieve the required orbit raise.

The group initiated at Drexel University, Philadelphia, and led by David Evynshtein, are working on the chipsat which will carry the sail, Project Pinpoint. They have a prototype design ready for assembly and testing.



Current iteration of Pinpoint electrical schematic,
Credit: i4is Pinpoint team



They have already tested the selected battery and capacitors in high vacuum for 2 months without any notable degradation.

Pinpoint components after extended vacuum testing
Credit: i4is Pinpoint team

A significant paper in the same field describes how a laser sail can be dynamically stable in the propelling beam - *Experimental Verification of a Bigrating Beam Rider*, Ying-Ju Lucy Chu (Rochester Institute of Technology, New York) et al, Physical Review Letters, December 2019 (journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.244302)

Another of the major challenges for an ultra lightweight interstellar probe is to slow down in a target system. i4is Technical Team member Nikolaos Perakis has recently described a technique to permit this - thus increasing observation times and even enabling rendezvous manoeuvres - *Maneuvering through solar wind using magnetic sails*, Nikolaos Perakis, Technical University of Munich, Acta Astronautica, Volume 177, December 2020 (www.sciencedirect.com/science/article/abs/pii/S0094576520304471?via%3Dihub).

About the Authors

Dr Dan Fries is a postdoctoral fellow at the Center for Aeromechanics Research of the University of Texas at Austin. His first degree was from Universität Stuttgart and his PhD from Georgia Tech.

John Davies has been editor of Principium since Issue 9 in 2015.

News Feature: The i4is Technical Team

Dan Fries

If we are to achieve our interstellar objectives then we must research both the universe we wish to explore, and ultimately populate, and the technologies we need to reach first the nearest stars and thence beyond them. This requires major advancements both in scientific knowledge and in engineering innovation and development. This is the purpose of our technical team.

Dr Dan Fries has been at the heart of i4is technical work since our founding in 2012. Here he explains how the technical team works, introduces some of the key contributors and suggests some of the key qualities you will need to contribute to our work.

The technical committee consists of a loose group of people from different career paths and with different levels of engagement at different times. A common denominator is that members usually have some sort of technical or scientific education or career. Age does not play a role and neither does the current status of one's professional career. Everybody is free to make suggestions and pursue topics they find interesting, with the general support of the committee. If other people find a project interesting, they will join in or suggest people outside of i4is that might be interested in helping out. People that are looking for support with their own ideas and project, but are not members of i4is, are also encouraged to contact us and many fruitful collaborations have been established this way in the past. We try to publicize and discuss the technical committee's work through media and in-person events, and usually we mentor at least a couple of students at the International Space University each year, for their Master's projects. On a regular basis we are proposing projects to funding agencies, such as ESA or NASA, with the goal to pursue rigorous scientific and technical studies directed at the establishment of human presence and utilization within our solar system and at interstellar distances.

Recently, we had the privilege to contribute mission architecture ideas to visit the first interstellar objects detected in our solar system (Project Lyra). We have been working hard to push the idea of visiting interstellar objects, when detected in our vicinity, in general, through different technological approaches, and we have been considering new missions to the upper clouds layers of Venus, in the search for potential signs of life.

Other recent projects include reviews for deceleration of interstellar missions, interstellar Bussard ramjets, and the exploration of the design space for near-term self-replicating space probes. A long-term goal of the technical committee has been the realization of laser sail propulsion systems for interstellar missions. One component of such a system could be chip-sized spacecraft, for which we acquired funding and started a collaboration with University students developing such a proof-of-concept ChipSat. Of course, all these efforts would be impossible without the people that actually drive them. An article naming every single person would probably take up the entire Principium issue, so I will put a spotlight on only a few of them, and hope I will be forgiven for such an incomplete list.

Project Lyra: OITS Simulation

Here a proposed ISO interceptor probe has just rounded Jupiter, resulting in a trjectory towards a close encounter with the Sun and an Oberth manourve to overtake 1I/'oumumua.

drive.google.com/file/d/1Pgcdl4kuz7rxSJ30PDkafvohbg2G63P8/view

Credit: Adam Hibberd/i4is

I, myself, recently completed my PhD in Aerospace Engineering at the Georgia Institute of Technology and now work as a Post-Doctoral fellow at the University of Texas at Austin. My research focus is on experimental high-speed, high-temperature flows and I am currently involved in a project to increase the fidelity of plasma simulations combining numerical and experimental results. I am originally from Germany, where I studied at the University of Stuttgart and led multiple project teams tackling space system engineering challenges. I started getting involved with i4is in 2012, initially on a fusion propulsion concept but then shifting to a larger scale project to engage university students in the development of beamed laser sail propulsion system architectures. Since then I have worked on a number of projects including proof-of-concept missions for laser sails, asteroid mining, ChipSat planetary reentry, and exploration of interstellar objects in our solar system. One of the main reasons I have stayed engaged with i4is is that the variety of projects within i4is is enormous and working with knowledgeable people willing to share their knowledge is very enjoyable. It is an entirely volunteer based organization, so seeing people come together to tackle various aspects of interstellar exploration is very inspiring, too. I also enjoy the educational opportunities a lot, where we mentor and work with students at the International Space University or hold lectures on a variety of subjects (eg ChipSat development or propulsion concepts based on the General Theory of Relativity).


Andreas Hein

Andreas Hein is the current i4is executive director and chairman of the Technical Research Committee. He received his PhD at the Technical University of Munich in the area of space systems engineering, focusing on the application of heritage technologies to space systems and doing part of his research at the Massachusetts Institute of Technology (MIT) System Architecture Lab. He also worked at the European Space Agency Strategy and Architecture Office on stakeholder analysis for future crewed space exploration. Currently he is working as an assistant professor of systems engineering at CentraleSupélec – Université Paris-Saclay.


Left to right: Robert Kennedy, Dan Fries, Ariel Ekblaw (Founder of the MIT Space Exploration Initiative)

Robert Kennedy is the president of the Institute for Interstellar Studies, our US organisation. When he is not pouring his heart into i4is, he is currently employed as a senior systems engineer at Tetra Tech. He studied mechanical engineering at California Polytechnic, with emphases in robotics, machine design, and optical physics. Fresh out of school, he designed industrial robotics systems at the Douglas Aircraft Company in Los Angeles, and pursued research in artificial intelligence at Oak Ridge National Laboratory. Robert's interests go far beyond the purely technical and he is a published commercial artist and author (nonfiction). He has written about space-based solar power, shell worlds, climate change, linguistics, energy parks, biofuels, and energy security. He also was a technical consultant on the movie "Deep Impact".


Adam Hibberd

Another essential member of the Tech Committee is Adam Hibberd. Adam lived in the East African country of Tanzania, where his father worked at the University of Dar Es Salaam, up to the age of four. The family then returned to the UK and Adam attended the University of Keele, gaining a joint honours degree in physics and mathematics. In the '90s, he worked as a software engineer on the on-board flight program for the European Ariane 4 launch vehicle; including the production, maintenance, real-time testing and post-flight analysis, his expertise being the guidance algorithm. He developed his Optimum Interplanetary Trajectory Software (OITS) in 2017 as a personal challenge to learn the MATLAB programming environment and language, then using it to investigate missions to the first known interstellar object, 1I/'Oumuamua. He contacted i4is with his results and his involvement with i4is started from there. His work on missions to interstellar objects has been published in Acta Astronautica and he has worked on two other papers on similar subjects since then.

Nikolaos Perakis is currently working towards his PhD at the Chair of Turbomachinery and Flight Propulsion of the Technical University of Munich, focusing on the combustion modeling of green propellants for space propulsion applications and specifically the combination of methane and oxygen. His involvement with interstellar travel began within Project Icarus (follow-up study to Project Daedalus) and continued with i4is' Dragonfly Project (Lasersails). His work on the Dragonfly project resulted in a novel method of combining magnetic and electric sails for deceleration in interstellar missions.

Nikolaos Perakis

Olivia Borgue is a PhD student at Chalmers University in Sweden in the division of Product Development. She is working on the introduction of new technologies in already established industries aimed at promoting innovation. For example, the introduction of additive manufacturing in the space industry. Recently, she led a project to explore the design space of self-replicating space probes and come up with a minimum feasible design.

Olivia Borgue

Marshall Eubanks

Marshall Eubanks has been instrumental in many i4is proposals and research papers. He is a physicist with extensive experience in experimental General Relativity, geophysics and planetary physics, and radio interferometry. A graduate student under Professor Irwin Shapiro at MIT, Marshall was the technical lead of Very Long Baseline Interferometry programs at both the Jet Propulsion Laboratory and the U.S. Naval Observatory, creating measurement systems essential for navigation of spacecraft and the operation of the Global Positioning System satellites. In 2018, he co-founded Space Initiatives Inc and is currently Chief Scientist there, where he has been working on low cost communication, positioning and instrumental arrays on the Moon, and also on the problems of exploring Interstellar Objects passing through the Solar System. He is also a member of the "Roadmap to Ocean Worlds" committee, which is advising NASA on its new initiative to search for life in the ice-covered oceans being found in the outer Solar System.

Manasvi Lingam

Manasvi Lingam is an Assistant Professor of Astrobiology, Aerospace, Physics and Space Sciences at the Florida Institute of Technology. Coming from Mumbai, India, he obtained his PhD at the University of Texas at Austin. Afterwards, he undertook postdoctoral stints at Princeton University, Harvard University and the Harvard-Smithsonian Center for Astrophysics. His current research interests are situated mostly within plasma physics and astrobiology. This includes exploring the multiple factors that regulate the habitability of planets and identifying potential signatures of extraterrestrial life. Manasvi has worked with the i4is technical team on a number of projects.

Angelo Genovese received a Master's Degree in Aerospace Engineering (specialising in Space Propulsion) at the University of Pisa, Italy, in 1992. He started to work as Electric Propulsion Engineer in the Italian space propulsion research centre "Centrospazio" in Pisa, developing Field Emission Electric Propulsion (FEEP) ion thrusters for ultra-precise positioning of scientific spacecraft. In 2000 he contributed to the development of an Indium FEEP micro-propulsion system for the ESA mission LISA Pathfinder. Within i4is, Angelo has made many valuable contributions relating to electric propulsion development and laser sail experiments.

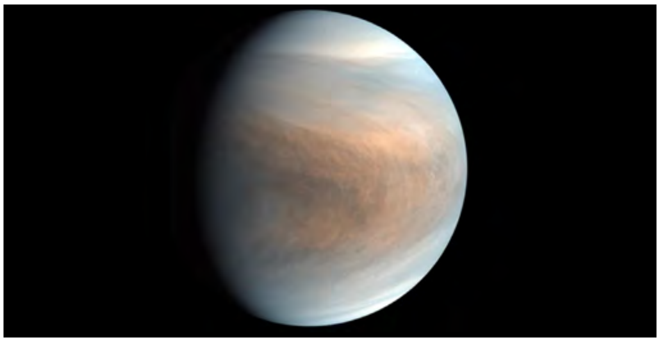
Angelo Genovese

News Feature: Hints of life on Venus

John I Davies

On the 14th of September 2020, the world was briefly distracted from its many present troubles by an announcement from the Royal Astronomical Society, *Hints of life on Venus* (ras.ac.uk/news-and-press/news/hints-life-venus). Subsequent analysis has questioned the discovery of the spectroscopic signature of molecule Phospine, chemical formula PH_3 (en.wikipedia.org/wiki/Phosphine). The problem remains unresolved and in situ examination might be the best way of solving the mystery.

Here John Davies summarises the research and the response by i4is and others.



Synthesized false colour image of Venus, using 283-nm and 365-nm band images taken by the Venus Ultraviolet Imager (UVI). JAXA / ISAS / Akatsuki Project Team

Source: CBS News

See also www.cbsnews.com/video/venus-potential-life-discovered-on-planet

Discovery

Two major classes of chemical process are known to produce phosphine elsewhere in the Solar system. One is the highly energetic convective storms found in the atmospheres of gas giants such as Jupiter and the other is from living processes on Earth. So have we found a biosignature on Venus?

The paper in Nature Astronomy is -

Greaves, JS, Richards, AMS, Bains, W et al. Phosphine gas in the cloud decks of Venus. Nature Astronomy (2020). doi.org/10.1038/s41550-020-1174-4. (Received 07 February 2020). The paper is available at -

www.nature.com/articles/s41550-020-1174-4.pdf.

The James Clerk Maxwell Telescope. Credit: Cambridge University

The lead author is Jane S Greaves, of the universities of Cardiff and Cambridge, UK. Other authors are from Jodrell Bank, MIT, Cambridge University, Kyoto Sangyo University, Imperial College London, Cardiff University, The UK Open University and East Asian Observatory Hawaii. They used two instruments, the James Clerk Maxwell Telescope (JCMT) in Hawaii and the Atacama Large Millimetre/submillimetre Array (ALMA) in Chile. It's worth quoting from the paper -

> If no known chemical process can explain PH_3 within the upper atmosphere of Venus, then it must be produced by a process not previously considered plausible for Venusian conditions. This could be unknown photochemistry or geochemistry, or possibly life.

- but it also says -

> Information is lacking—as an example, the photochemistry of Venusian cloud droplets is almost completely unknown. Hence a possible droplet-phase photochemical source for PH_3 must be considered (even though PH_3 is oxidized by sulfuric acid).

ALMA
on the Chajnantor Plateau with Large and Small Magellanic Clouds, Credit: ESO /Malin

So the researchers themselves are cautious about the possible biosignature.

Our interstellar colleague, Paul Gilster, was on the ball as usual. His indispensable Centauri Dreams blog published *What Phosphine Means on Venus* (www.centauri-dreams.org/2020/09/15/what-phosphine-means-on-venus/) on 15 September, gathering comments and related work. He also flagged another paper *Phosphine on Venus Cannot be Explained by Conventional Processes* (arxiv.org/abs/2009.06499) dated 15 September, by a team having a clear overlap with paper by Greaves et al.

Support and Doubts

Reactions to the Greaves et al paper have ranged from support to scepticism. A couple of examples -

Mogul (Cal Poly Pomona, USA) et al conclude "...that LMNS data support the presence of phosphine; although, the origins of phosphine remain unknown" [1].

Villanueva et al (Caltech) express doubts: "We here demonstrate that the observed PH3 feature with JCMT can be fully explained employing plausible mesospheric SO2 abundances (~100 ppbv as per the SO2 profile given in their figure 9), while the identification of PH3 in the ALMA data should be considered invalid due to severe baseline calibration issues." thus "We ultimately conclude that this detection of PH3 in the atmosphere of Venus is not supported by our analysis of the data" [2].

Missions

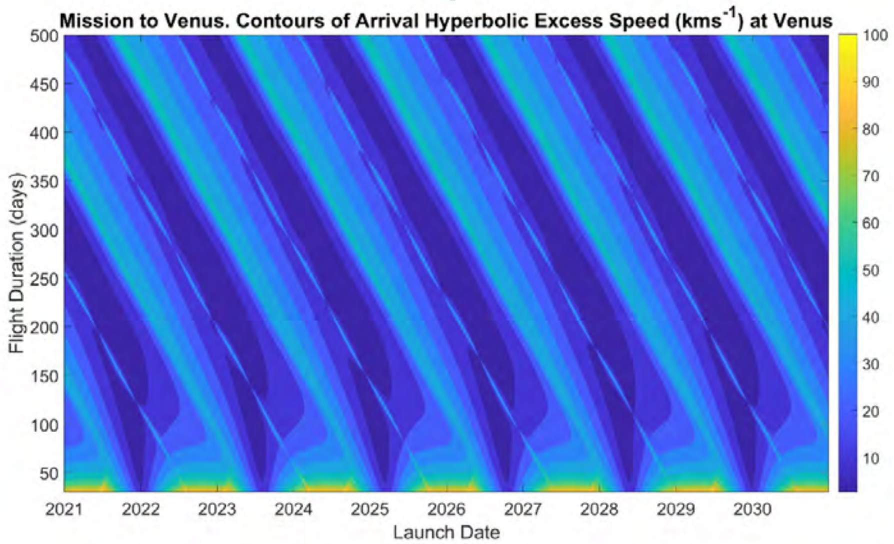
The original Greaves et al paper suggests "Ultimately, a solution could come from revisiting Venus for in situ measurements or aerosol return."

The i4is technical team have a worldwide reputation for timely mission studies, starting with the three-day Andromeda study delivered to Breakthrough Starshot in March 2016 [3]. And the first Project Lyra study in November 2017, only a month after the discovery of the first interstellar object (ISO), subsequently named 1I/'Oumuamua.

When Professor Greaves and her colleagues announced what might turn out to be the first life beyond our planet the i4is technical team responded quickly. The result is Hein et al, *A Precursor Balloon Mission for Venusian Astrobiology* which was published as a preprint on 24 September (arxiv.org/abs/2009.11826), ten days after the Greaves et al paper was published. The i4is team propose a precursor astrobiological mission to search for life forms in situ with instrument balloons floating in the Venusian cloud deck. This could be delivered to Venus via launch opportunities in 2022-2023. The mission would collect aerosol and dust samples by means of small balloons and would -

- directly scrutinize whether they include any apparent biological materials and, if so, their shapes, sizes, and motility.
- Use a miniature mass spectrometer to permit the detection of complex organic molecules.
- Contextual cameras to search for macroscopic signatures of life in the Venusian atmospheric habitable zone.

Formal publication was on 9 November 2020 in The Astrophysical Journal Letters [4].



Porkchop plots (en.wikipedia.org/wiki/Porkchop_plot) for encounter velocities at Venus from Earth in km/sec. An ideal mission would have both a short transfer time and low entry velocity. As the plot shows, such missions are possible every synodic period (~584 days) with the next such launch opportunity arising at the end of 2021.

Credit: Hein, Hibberd et al, Figure 2.

The plot was generated via Hibberd's Optimum Interplanetary TrajectorySoftware (OITS) (github.com/AdamHibberd/OptimumInterplanetaryTrajectory). More details in the paper.

[1] *Is Phosphine in the Mass Spectra from Venus' Clouds?*, Rakesh Mogul, Sanjay S Limaye, MJ Way, Jamie A Cordova Jr, arxiv.org/abs/2009.12758, LMNS is Large Probe Neutral Mass Spectrometer.

[2] *No phosphine in the atmosphere of Venus*, Geronimo Villanueva and 26 others, authors.library.caltech.edu/106365/s.

[3] i4is.org/what-we-do/technical/andromeda-probe/ and arxiv.org/ftp/arxiv/papers/1708/1708.03556.pdfs.

[4] *A Precursor Balloon Mission for Venusian Astrobiology*, Andreas M Hein, Manasvi Lingam, T Marshall Eubanks, Adam Hibberd, Dan Fries and William Paul Blase, Published 2020 November 9. The Astrophysical Journal Letters, Volume 903, Number 2, The American Astronomical Society, The Institute of Physics.

Amongst others, Forbes magazine noticed our proposal: *Proposed Venus Balloon Mission Could Detect Life By 2022* (www.forbes.com/sites/brucedorminey/2020/09/28/low-cost-privately-funded-balloon-mission-could-scope-out-venus-life-by-2022) interviewing both i4is Technical Director Dr Andreas Hein and Prof Manasvi Lingam (Florida Tech and Harvard).

Also in the wake of the Greaves et al paper the Venus flybys of BepiColombo enroute to Mercury last month and next year (sci.esa.int/web/bepicolombo/-/bepicolombo-flies-by-venus-en-route-to-mercury) may yield some clues.

Other new missions to Venus are under consideration including Breakthrough Initiatives funding a study led by Professor Sara Seager of MIT, who was one of the authors of the Greaves et al paper (breakthroughinitiatives.org/news/31).

Venus has recently been of wider astronautical interest with earlier proposals such as ESAs EnVision radar mapping orbiter (www.esa.int/ESA_Multimedia/Images/2019/03/EnVision_mission_concept) and NASA's Seismic and Atmospheric Exploration of Venus (SAEVe) lander (ntrs.nasa.gov/citations/20190001916).

Conclusion

Why does i4is take an interest in Venus? In our quest for interstellar exploration and ultimately, settlement, i4is is interested in many related fields. The search for extraterrestrial life in the solar system, if successful, supports the possibility of life beyond the solar system. The i4is Project Lyra studies were first prompted by the discovery of the first interstellar objects (ISOs) in the solar system and happily brought together a team capable of rapid mission planning. The paper *A Precursor Balloon Mission for Venusian Astrobiology* is the result of the convergence of these two.

Onward and upward!

Visualisation of balloons with payload near the Venusian cloud decks.
Credit: Adrian Mann.

The i4is Members Page

The i4is membership scheme launched in December 2018 and we are now adding new members-only material to the website regularly. This page features currently available content and what is planned. Membership of i4is draws together all who aspire to an interstellar future for humanity. Your contribution, together with the voluntary work of our team and their donation of their own expenses, helps us to take the vital early steps toward that goal.

You need to login with your i4is identity to access members' content. If you are not yet a member you can sign up via - i4is.org/membership - or simply find out more about membership. We'll keep you up to date as we add to this content, both in the next issue of Principium and in our members' email newsletter.

Members' Newsletter

Members have received 11 Newsletters so far this year-

- Newsletter: i4is online talk this Tuesday plus more member content! 8/11/20
- Newsletter: New i4is online talk series for members! 18/10/20
- Newsletter: 2023-2032 Planetary Science and Astrobiology Decadal Survey & five new preprints 20/08/2020
- Newsletter: New videos & Technical Team updates 28/07/2020
- Newsletter: Opportunities to Get Involved, and Limitless Space Institute student competition. 07/06/2020
- Newsletter: Videos from our ISU module now available 28/05/2020
- Newsletter: Share a One Year Free Trial with a friend, and much more... 06/05/2020
- Newsletter: i4is Annual Report, mini-research projects and more.. 01/04/2020
- Newsletter: Opportunities to Get Involved + more preprints 28/02/2020
- Newsletter: Could electric sails be better than light sails? + Membership Survey 02/02/2020
- Happy New Year from the Initiative for Interstellar Studies 03/01/2020

Help our Education and Outreach Activities

i4is volunteers talk to students from primary school to postgraduate and to scientific professional and cultural organisations. Members who would like to join the Education and Outreach team can access our materials and advice. Contact us via our universal address info@i4is.org. Some examples of events we can deliver and you can help with -

- To the Stars in Two Equations - a workshop to take school students on a journey from the fundamental equations underpinning all space travel, to the current research projects exploring interstellar travel.
- The Interstellar Challenge - a competition for secondary/high school teams setting a series of problems ranging from maths, via physics and engineering, to biology, economics, sociology, creative writing and art. All focussed on how we can reach the stars.
- Skateboards to Starships - an intensive day of workshops from i4is researchers aimed at secondary students. Using the work of three great thinkers; Al- Karismi, Newton and Tsiolkovsky, students learn to apply mathematical equations to the world around them. They will build up their skills from working out how fast a skateboard travels, to how long it will take to fly to distant stars.

And individual talks on i4is projects including Lyra and Glowworm. Whether you want to deliver them yourself or facilitate delivery by the team there are things to do. We already deliver from Vietnam to Georgia, USA, and from Edinburgh to southern Nigeria but we would like to go further.

Help us to do more and better!

Help us to grow!

Tell your friends and colleagues. Share a One Year Free Trial with a friend if you have been a member for at least one year (see your personalised link in your 6 May Newsletter).

And our student discount is now 90%!

Our latest revised posters are in this issue on pages 4 (student, white background), 26 (general, black), 42 (general white) and 66 (student white 66). Print one out and post it prominently!

Become an i4is member

John I Davies

How becoming a member of i4is helps our work and delivers exclusive benefits to you

We are a growing community of enthusiasts who are passionate about taking the first steps on the path toward interstellar travel now. But we appreciate that not everyone who shares our interstellar vision has the time or resources to do this. The best way to support the mission of i4is is to become a subscribing member. You will be directly supporting the interstellar programme. If you do wish to, and have the time, we would of course love you to get actively involved with our projects.

Interstellar Studies has growing visibility in peer-reviewed journals including the Journal of the British Interplanetary Society (JBIS) and Acta Astronautica (see Interstellar News in this issue) but the wider public is increasingly interested in both exploring the Solar System and expanding into the Galaxy.

In addition to supporting our work, our members receive privileges including -

• early access to select Principium articles before public release;

• member exclusive email newsletters featuring significant interstellar news;

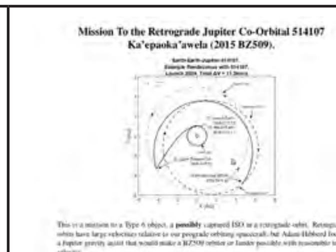
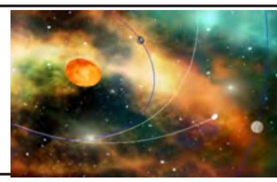
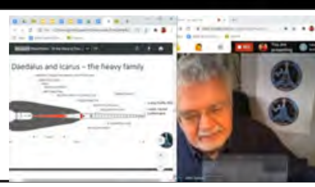
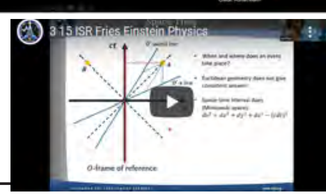
• access to our growing catalogue of videos;

• participatation in livestreams of i4is events and activities;

• publication of our annual report.

New videos

Just a few of those we have added to the website since our last issue-

Talk Series: Marshall Eubanks: Missions to Interstellar Objects - An i4is Initiative			
John Davies: Interstellar Objects — 'Oumuamua, Borisov and Objects in Between- Loughton Astronomical Society, UK			
To the Stars in Two Equations — Barrow Arts & Sciences Academy (8th grade), Winder, GA, USA			
ISU Interstellar Studies Module - 13 videos			
			

To see the other benefits of membership, or to join, go to i4is.org/membership.

News Feature: Breakthrough Starshot Communications Workshop - May 2020

Summary and i4is contributions

Reported by Robert G Kennedy III and the i4is team

The Starshot Communications Workshop in May 2020 included Robert Kennedy, Robert Swinney, Dr Andreas Hein, Eric Hughes and Marshall Eubanks (Space Initiatives Inc). In this article Robert summarises the workshop and i4is contributions - with inputs from other team members.

See elsewhere in the issue for *The Interstellar Downlink - Principles and Current Work*. John Davies introduces the downlink problem and reviews the current status of the subject.

Introduction

Last year, on 11-12 April 2019, i4is sent an international team (Andreas Hein, Kelvin Long, Nikolas Perakis, Robert Kennedy; Marshall Eubanks could not attend) to Berkeley, California to participate in Breakthrough Discuss, which is part of Breakthrough Starshot. Because the Breakthrough Initiatives are funded by a Russian, the big springtime events always coincide with Yuri's Night on 12 April every year. The story about that wonderful event can be found in Principium 25, beginning p.13.

As an outgrowth of that participation, plus our own exploratory work on the challenge of interstellar communications, i4is was formally invited to participate in Starshot Communications Workshop this year. The organizers state-

> "The Starshot program envisions and intends to demonstrate proof of concept and technological capability for ultra-fast light-driven nanocrafts [sic], and lay the foundations for a first launch to the nearest star systems, within the next generation. One of the main challenges for this program is to send data back from distances of several light years, given the extreme constraints on size, volume, mass, and power. The aim of the workshop is to set out and discuss the parameters of the communications challenge, and propose system concepts, and the associated technology research and developments required."

Just a few of the major challenges are:

- A propagation distance back to Earth that is four orders of magnitude greater than the outer planets in our system.
- Severe mass limitation on the probe in order that it be accelerated to relativistic speeds by the beamer.
- Attitude control of the probe for purposes of scientific observations and pointing of an antenna or aperture to Earth.

This time the i4is contingent included Andreas Hein, Rob Swinney, Marshall Eubanks, Eric Hughes, and Your Humble Narrator (Robert Kennedy). Originally planned as a two-day in-person meeting, like every other thing on Earth, it got converted to a virtual event due to the COVID-19 pandemic and postponed to a new date, also historic: 8-9 May, the 75th anniversary of VE Day and Den Pobeda (Victory Day) in Russia. Its formal title was: "Breakthrough Starshot's first (virtual) workshop on Communications/Downlink for Low Mass Interstellar Probes".

Approximately 75 people from all over the world tuned in via Zoom to the first day's program, a five-hour series of introductions and presentations by Breakthrough's volunteer scientists on the overall communications problem. This included a briefing on what would be the approach to the following day's program, the actual workshop, which was subdivided into eight breakout groups, also five hours long.

Group 1 – Physical basis of communication

Group 2 – Transmitter optics (including opportunities for light sail/comms integration)

Group 3 – Probe transmitter signal generation (including, eg laser technology)

Group 4 – Receiver optics (including opportunities for beamer/comms integration)

Group 5 – Receiver optical detection

Group 6 – Receiver noise sources and mitigation

Group 7 – Transport layer options

Group 8 – Accommodating and exploiting multiple probes

Approximately half of the attendees on the first day showed up for the second day, including all of the i4is team. During online pre-registration, people had generally been allowed to pick which breakout group they would join, but in a few cases the organizers overruled that and made their own assignments to ensure an even spread of minds. For i4is, the assignments turned out to be strangely fortunate and productive. Eric Hughes participated in Group 1 led by JPL's Slava Turyshev; Marshall Eubanks in Group 4 led by Jeff Kuhn of the Institute for Astronomy at University of Hawaii; Andreas, Rob, and Robert all ended up in Group 8, led by Danny Jacobs of Arizona State University. Other than Danny Jacobs the lead, Group 8 was composed entirely of i4is members! The other registrants didn't show up. But in this case, "less was more". After a morning of brainstorming that can only be described as exhilarating, the entire crowd reconvened for the final hour, during which each lead got 5-10 minutes to summarize their group's results.

In the course of this cooperative effort, we all came to appreciate much more the challenges of Breakthrough Starshot. But the learning went both ways. Five of the eight groups independently came to the same conclusion: that the only hope of successful communication at such range with such small spacecraft was to launch a multiplicity of probes working in parallel. This was, as I understand it, outside the ground rules—nevertheless that was the collective judgement. Fascinating.

The Group topics

The Starshot Communications Workshop Summary, sent to all participants, summarised the group topics for the workshop see the table on the next page.

Eric Hughes observations on Group 1 - Physical basis of communication

The most notable takeaways/realizations of Group 1 (Physical Basis of Communication) Breakout Session on Saturday May 9 were that:

(1) If you can beam a probe in one direction, you can beam an SGL (solar gravitational lens) receiver in the other.

(2) That relay communications subdivided into N segments can be N times as efficient, just on the basis of transmitted and received power. For a twenty-year campaign and weekly launches, N ~1000. (For hourly launches, see VIII below, N would be ~100,000).

Equally spaced probes relaying data back. If no velocity differences are imposed, the average distance would be 2 to 3 AU. Using a combination of initial velocity tuning, timing, and navigation control, closer approaches could be arranged.

Credit: from Jacobs et al, Starshot Interconnect Report (Starshot Communications Workshop Report from Interconnect Focus Group, Daniel Jacobs, Andreas M Hein, Robert Swinney and Robert Kennedy) not yet published

Robert Kennedy's observations on Group 8 - Accommodating and exploiting multiple probes

The most significant takeaway from Group 8's collaboration was that a chain (or "bucket brigade" in the words of the lead, Danny Jacobs) of relatively closely-spaced probes was the only feasible way (with known science and foreseeable engineering) to provide communication link between here and another star. "Closely spaced" in this context means an inter-probe separation of order 2-3 astronomical units. This in turns means a continuous firing tempo by the launch laser, say every other hour, boosting circa 100,000 probes to their 0.2c cruise velocity over 20 years. (Even so, the unit price per probe is still dominated by the launch energy.) Furthermore, by "modulating" (Andreas's word) the initial launch velocity of each probe, Robert and Andreas argued that it would be possible to arrange massive albeit temporary clusters of probes to form precisely at the time of encounter with the target star. In artillery this is called "time on target, ToT".

Network geometry formation example by adjusting launch velocity and launch time.
Credit: Jacobs et al, Starshot Interconnect Report cited above

The clusters in turn permit the basis for parallel networks with large virtual apertures as developed by Marshall Eubanks in our proposal to NIAC two years ago. Finally, modulated the launch velocity allowing some probes to overtake other probes enroute provides redundancy and resilience along the entire chain from the homeworld to the target star so that the continuity is maintained (to whatever factor of safety is defined by the architects) despite the inevitable loss of individual probes.

Eric Hughes also comments on Group 8 "It's a very different vision than what was first proposed by Breakthrough four years ago. However five different groups independently arrived at similar conclusions, which speaks powerfully to the validity of the idea"*.

What happened next - Robert Kennedy reports

The work didn't end there. In the following two weeks, all the groups put their thoughts down on paper and fleshed them out in Summary Reports. For Group 8, this meant writing a proper paper consistent with the format of Astrophysical Journal (known as "ApJ"). For Your Humble Narrator this involved dusting off some very old rusty skills in text processing-typesetting, a distant cousin to LaTeX. The Summary Reports were all finished and uploaded to Breakthrough by May 26.

The draft report was issued to the participants for review and comment earlier this month. The final report is expected to be posted as soon as next month. The work in this report, mostly by volunteers, will inform the first series of Requests for Proposal for Communications to be let hopefully later this year.

i4is participation in Breakthrough has been highly favorable, in terms of improving our working knowledge, building new relationships and partnerships, and raising the field's awareness of us. It has also beneficially influenced the White Papers that we are writing for the Decadal Survey.

* The paper "Relaying Swarms of Low-Mass Interstellar Probes", Messerschmitt et al (see reference 8 in *The Interstellar Downlink Principles and Current Work* elsehere in this issue, will be the subject of a review paper in a later issue of Principium.

Save the Date!
IRG
7th Interstellar
Symposium
September 24-27, 2021
Tucson Marriott University Park
Tucson, Arizona
IRG

News Feature: The 2020 ISU Masters Elective Module Part 2 of 2

John I Davies

This year the i4is team again led an Elective Module on Interstellar Studies for students of the Master of Space Studies at the International Space University Strasbourg. Here we summarise the rest of the presentations by the i4is team which preceded them.

The current situation meant that this was all conducted online. We missed the personal element of being in Strasbourg with students and faculty at the ISU and we hope to be back in person next year.

The i4is Interstellar Studies Elective Module was run 'virtually' for the two weeks 27th April to 7th May. 23 students took part, we delivered 17 lectures and the four student teams each submitted a report.

The theme this year was Worldships and their implications.

The Lectures

This is a brief summary of the rest of the lectures which introduced the two-week elective. The presentations and videos are available in the member's area of the i4is website at - i4is.org/videos/isu-interstellar-studies-module/. The videos are at - i4is.org/videos/isu-interstellar-studies-module- and presentations are linked from the section headings - marked **IMPRESS**

Lecture	Reported
M8-ISR-L01 Introduction to Interstellar Studies Elective	Principium 30 (last issue)
M8-ISR-L02 Background to Interstellar Studies and Scaling the Problem	Principium 30 (last issue)
M8-ISR-L03 Introduction to Worldships	Principium 30 (last issue)
M8-ISR-L04 Introduction to Assignment	Principium 30 (last issue)
M8-ISR-L05 Precursor Missions	Principium 30 (last issue)
M8-ISR-L06 Destinations	Principium 30 (last issue)
M8-ISR-L07 Spacecraft Systems	Principium 30 (last issue)
M8-ISR-L08 Worldship Conceptual Design	Principium 30 (last issue)
M8-ISR-L09 Artificial Intelligence for Worldships	Principium 31 (this issue)
M8-ISR-L10 Worldships in Science Fiction	Principium 31 (this issue)
M8-ISR-L11 Advanced Propulsion Systems 1	Principium 31 (this issue)
M8-ISR-L12 Advanced Propulsion Systems 2	Principium 31 (this issue)
M8-ISR-L13 Artificial Intelligence on Worldship Missions	Principium 31 (this issue)
M8-ISR-L14 Worldship Population Dynamics	Principium 31 (this issue)
M8-ISR-L15 Interstellar Travel using Einstein Physics	Principium 31 (this issue)
M8-ISR-L16 Worldship Documentary	Principium 31 (this issue)
M8-ISR-L17 The Case for Interstellar	Principium 31 (this issue)

2.9 M8-ISR-L09 Artificial Intelligence for Worldships **VIDEO IMPRESS**

John Davies introduced the first of two presentations on AI applied to worldships. He began with a three minute video dramatisation by Holly Spence[1] raising questions which will arise if and when we create artificial intelligences sophisticated enough to be arguably human.

John asked why we should apply AI to interstellar and pointed to spacecraft become increasingly “intelligent" (however defined) and to the greater need for autonomy as spacecraft go further from humans. But given "good enough" AI, need humans go at all?

However if we want to send biological humans then unless FTL can be achieved then we will need worldships. He quoted from a 2016 paper by Andreas Hein "Given current levels of increase in computational power …a payload with a similar computational power as the human brain would have a mass of hundreds to dozens of tons in a 2050 –2060 timeframe" [2] but asked - What is Artificial General Intelligence (AGI)? Current AI is designed for specific purposes such as analysis of medical imaging, driving a car or playing games. AGI implies a capability for learning a variety of skills rather than for accomplishing particular tasks.

Views differ as to the need for AGI for interstellar missions. An early proponent Arthur C Clarke said "Creatures of flesh and blood such as ourselves can explore space and win control over infinitesimal fractions of it. But only creatures of metal and plastic can ever really conquer it, as indeed they have already started to do. The tiny brains of our Mariners and Pioneers barely hint at the mechanical intelligences that will one day be launched at the stars.“ [3]. An early sceptic was Ada Lovelace - "The Analytical Engine has no pretensions whatever to originate anything. Its province is to assist us in making available what we are already acquainted with." [4].

John cited a number of investigations by Andreas Hein, including a detailed study jointly with Stephen Baxter[5] and some wider sources on subjects including AI implications of Fermi’s Paradox, space colonisation and brain simulation. What sort of AGI is achievable? "Mind uploading" as in the film Transcendence (directed by Wally Pfister, 2014) has been much discussed (and much dismissed!). More plausibly an AGI might arise out of advances in machine learning.

[1] Based on Overture from the 2500s from the article - Sending ourselves to the stars? in Principium issue 12, February 2016 (video: i4is.org/videos/sending-ourselves-to-the-stars).

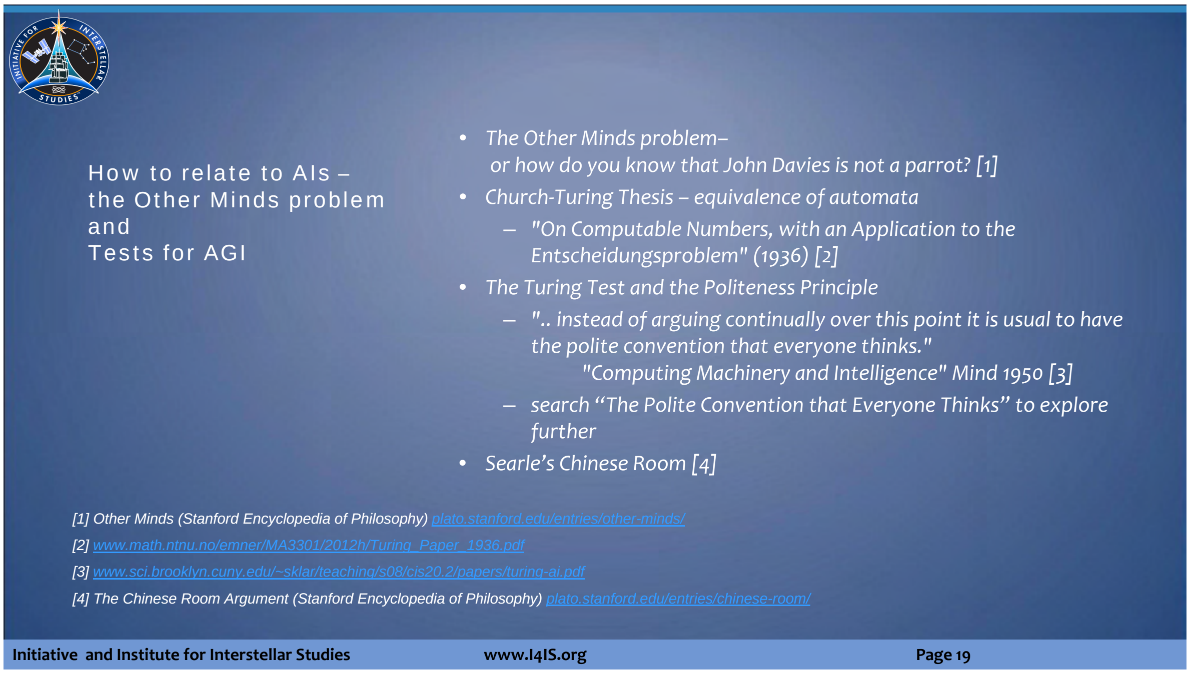
[2] Artificial Intelligence Probes for Interstellar Exploration and Colonization, arxiv.org/abs/1612.08733.

[3] In "The Obsolescence of Man" in the book "Profiles of the Future: An Inquiry into the Limits of the Possible", Gollancz, 1962.

[4] Notes on a translation of "Sketch of the Analytical Engine invented by Charles Babbage Esq" By L F Menabrea, of Turin, Officer of the Military Engineers, 1842 scan: repository.ou.edu/uuid/6235e086-c11a-56f6-b50d-1b1f5aaa3f5e text: pdfs.semanticscholar.org/b61b/9248dfd112b282e116c7bfaa21a681d2ecad.pdf.

[5] Artificial Intelligence for Interstellar Travel, Andreas M Hein & Stephen Baxter, JBIS v72 April 2019 arxiv.org/abs/1811.06526.

Whichever route is taken how are we to regard these apparent peers to biological humans? John introduced the long established philosophical issue, the Other Minds problem[1].



In any case Hein's conclusion in his 2016 paper cited above is that AGI will likely require very massive craft, not the chipsat-sized probes implied by early laser propulsion.

John next considered what worldship configurations might we expect and how AI and/or AGI could contribute to their mission. Citing a paper given by philosopher James Schwartz at TVIW 2017, Worldship Ethics 101: The Shipborn [2], we need to make life en route as desirable as possible, learning from successful and unsuccessful human settlements in the Solar System but he noted that we don't yet know the fate of liberal democratic governance beyond Earth (or even on Earth given recent history!). But might AI or AGI assist the worldship travellers with problems which happen too fast (eg projectiles can easily be dealt with but sabotage would be much harder), are too complicated (eg ethical dilemma such as a food shortage are much harder), too unknown (eg pathogens, political instability or loss of key skills) or pure Black Swan events (imagine your own!)

How can AI/AGI help with planning for worldships? Clearly we first need to simply "run the numbers" as in the Hein Acta Futura paper cited in 2.3 M8-ISR-L03 Introduction to Worldships and elsewhere in this report. Agent-based simulation is the classic way of dealing with these sorts of issues (eg building evacuation, traffic flow). AI via machine learning has already been used to investigate human behaviour and working with agent based models to attempt to solve social dilemmas like the El Farol Bar problem. Human "guinea pigs" have already been both proposed and used to simulate isolated communities and, in typical Ballardian fashion, fictionalised as unknowing guinea pigs in Ballard's "Thirteen to Centaurus" [3].

If AI and/or AGI are to have significant onboard responsibilities then the ethics and politics of their relationship with humans must be considered. How far will we have progressed with AI/AGI at the point of worldship launch? The degree of trust, responsibility and authority given to AI and/or AGI might vary enormously dependent on how far this has progressed by that point in time. John examined two broad scenarios, moderate and advanced AI/AGI and issues in administration, health, justice and vehicle control.

Finally John summarised and offered some speculations on the emergence of AGI "Superintelligence" and the possibility of AI proxies (eg "AI-Attenborough" brought to our sitting rooms).

[1] *Other Minds* in the Stanford Encyclopedia of Philosophy plato.stanford.edu/entries/other-minds/

[2] www.academia.edu/34432202/Worldship_Ethics_101_The_Shipborn see also Worldship Ethics Obligations to the Crew James S J Schwartz, JBIS V71 #2 February 2018, TVIW video Worldship Ethics 101: The Shipborn at - https://www.youtube.com/watch?v=dIpXINcQixE&feature=youtu.be

[3] Discussed in Thirteen to Centaurus by Paul Gilster www.centauri-dreams.org/2016/03/25/thirteen-to-centaurus

2.10 M8-ISR-L10 Worldships in Science Fiction IMPRESS

Simone Caroti of Full Sail University, Florida, introduced the history of the worldship in science fiction including story patterns, speculative content transferable to the discipline of interstellar studies and material for thought experiments applicable to academic studies.

Dr Simone suggests that we currently try to avoid Earth-bound ships becoming technologically, logistically or socially autonomous. We want them to remain nationals of their countries rather than "people of the ship". But this tendency will be hard to resist on worldships.

He identified early exponents of worldship thinking including rocket pioneers Robert Goddard ("The Last Migration," 1918) [1] and Konstantin Tsiolkovsky ("The Future of Earth and Mankind," 1928) - and J D Bernal (The World, the Flesh, and the Devil, 1929 [2]). Dr Simone identified five periods of SF and examined the treatment of worldships in each -

1. The Gernsback period (1920s-early 1940s)

Hugo Gernsback, publisher of Amazing Stories, who britannica.com describes as "largely responsible for the establishment of science fiction as an independent literary form".

worldship themes in the Gernsback period Credit: Caroti

2. The Campbell/Astounding period (1940s-1960s)

John W Campbell editor of Astounding Science Fiction and "responsible for setting a tone for science fiction that haunts this genre to this very day" according to the last winner of the annual award conferred by the same magazine (now called Analog Science Fiction and Fact) before its name was changed to reflect repudiation of his political views.

worldship themes in the Campbell period Credit: Caroti

The founder of modern interstellar studies, Leslie Shepherd (see 2.2 M8-ISR-L02 Background to Interstellar Studies above) commissioned art for his piece Interstellar Flight (JBIS, 1952). Simone commented that Shepherd's text is revealing of the biases of the time: propulsion systems, engineering, and logistics - but that the accompanying Frank R Paul artwork addresses the psychological, cultural and human elements.

worldship studies meets SF art
credit: Caroti / Frank R Paul

[1] Discussed in The Ultimate Migration, David Baker - www.bis-space.com/2012/03/23/4110/the-ultimate-migration

[2] The World, the Flesh & the Devil: An Enquiry into the Future of the Three Enemies of the Rational Soul www.quarkweb.com/foyle/WorldFleshDevil.pdf

3. The New Wave (1960s-late 1970s) the "inner space" era

Epitomised by New Worlds magazine under the editorship of Michael Moorcock.

Aldiss (1925-2017), Harrison (1925-2012) and Brunner (1934-1995) all imagined worldships - the first two having inhabitants who did not know they were on the ship!

three new wave era worldship novels Credit: Caroti

4. The Cyberpunk – or modern – period (1980s-1990s)

When the information age "washed over science fiction" [1].

Wolfe's novel series and a novel from the Cyberpunk era Credit: Caroti

Gene Wolfe took the dystopia of the Book of the New Sun series onto a worldship. Richard Paul Russo imagined another worldship with governance gone wrong.

5. The contemporary period (2001-today).

Simone suggests we now recast the narrative modes of the past into new shapes.

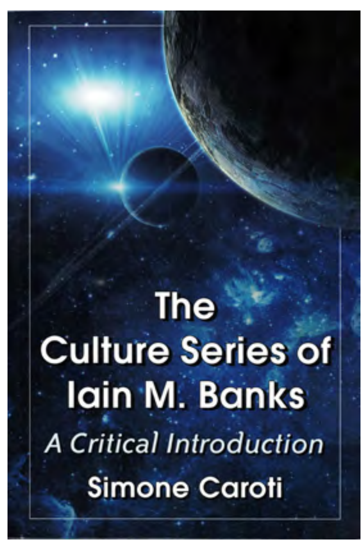
two novels and a collection of papers bring us almost up to date Credit: Caroti

Ken Macleod uses a worldship in a first contact story; Kim Stanley Robinson creates a worldship disaster story, though in this case the travellers knowing exactly what is going on!

Dr Simone wrapped up with some examples of worldships in other media.

- Original series Star Trek episode "For the World Is Hollow and I have Touched the Sky" [2]
- The Starlost was a single 1973 TV series [3]
- Metamorphosis Alpha (TSR) 1976 - a worldship-based role playing game
- Phoenix Without Ashes. IDW, 2011 is a graphic novel/comic by Harlan Ellison
- Pandorum 2009, a film by Christian Alvart, again most aboard no longer know they are on a worldship

Dr Simone Caroti is Course Director in Creative Writing at Full Sail University, Florida. He is the author of of *The Culture Series of Iain M Banks: A Critical Introduction* and of *The Generation Starship in Science Fiction: A Critical History, 1934-2001* - which we will be reviewing in the next issue of Principium. Dr Simone has degrees from Purdue University and the University of Trieste.



The Culture Series of Iain M Banks: A Critical Introduction, McFarland 2015.
In your reporter's opinion the finest introduction to Banks' seminal series yet published.

[1] Writer Bruce Sterling characterised cyberpunk as a "combination of low-life and high tech"

[2] Which has the Enterprise team rescuing another unknowing crew of a worldship

[3] Again the travellers on a worldship forget their situation. Despite the involvement of Douglas Trumbull, Ben Bova, Harlan Ellison and even Keir Dullea from *2001: A Space Odyssey*, the series flopped.

2.11 M8-ISR-L11 Advanced Propulsion Systems 1 VIDEO IMPRESS

Rob Swinney delivered the first of his two briefings on the core problem of interstellar travel : propulsion.

He covered of -

Advanced Propulsion 1:

• Solar Sails

• Laser Sails

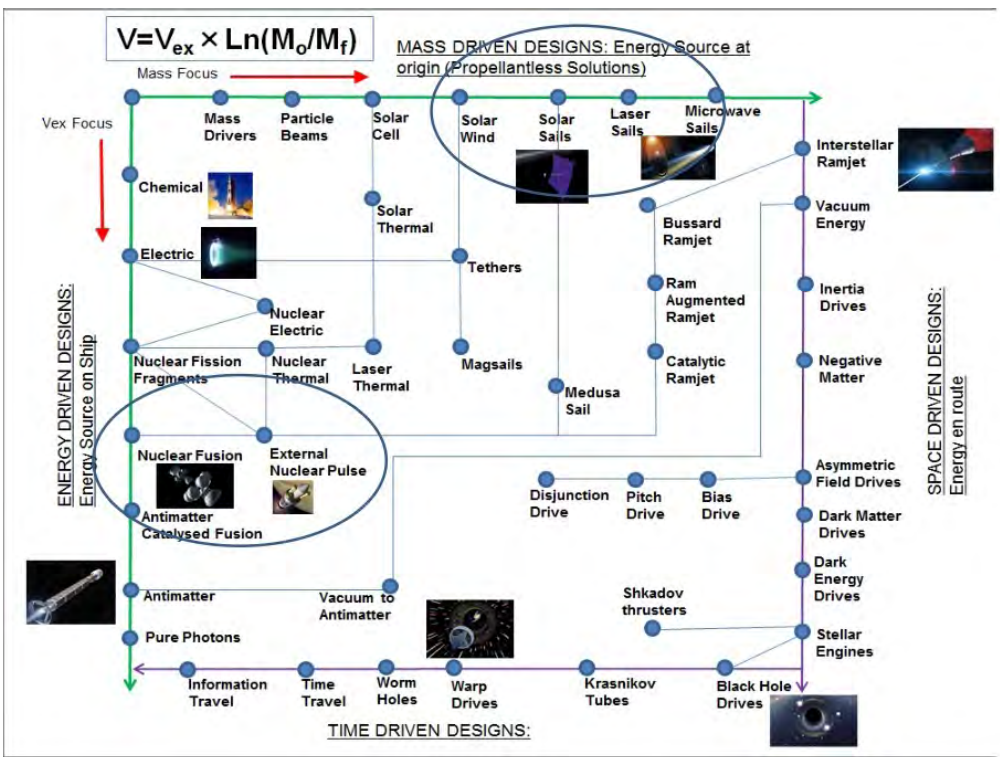
Advanced Propulsion 2:

• Nuclear Fission/Fusion

• Interstellar Ramjets

• Antimatter

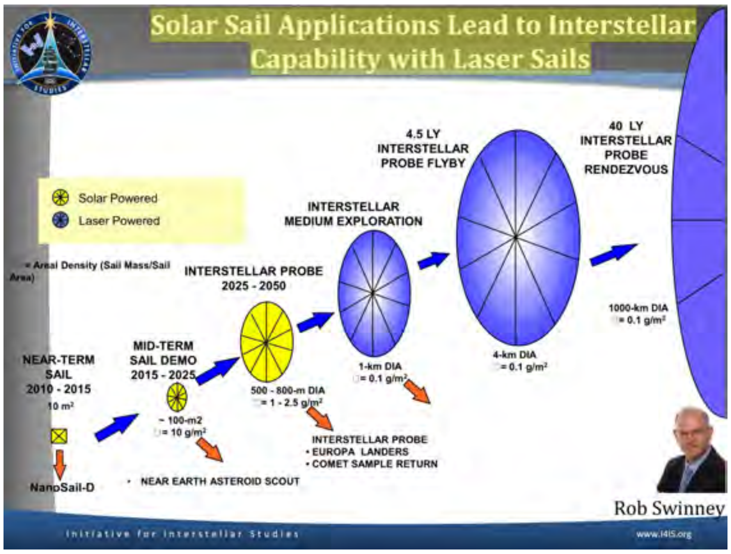
He recommended 18 texts from Les Shepherd's JBIS paper in 1952 to Kelvin Long's 2012 book Deep Space Propulsion: A Roadmap to Interstellar Flight and a taxonomy of propulsion solutions showing where his two lectures would concentrate.



Sailing and reaction methods identified in a taxonomy of propulsion solutions.

Credit: Swinney / Long

Sailing in space has similar benefits to sailing on the oceans - no fuel load - and similar difficulties - finding a strong enough wind! The Sun provides a solar "wind" in the form of photon pressure. The first such probe was Japan's IKAROS: Interplanetary Kite-craft, launched in 2010, and extrapolations of the idea to interstellar probes have been suggested. Rob showed some characteristic equations for solar photon propulsion and gave the example that pressure at 1 astronomical unit (AU) from the Sun, ie where the Earth is, amounted to about 9 Newtons per square kilometre of sail or $9*10^{-6}$ Newtons per square metre. This drops off by the inverse square law leaving $5.8*10^{-9}$ Newtons per square metre at Pluto, 39.54 AU from the Sun.



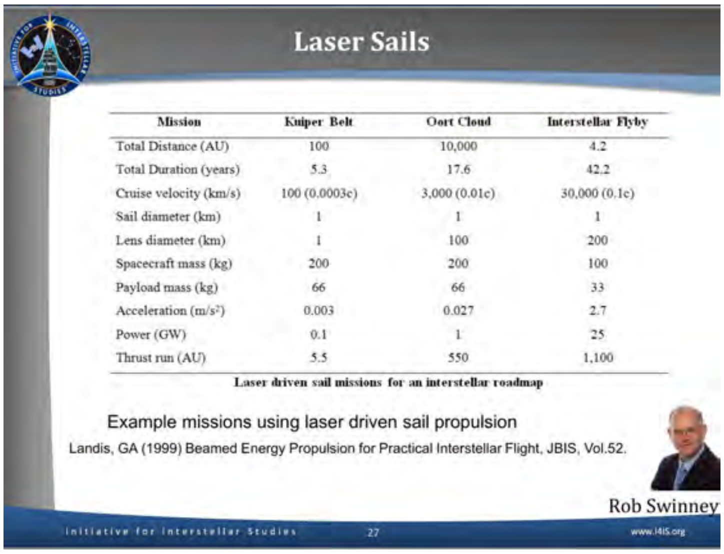
Solar sailing has limits but leads to laser sails & interstellar capability. Credit: Swinney

Rob derived and presented a basic equation for a photon-driven sailcraft the photon power required, in watts -

$$P_s(W) = \frac{mca}{2\mu}$$

- where m=spacecraft mass, μ= sail reflectivity, α =absorption coefficient, c = speed of light [1].

Rob showed us Robert Forward's Starwisp ideas, using a microwave beam (Starwisp) and his laser alternative in 1984 and 1985 - and the results of a 1999 study by Geoff Landis.



Mission	Kuiper Belt	Oort Cloud	Interstellar Flyby
Total Distance (AU)	100	10,000	4.2
Total Duration (years)	5.3	17.6	42.2
Cruise velocity (km/s)	100 (0.0003c)	3,000 (0.01c)	30,000 (0.1c)
Sail diameter (km)	1	1	1
Lens diameter (km)	1	100	200
Spacecraft mass (kg)	200	200	100
Payload mass (kg)	66	66	33
Acceleration (m/s²)	0.003	0.027	2.7
Power (GW)	0.1	1	25
Thrust run (AU)	5.5	550	1,100

Laser driven sail missions for an interstellar roadmap

Example missions using laser driven sail propulsion

Landis, GA (1999) Beamed Energy Propulsion for Practical Interstellar Flight, JBIS, Vol.52.

Example missions using laser driven sail propulsion

Landis, GA (1999) Beamed Energy Propulsion for Practical Interstellar Flight, JBIS 1999, Vol.52.

Most recently laser sail ideas have again come to the fore with the i4is Dragonfly study and the later Project Andromeda study delivered to Breakthrough Starshot.

Yuri Milner's Breakthrough Starshot initiative exploits recent progress in microminiaturisation, nanotechnology materials science and fibre optics. A fully functional "chipsat" weighing less that one gram is now close to feasibility. Very low mass and highly reflective sails and phase locking of multi-gigawatt laser arrays complete the proposed propulsion approach with the aim of reaching Alpha Centauri in 20 years at 20% of lightspeed. Rob listed 19 areas of challenge to be overcome, not all of them technological.

Summing up, Rob concluded -

1. Solar sails are flight tested and are an option for the inner solar system.
2. Beamed sailing looks viable for further distances away from the sun and for higher velocity.
3. Breakthrough Starshot is a live project backed by $100M over 10 years to solve the challenges posed.
4. Sails appear to have limits to their use in terms of payload/crewed missions...but given future developments?

[1] Robert Forward's equation from his 1984 paper, *Roundtrip Interstellar Travel Using Laser-Pushed Lightsails*, states that "The acceleration α of a vehicle of mass M and reflectance η driven by an incident laser power P is -

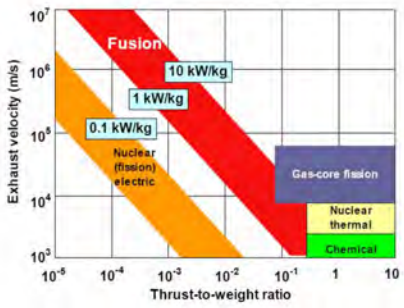
$$\alpha = \frac{2\eta P}{Mc}$$

where c is the velocity of light and the factor 2 comes from the double momentum transfer to the sail by the reflected photons."

2.12 M8-ISR-L12 Advanced Propulsion Systems 2 VIDEO IMPRESS

Rob Swinney continued his propulsion briefing by considering reaction-based propulsion : rockets. He considered -

- Nuclear Fission/Fusion - All carrying their fuel onboard rather than being pushed by external forces[1]
- Interstellar Ramjets - Using material scooped up from the interstellar medium (ISM)

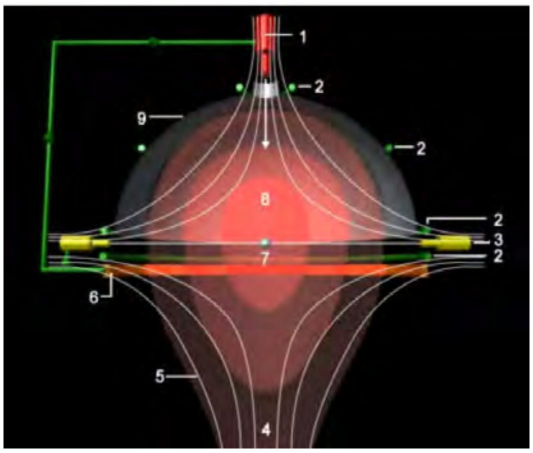


Fusion has the clear advantage.
Credit: Swinney

Nuclear Fission/Fusion

Fusion requires very high pressures and temperatures. Three confinement methods are classified as - gravitational (as in the Sun and other stars), magnetic (as in the Tokamak reactors under development for power generation) and inertial (ICF) using the inertial mass of material to confine the plasma. Rob outlined a number of possible reactions using Deuterium, Tritium, Helium3 and isotopes of Lithium and gave us an equation for the Lawson criterion - comparing the power generated by fusion to the rate of energy loss to the environment.

Reaction propulsion is clearly best suited to large probes or human carrying starships. The probes of the Daedalus (1970s) and Icarus (2010s) studies - and for proposed colony ships and world ships.



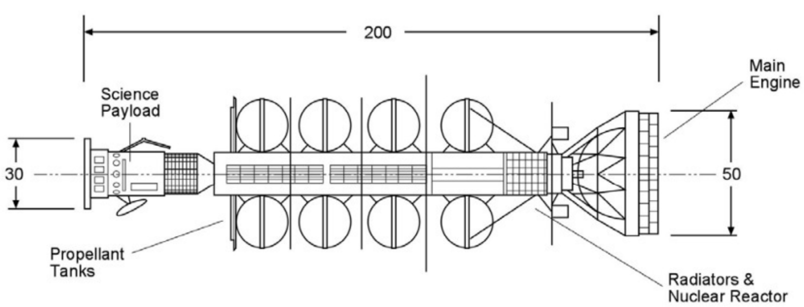
Inertial Confinement Fusion: Daedalus style
1 Pellet injection gun
2 Superconducting field coils (4)
3 Electron beam generators
4 Plasma exhaust jet
5 Magnetic field
6 Energy extraction coils
7 Frozen nuclear pellet
8 Nuclear explosion
9 Reaction chamber
Credit: Adrian Mann www.bisbos.com/space_n_daedalus_prop.html

The pioneering Daedalus study proposed deuterium/helium-3 pellets as fuel and ICF using electron beams. About $3*10^{10}$ pellets would be required. Rob took us through the mass/energy/thrust/exhaust velocity equations noting that the Daedalus reaction yields 42.4 Megawatts per kilogram.

Rob is the long-established Project Director of Project Icarus, the study to build on Daedalus applying new technology and achieving a rendezvous rather than a flyby mission but with a relaxed mission time of 100 years. He noted that a number of intermediate studies were carried out between the publication of the Daedalus results in the late 70s and the inception of Icarus in 2009. Several teams worked on parallel designs within the Icarus programme. They also addressed a number of issues arising from Daedalus including fuel source, pellet rate and use of electron beams to achieve ICF.

Here are the concepts Rob introduced -

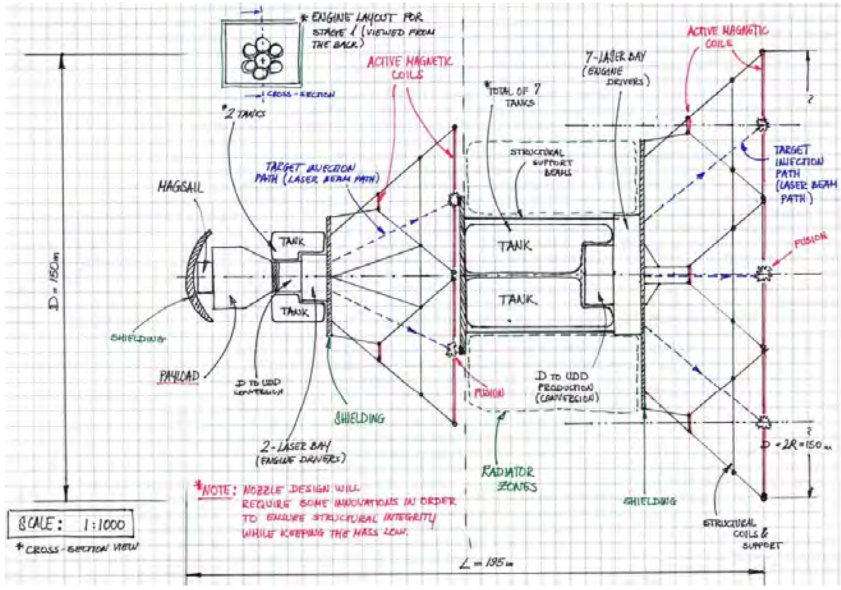
Icarus: Resolution 2013 configuration. Dimensions in metres. Note the similarity to Daedalus.
Credit: Swinney



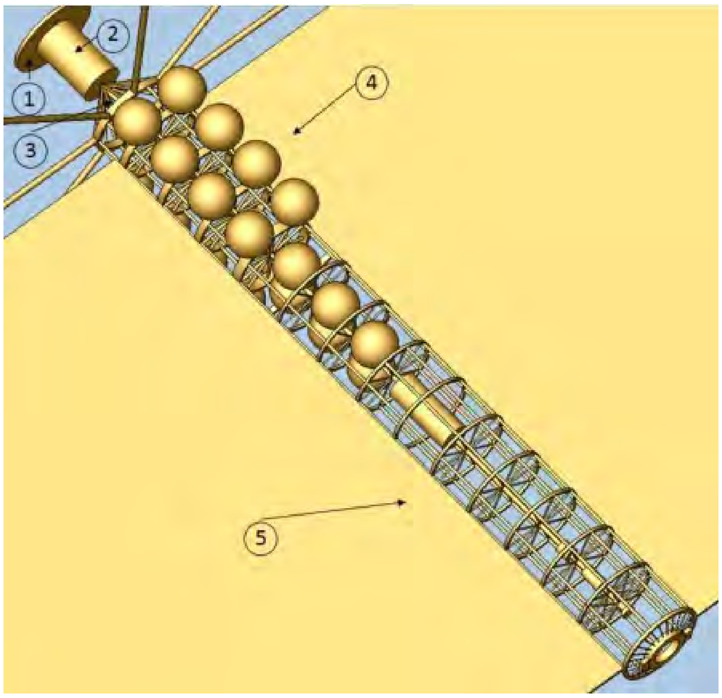
Icarus: Resolution was revised as Icarus: Endeavour with more engines and a faster boost phase.

[1] Thus being subject to the Tsiolkovsky rocket equation DeltaV=ExhaustVelocity*ln(OriginalMass/FinalMass) - a direct consequence of Newton's second law, transposed as Acceleration=Force/Mass.

Icarus: UDD Concept. Credit: Swinney



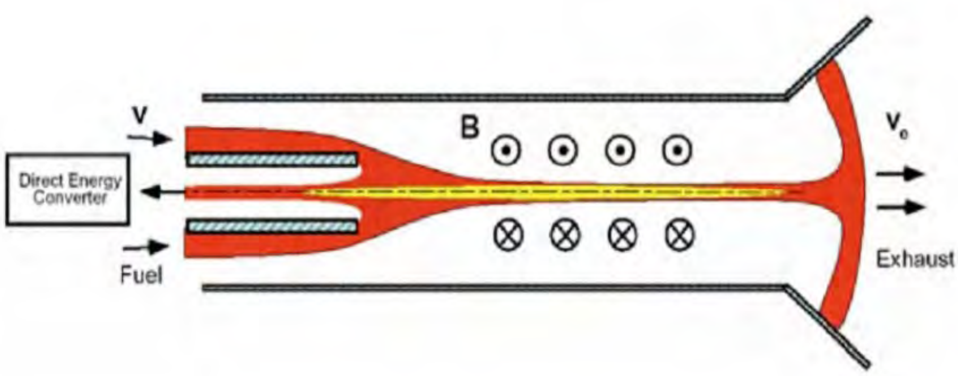
The UDD Concept, based on use of Ultra Dense Deuterium as fuel, offers advantages including simpler reactions, less mass, abundant fuel source and added system robustness and reliability. However producing this fuel in a usable form remains a challenge.



Project Icarus: Ghost Configuration
1.Dust Shield
2.Payload
3.Magnetic Sail
4.Tank Sections
5.Radiators
Credit: Swinney

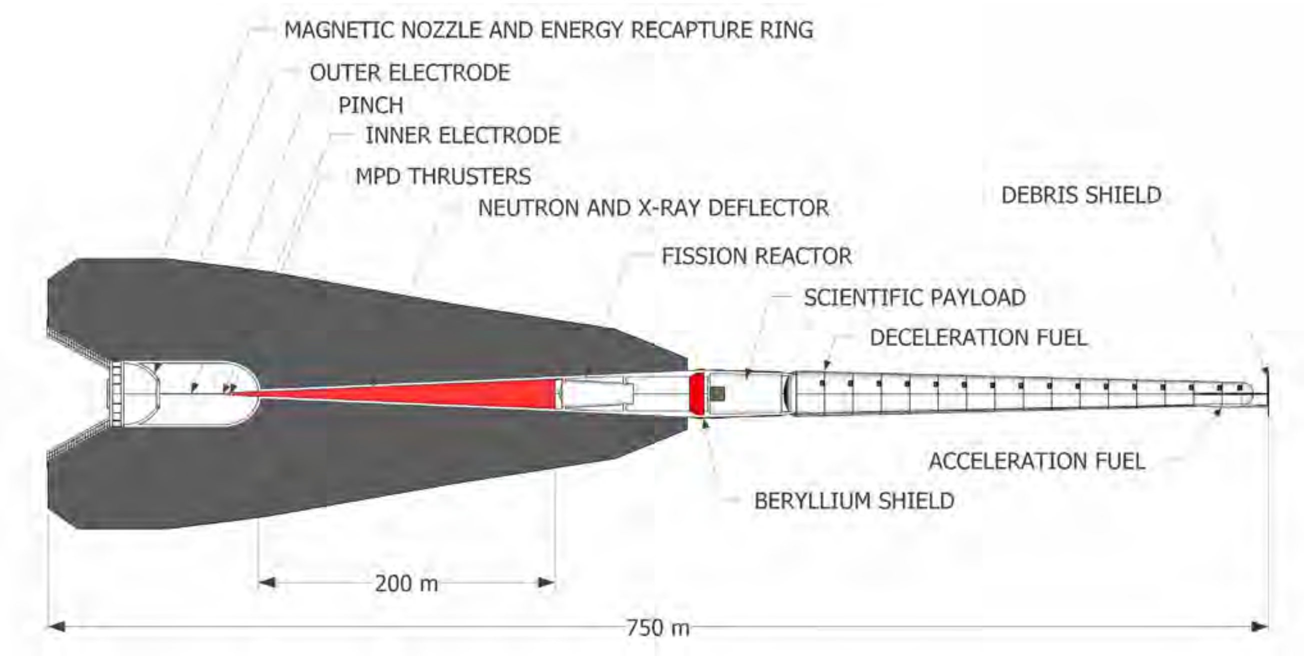
The Ghost team have revised their study, relaxing mission duration to 118.5 years and deriving a new mass budget.

Perhaps the most active and well defined of the Icarus projects has been Icarus: Firefly. This uses a variant of magnetic confinement called a Z-Pinch, relying on the circular magnetic field around any current-carrying conductor. In this case a plasma flow carrying a very substantial current thus producing an inward magnetic force sufficient to achieve fusion-



Simple Z-pinch thruster design by Shumlak. The cylindrical magnetic field is towards (above the plasma) and away (below) from you.
Credit: Shumlak / Swinney

The developed Firefly design has wing-like radiators with a sophisticated liquid metal coolant conveying heat away from the central Z-pinched plasma.



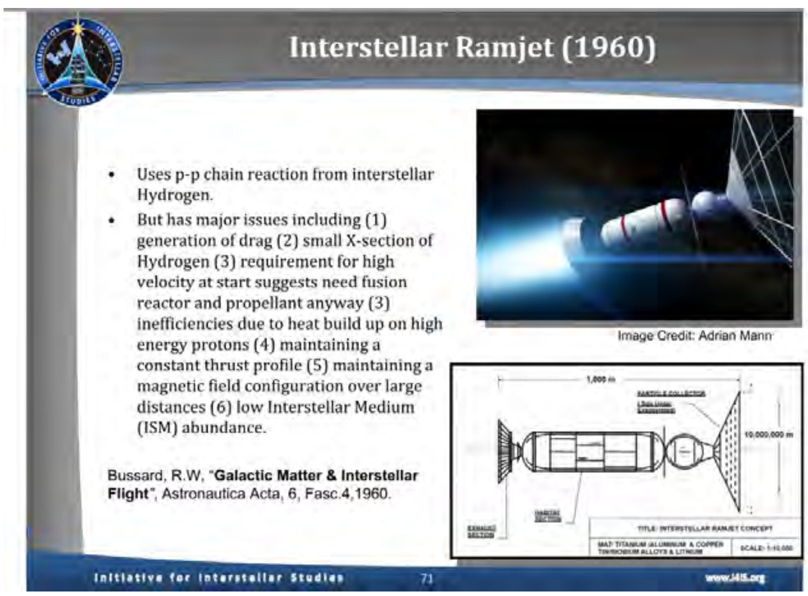
Developed Firefly design (not in the presentation). [1]

Credit: Michel Lamontagne

Another idea under the Icarus programme is Icarus: Zeus - Plasma Jet Magneto-Inertial Fusion (PJMIF) using magnetic confinement fusion.

Interstellar Ramjet

The 1960 Interstellar Ramjet idea of Robert Bussard avoids carrying fuel by using interstellar hydrogen scooped up by the craft's magnetic field. This very attractive idea has been found to have a number of technical flaws which Rob outlined.



Bussard's orginal concept :

Bussard, RW “Galactic Matter & Interstellar Flight”, Astronautica Acta, 6, Fasc.4,1960.

Two of them are easily stated - there is not enough interstellar hydrogen and, like terrestrial ramjets, the process only starts to work after a high initial velocity has been achieved.

Rob summed up by reiterating that the BIS Project Daedalus study remains the only full starship “design” and all others are concepts at best. In conclusion, though interstellar travel is very difficult technically, these studies show that it is certainly possible.

[1] Reaching the Stars in a Century using Fusion Propulsion A Review Paper based on the ‘Firefly Icarus’ Design Patrick J Mahon, Principium | Issue 22 | August 2018.

Also at - i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/

2.13 M8-ISR-L13 Artificial Intelligence on Worldship Missions VIDEO IMPRESS

John Davies introduced the second session on the application of Artificial Intelligence (AI) and Artificial General Intelligence (AGI) to worldships.

"Vanilla" AI is all we have now. Much has been achieved, especially by machine learning in recent years but there have been false dawns before.

Artificial General Intelligence is "... designed not for particular tasks but for being capable of learning various skills" Arakawa 2014[1]. AGI approaches take two routes-

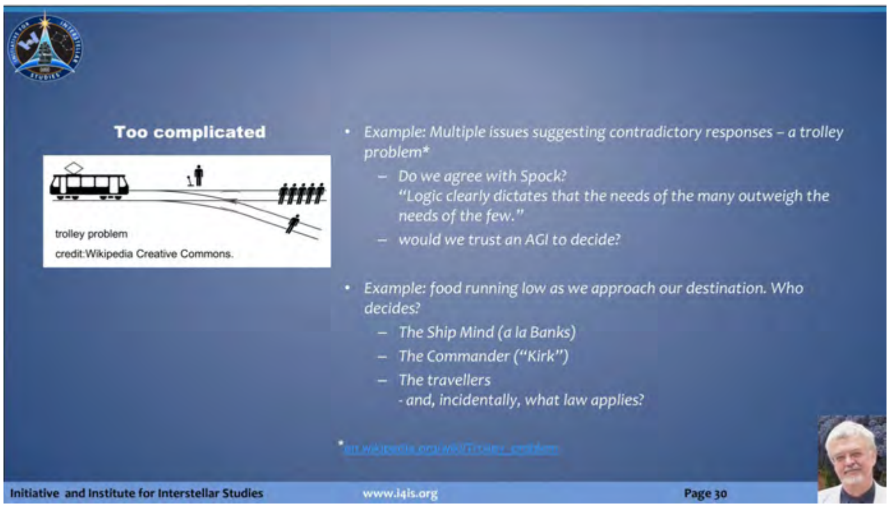
- Bottom up – Simulation of Nervous Systems such as the SpiNNaker - simulation of a billion neurons (maybe 1% of human brain?) of Steve Furber's team at the University of Manchester and its second generation at TU Dresden. Also the Blue Brain and Human Brain Projects at EPFL, Lausanne.
- Top Down: Simulation of Human Behaviour - machine learning via deep neural networks - recently in gaming and pattern recognition notably Google Deepmind.

The theoretical background to simulation is the Church-Turing thesis of 1938 proving that all computers[2] are equivalent and Turing's 'polite convention' of 1950 - that if an entity seems human then treat it as such[3]. What would be the status of Digital Persons- how can we know that a digital "person" is a real person? – If "uploaded" from a biological human ("Transcendence") how can we know that the copy is identical? – If "educated" how to determine their "personhood"? And finally if only Digital Persons go to the stars, will we feel that the human race has really visited another stellar system?

However there have been false dawns of AGI (USA 1966, UK 1973) and sceptics include a legend of computer science, Edsger W Dijkstra (who dismissed the AI optimism of both Alan Turing and John Von Neumann) and polymath Roger Penrose (The Emperor's New Mind, OUP 1999).

John asked what Worldship configurations should we expect and how can AI/AGI contribute to the mission? The sociology and ethics of worldship societies have been considered recently by Hein et al in the ESA journal Acta Futura (www.esa.int/gsp/ACT/resources/acta_futura) and by James Schwartz, Wichita State University[4].

John considered the following premise - that humans plus AIs (and maybe AGIs) can fix whatever is fixable on a worldship. But what might not be fixable in this way? He gave examples where the occurrence may be too fast, too complicated, too unknown or was a Black Swan event - and what AI or AGI can do in these cases.



The "Too complicated" case illustrated by the Trolley Problem in moral philosophy [5] and Mr Spock's utilitarian response, and exemplified by a worldship scenario.

[1] Planning with Brain-inspired AI, Naoya Arakawa arxiv.org/abs/2003.12353

[2] Strictly speaking finite state automata

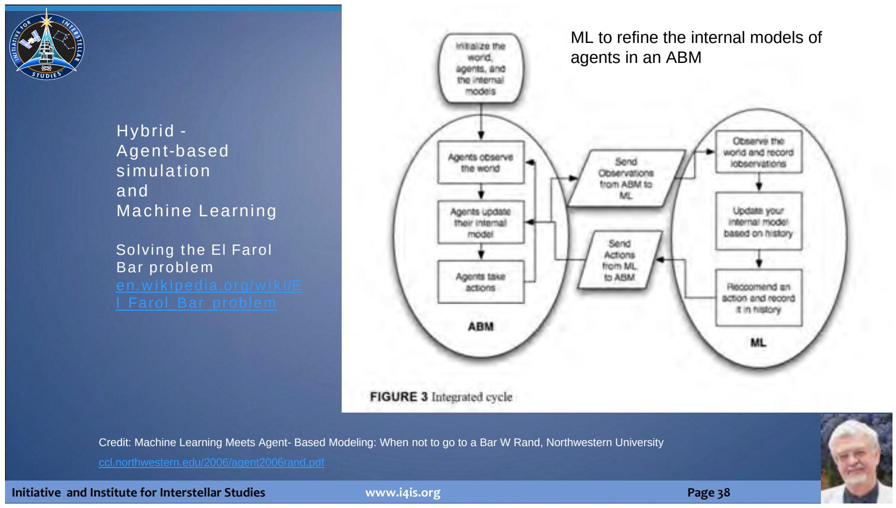
[3] Computing Machinery and Intelligence, A M Turing, Mind, Volume LIX, Issue 236, October 1950 academic.oup.com/mind/article/LIX/236/433/986238

Some key quotes "Instead of trying to produce a programme to simulate the adult mind, why not rather try to produce one which simulates the child's?" "We cannot expect to find a good child machine at the first attempt. … experiment with teaching one such machine and see how well it learns… then try another and see if it is better or worse." and refuting The Argument from Consciousness "it is usual to have the polite convention that everyone thinks"

[4] Worldship Ethics Obligations to the Crew James S J Schwartz, JBIS V71 #2 February 2018, TVIW video Worldship Ethics 101: The Shipborn at -www.youtube.com/watch?v=dIpXINcQixE&feature=youtu.be

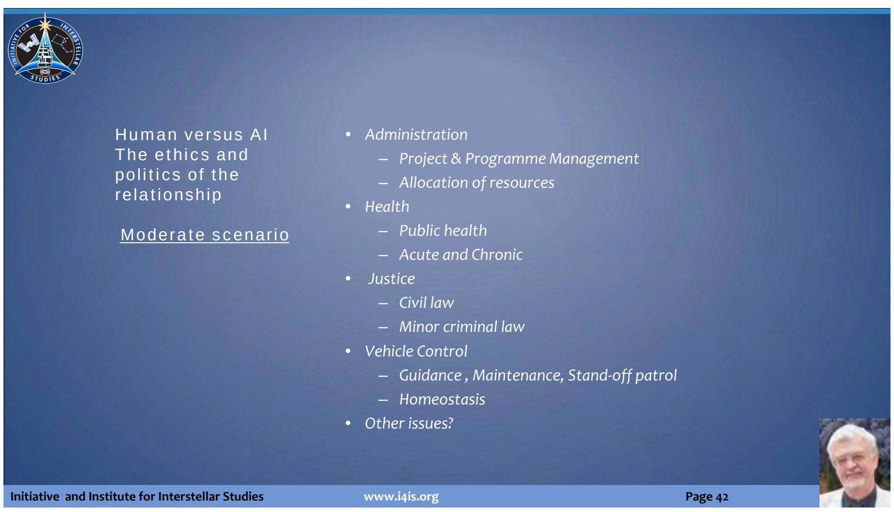
[5] Doing vs Allowing Harm - 2. Distinguishing Distinctions plato.stanford.edu/entries/doing-allowing/#DistDist

So can simulations of worldships help us to think about missions well before launch? We can simply "run the numbers" as in Andreas' Acta Futura paper. If numbers and statistics don't work then can we simplify and thus simulate human societies? Agent based simulations are used for situations such as building evacuation and road traffic. Can AI, and in particular machine learning, help? And there are also hybrids of these two approaches.

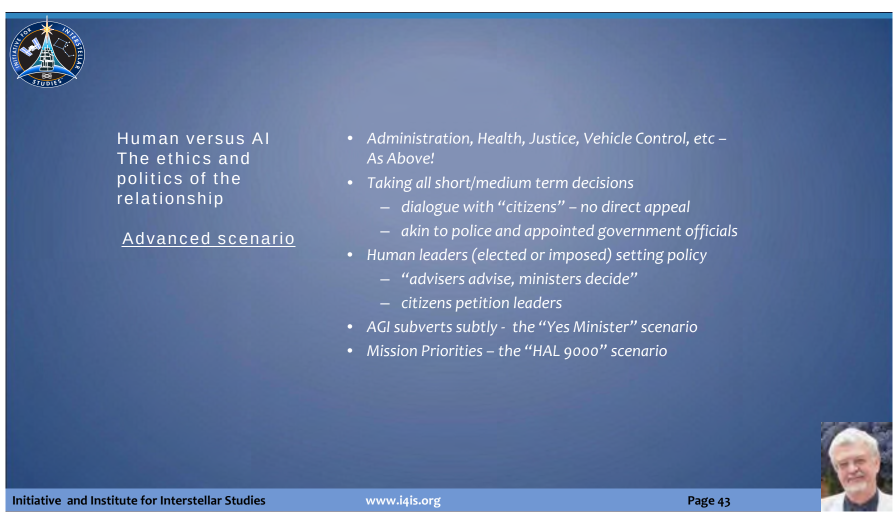


Hybrid - Agent-based simulation and Machine Learning Solving the El Farol Bar problem
Credit: *Machine Learning Meets Agent- Based Modeling: When not to go to a Bar* ,W Rand, Northwestern University
ccl.northwestern.edu/2006/agent2006rand.pdf

On the ship itself how do we balance onboard roles – human versus AI? How far will we have progressed with AI/AGI at the point of launch? John considered moderate and advanced scenarios, with a human only setting policy in the latter case.



moderate (above) and advanced (below) scenarios for worldship AI / AGI



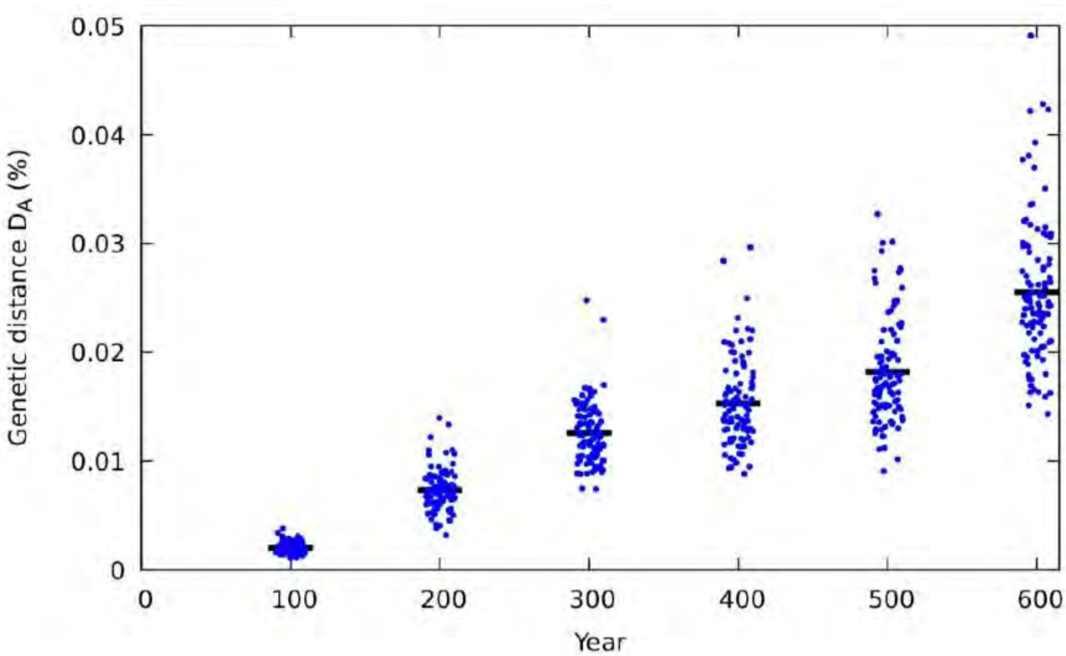
A safe assumption is probably that worldships will adopt current technological practice (as did the Apollo and Shuttle programmes for their computer architecture).

2.14 M8-ISR-L14 Worldship Population Dynamics IMPRESS

Dr Frédéric Marin took us inside the worldship to consider how the human population might fare on their long journey. He introduced us to the early worldship thinking of Robert Goddard and Konstantin Tsiolkovsky, the NASA/Stanford ideas in the 70s. There has been a limited amount of work so far from the population point-of-view [1].

Dr Marin introduced us to the international HERITAGE project, based at the University of Strasbourg, to simulate evolution of a population of digital humans in a closed system (a Moon colony, a space station, an interstellar spacecraft) for hundreds to thousands of years [2]. An example is a simulation of a 600 year interstellar journey with a starting population of 50 people, gender balanced, leading to an exponential-growth population to about 8,000 at journey's end so he aims to limit growth to 1200 people. This initial simulation leads to inbreeding but artificially limiting consanguinity to prevent this leads to population collapse. Simulations starting with 100 people and the same population and consanguinity limits show problems with the lower figure of skills transfer and resilience to widespread diseases or disasters. Starting with 500 people leads to a stable outcome, addressing the issues of skills transfer and resilience.

Dr Marin considered the population sizes from a genetic point of view. The population size considered appears to be adequate in terms of Hardy-Weinberg equilibrium (ie the frequency of alleles[3] should tend to be stable over long periods). However genetic evolution will naturally occur and the population will drift away from the genotypes seen at the start of the journey.



Evolution of the Nei's minimum genetic distance D_A as a function of time for a given HERITAGE parametrization. Each point (at a given time-step) represents the outcome of one out of one hundred simulations. The averaged genetic distance is highlighted by a black bar. The annual equivalent dose of cosmic ray radiation is similar to the Earth radioactivity background at sea level (0.3 mSv).

Credit (image and caption): Marin

Radiation is clearly a threat both genetically and in causing disease, notably cancers. The solar storms especially feared for astronauts outside the Earth's Van Allen belts will naturally be less significant as the journey progresses but Dr Marin identifies cosmic ray radiation as a major issue.

[1] *Evaluating Five Models of Human Colonization*, John H Moore 2001 www.jstor.org/stable/683473

J H Moore. *Kin-Based Crews for Interstellar Multi-Generational Space Travel* - in Kondo, Bruhweiler, Moore and Sheffield (eds). Interstellar Travel and Multi-Generational Space Ships, pages 81–88. Apogee Books, Wheaton, Illinois, USA, 2003

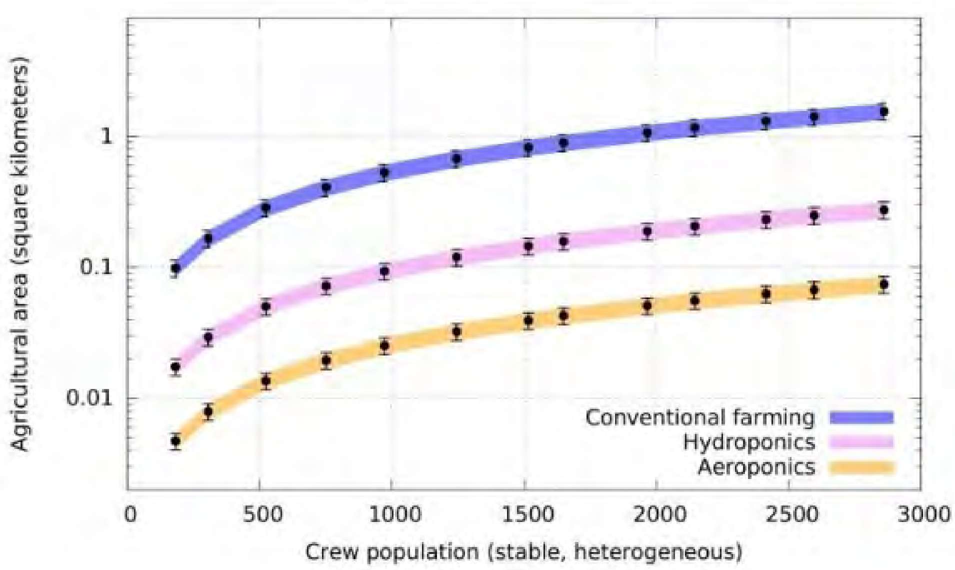
C M Smith, *Estimation of a genetically viable population for multigenerational interstellar voyaging: Review and data for project Hyperion*, Acta Astronautica, 97, pp.16–29, 2014. doi:10.1016/j. actaastro.2013.12.013 open at:tinyurl.com/CMSmith2014

Jean-Marc Salotti, *Minimum Number of Settlers for Survival on Another Planet*, Scientific Reports volume 10, Article number: 9700 2020, www.nature.com/articles/s41598-020-66740-0

[2] The HERITAGE project is entirely voluntary (no specific funding so far). The team would welcome any expert with ideas to improve the code or exploit the data. Human science experts would be especially welcomed as would female academics. More at - astro.u-strasbg.fr/~marin/HERITAGE.html.

[3] en.wikipedia.org/wiki/Allele_frequency

The HERITAGE simulation shows the requirements for food, water and breathable gases. Food requirement is set by the BMR, basal metabolic rate of an individual and physical activity (PAL). The sum of these sets the total energy expenditure. A stable population of 1,100 leads to a requirement of 1 billion kilo-calories per year (equivalent to about 1.15 billion tonnes of potatoes per year!). This is clearly not a practical cargo mass so agriculture is required. The choices are Geoponics (old-fashioned soil-substrate farming), Hydroponics (using inert substrate irrigated with a nutrient solution) and Aeroponics (above-ground with sprays, a fog, of water and nutrients in a closed circuit). The latter requires no substrate and has been shown, on the ISS, to be insensitive to gravity. It is also the most space-efficient of the three.



Required agricultural surface area (in square kilometers) as a function of the crew size for a single-food diet (sweet potatoes). The colors highlight the different, farming techniques used.

Credit (image and caption): Marin

However, considerations of dietary diversity including some provision for animal and orchard sources suggests a proportion of geoponics and thus with a population of 1,100 people, 0.95 square km of agricultural area.

Water is a major challenge - both for human and agricultural use - so both production and recycling will be required. Dr Marin suggests two possible reactions for production the Sabatier reaction (as on the ISS [1]) and the Bosch reaction [2].

Air, and specifically oxygen, is required of course. About 180 million litres of oxygen must be produced per year. Chemical reactions on the ISS cannot be reproduced where there are no incoming supplies so the only way to provide enough breathable gases and recycle gas wastes is to mimic the Earth system and rely on agriculture.

Along with genetic drift there will be social drift. Isolated populations evolve new traits such as (in approximate order) new vocabulary and accents, body language, value scales, artistic expression, philosophy and religious beliefs, language and finally ethnogenesis - the formation of a new culture or nation.

Dr Frédéric Marin is at the Astronomical Observatory of Strasbourg, part of the University of Strasbourg. His scientific interests include both astrophysics (theory and modelling of black holes, polarisation and radiative transfer, galactic nuclei and quasars) and anthropology of space (interstellar travel, multi-generational populations, and worldship design and reliability studies) - more at -astro.u-strasbg.fr/~marin/. He has published a number of papers in JBIS since 2017 [3]. He has degrees in physics and in a variety of astrophysical topics from the universities of Dublin, Annecy-le-Vieux, Montpellier and Strasbourg (PhD).

[1] en.wikipedia.org/wiki/Sabatier_reaction#International_Space_Station_life_support

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

[3] JBIS papers : see *Recent Interstellar Papers in JBIS* in Interstellar News in this issue and earlier -

Computing the Minimal Crew for a multi-generational space journey towards Proxima Centauri b - V71 #1 2018, pages 45-52 V71 #2 February 2018

Numerical Constraints On The Size Of Generation Ships from total energy expenditure on board, annual food production and space farming techniques - V71 #10, pages 382-393 October 2018

Heritage: A Monte Carlo Code To Evaluate The Viability Of Interstellar Travels Using A Multi-Generational Crew, V70 # 5/6 May/June 2017, pages184-195

2.15 M8-ISR-L15 Interstellar Travel using Einstein Physics VIDEO IMPRESS

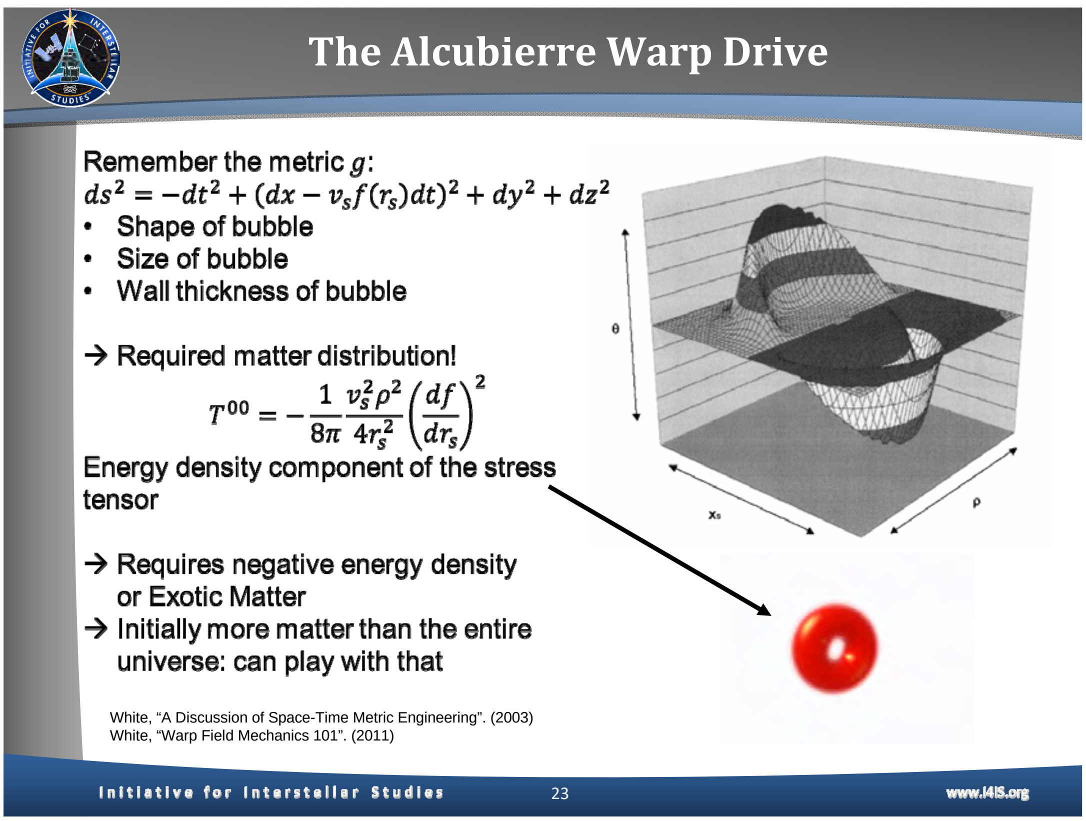
Dan Fries, Deputy Director of the i4is Technical team, examined how some more advanced propulsion technologies might become possible whilst remaining within the framework of Einstein physics - special relativity, general relativity, the Mach-effect thruster, faster than light travel, black holes and wormholes. Special relativity gives us the equivalence of all inertial (non-accelerated) observers and the invariance of c leading to indeterminacy of simultaneity and space-time dilation (with effects on mass, length, time and velocity).

Dan startled us with the assertion "GRAVITY IS NOT REAL". Gravity only appears to be 'the force of attraction between two bodies at rest or in motion' as Newton asserted (and as the everyday world testifies). Einstein's general relativity theory of gravitation teaches us that acceleration and gravity are equivalent. Dan presented the Einstein field equation -

$$\boxed{\underbrace{\overset{\text{Ricci tensor}}{R_{\mu\nu}} - \frac{1}{2} g_{\mu\nu} \overset{\text{Scalar curvature}}{R}}_{\text{Geometry of spacetime}} + \Lambda \underset{\text{The metric}}{g_{\mu\nu}} = \underbrace{-\frac{8\pi G}{c^4} \overset{\text{energy-momentum tensor}}{T_{\mu\nu}}}_{\text{Mass-energy}}}$$

Propellantless space flight is an attractive prospect. Dan illustrated this by citing the payload mass fraction of launchers from Soyuz to Saturn 5. Typical payload is just a few percent of total mass. The hypothetical Mach-effect thruster applies Mach's principle, that "local physical laws are determined by the large-scale structure of the universe" originated by Einstein to deal with phenomena such as the ability of gyroscopes to establish what seems to be a fixed frame of reference. Experimental rigs have yet to show incontrovertible results but if we could find an "inertialess drive" then it might revolutionise how we get around the universe.

Faster than light (FTL) travel has long been a dream of SF and ideas have included slowing down light, using light spots and shadows, aspects of quantum mechanics, hyperspace, superfluid theories and tachyons. However a glimmer of possibility only appeared with the Alcubierre warp drive[1].

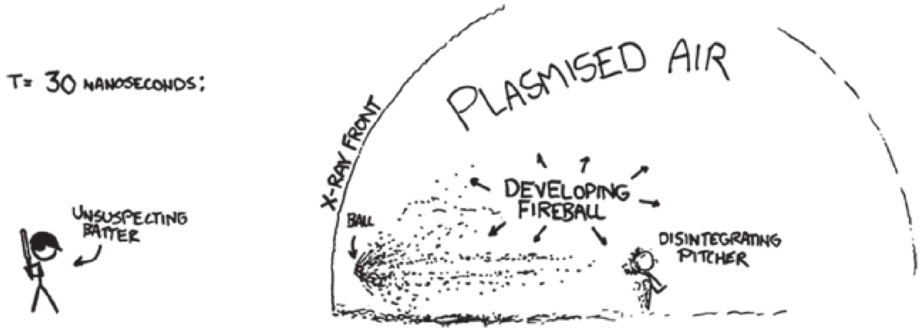


Dan's summary of Alcubierre mathematics

[1] The warp drive: hyper-fast travel within general relativity, Miguel Alcubierre, Classical and Quantum Gravity, Volume 11, Number 5 1994 - synergetics.io/docs/Alcubierre-Warp-Drive-Hyperfast-Travel-With-General-Relativity.pdf

But Dan outlined some problems with FTL - causal violations and energy condition violations, navigation, various forms of radiation and time dilation (the twin paradox). He cited a nice physics joke about just 90%c velocity applied to baseball -

The awful consequences of playing near-light-speed baseball
Credit: what-if.xkcd.com/1/

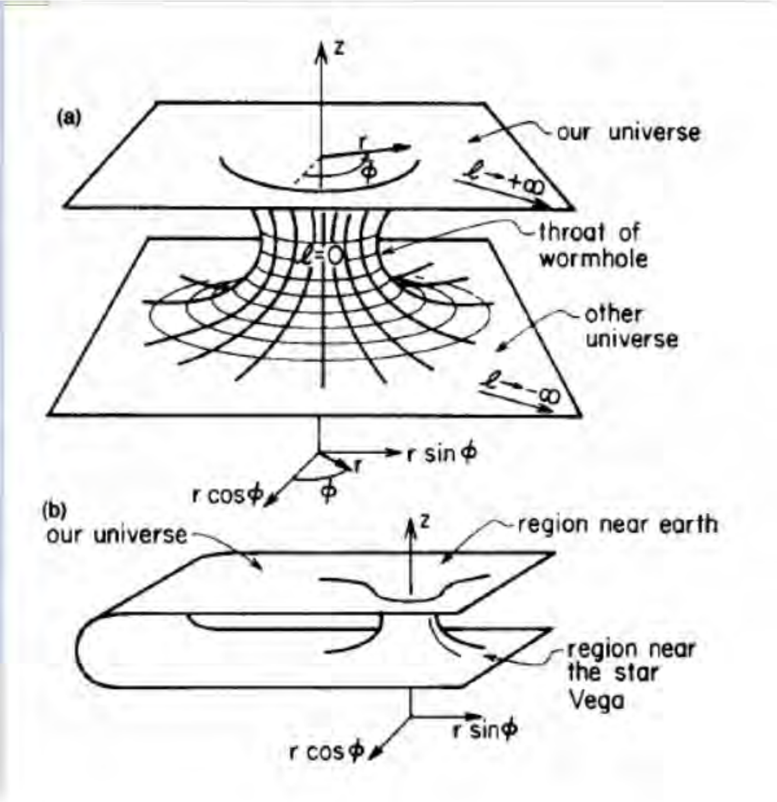


Black holes and wormholes also offer interesting, though somewhat far-fetched, possibilities. Dan gave us a tour of black hole physics - static vs rotating, Schwarzschild and Kerr solutions, the “No hair” theorem (the only parameters black holes have are mass, charge and angular momentum - they are otherwise featureless and indistinguishable).

For propulsion the interesting possibility is the extraction of energy from black holes - for example as Hawking radiation or the Penrose process to extract angular momentum from a rotating black hole. Another possible exploitation of black hole energy is a Black Hole Interstellar Ramjet (BAIR)[1].

Wormholes offer a tempting bypass to the problem of achieving FTL. Dan summarised the work of Albert Einstein and Nathan Rosen (1935), Wheeler & Fuller (1950’s) and Morris & Thorne (1980’s).

Dan showed us an example from a Morris and Thorne paper [2].



Morris and Thorne, “Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity”. American Journal of Physics 56, 395 (1988)

As always there is a "BUT": a wormhole requires exotic matter with negative energy.

Dan concluded with a warning to be careful with grand claims and grandiose promises!

His presentation includes two pages of futher learning resources (see the members area of the i4is website - linked from the heading of this article).

[1] i4is.org/what-we-do/technical/black-hole-engine

[2] Thorne also advised on black holes and wormholes for the Christopher Nolan film, Interstellar. His ideas were part of the initial inspiration for the film. He also worked with the effects team at Double Negative (www.dneg.com) gaining new insights into the physics via the detailed CGI work required. Thorne's book *The Science of Interstellar* is a fairly deep dive into the physics. The film and the book were reviewed by Keith Cooper in Principium | Issue 9 | May 2015 Page 19 and Page 22.

2.16 M8-ISR-L16 Worldship Documentary

Michael Madsen's tells us that his documentary is being further refined. It will be reviewed in a later issue of Principium

2.17 M8-ISR-L17 The Case for Interstellar **VIDEO IMPRESS**

John Davies tackled the issue of how to convince people that interstellar travel and communications deserve their attention and support, in short - How can we convince our fellow human beings to commit to interstellar?

John started with some quotations from three visionaries of interstellar studies -

> *Earth is the cradle of humanity, but one cannot live in a cradle forever.*
>
> Konstantin Eduardovich Tsiolkovsky 1911
>
> *Our exploring ships will spread outwards from their home over an ever-expanding sphere of space. It is a sphere which will grow at almost - but never quite - the speed of light.*
>
> Arthur Charles Clarke, Profiles of the Future - 1962
>
> *…interstellar travel will always be difficult and expensive, but it can no longer be considered impossible.*
>
> Robert Lull Forward, 1996

John listed arguments against interstellar - technical (too far, takes too long, fuel demands, impact hazards) and human (space and zero gravity, life support, radiation, the wait calculation, relativistic effects) and arguments in favour - all human (long term survival of our species given finite age of Sun, over population, energy limits, find habitable worlds & life, the simple Outward Urge, scientific advancement, possible cultural interactions with intelligent life and spiritual - our place/purpose in the Universe).

Sceptics argue that we have enough to do on Earth and many of them are technology pessimists. Arguments range from accusations of technological hubris all the way to technological eschatology - the theology of end times. The tension between -

- technological optimists from Samuel Smiles in the 19th century via Konstantin Tsiolkovsky, Isaac Asimov, Raymond Kurzweil, Nikolai Kardashev to Neil De Grasse Tyson and others in the present day.
- technological pessimists from E M Forster in the early 20th century [1] to today's James Lovelock.

Lovelock suggests “an orderly withdrawal to live in harmony with Gaia” and there are even those who suggest our end times are coming, from religious eschatologists to the extreme technological pessimism in fictions from E M Forster's novel, *The Machine Stops*, to the *Terminator* films.

Revisiting some arguments in favour - and adding commercial drive, civilisation life-cycles (Spengler) and avoiding intellectual stagnation[2]. John asked - are any of these are specific to interstellar? He mused that successful SETI might be “the joker in the pack”. Further negative issues include the human tendencies to isolationism (and even autarky - the motivation to simply "pull up the drawbridge") and general purposelessness. Will we simply decide that the solar system is sufficient or anticipate incessant obsolescence as characterised by the Wait Equation [3].

So who has made "the case for space" and who is doing so now? In the USA Robert Goddard and the American Rocket Society were the 1920s pioneers. More recently the Planetary Society and its founder Carl Sagan - who himself was an early interstellar advocate. In more recent times the interstellar champions have been the Tennessee Valley Interstellar Workshop (tviw.com) and, from 2016, Yuri Milner at Breakthrough Starshot, with supporters as diverse as Mark Zuckerberg and Stephen Hawking [4]. Russia and the USSR of course, had the early vision of Tsiolkovsky and the later engineering leadership of Sergei Korolev but John could see no clear advocates currently.

[1] Also anti-industrialists in the 19th century such as John Ruskin and William Morris and - to an extent - Gandhi in the 20th

[2] See Avoiding Intellectual Stagnation: The Starship as an Expander of Minds, I A Crawford, JBIS, V67, #6 June 2014, pp.253-257, 2014, www.homepages.ucl.ac.uk/~ucfbiac/Starship_philosophy_paper.pdf

[3] See "Interstellar Travel: The Wait Calculation and the Incentive Trap of Progress" JBIS, V59, July 2006 tinyurl.com/kennedywait

[4] Most recently the Limitless Space Institute (www.limitlessspace.org) - President Brian “BK” Kelly, Director of Advanced R&D Dr Harold “Sonny” White, formerly of NASA Eagleworks)

In Europe we had the German Rocket Society, founded by Herman Oberth in the 1920s, and the British Interplanetary Society (BIS) - with Arthur C Clarke as its most famous founding member in the early 1930s. German engineers produced the V2 short range ballistic missile and went on to enhance the space programmes of the USA and USSR. More recently Alan Bond and the BIS Daedalus team produced the first serious interstellar probe design and only last year the Advanced Concepts Team of the European Space Agency held its first Interstellar Workshop, 20-21 June 2019. China is now a major spacefaring nation with Ouyang Ziyuan of the Chinese Academy of Sciences a prominent public advocate. India already has a Mars orbiter probe and has had major space advocates including Vikram Sarabhai, founder of ISRO, and A P J Abdul Kalam, perhaps the first aerospace scientist to be president of a major country.

How will we take our first steps towards interstellar? Can we first build near Earth demonstrators like the i4is Glowworm laser-push demonstrator? How can we fund these? Is faster interplanetary the way to start? Will tourism followed by space habitats be stepping stones?

There are lots of potential destinations with new exoplanets being identified daily and missions to do more in the Kuiper belt and Oort cloud being planned for the coming decade.

Worldships need travellers and the inhabitants of space colonies may be the most likely enthusiasts. In the longer term there may be migration programmes like those for Australia in the 20th century.

Fiction continues to suggest both optimistic and pessimistic scenarios varying from the limping, returning, starship in Aurora by Kim Stanley Robinson to the long-term optimism of Iain Banks' Culture stories - "… to live in a fundamentally rational civilisation"[1].

The ISU Astra Planeta report advocated an "International Interstellar Fund (IIF)" (isulibrary.isunet.edu/doc_num.php?explnum_id=731). This is very long term finance and there may be another fictional parallel, "slow money" in the novel *Neptune's Brood* by Charles Stross.

Andreas Hein has suggested that long-term economic development will "close the gap" in funding [2].

Inevitably we must create an interstellar focussed society "Starships must first conquer people's hearts and minds before they can conquer space." [3]. We must be serious about marketing interstellar with inclusive processes & methods, diplomacy, ethics and leadership.

Robinson's limping starship versus Banks' optimistic Culture. Credit: Barnes and Noble / Livre Poche

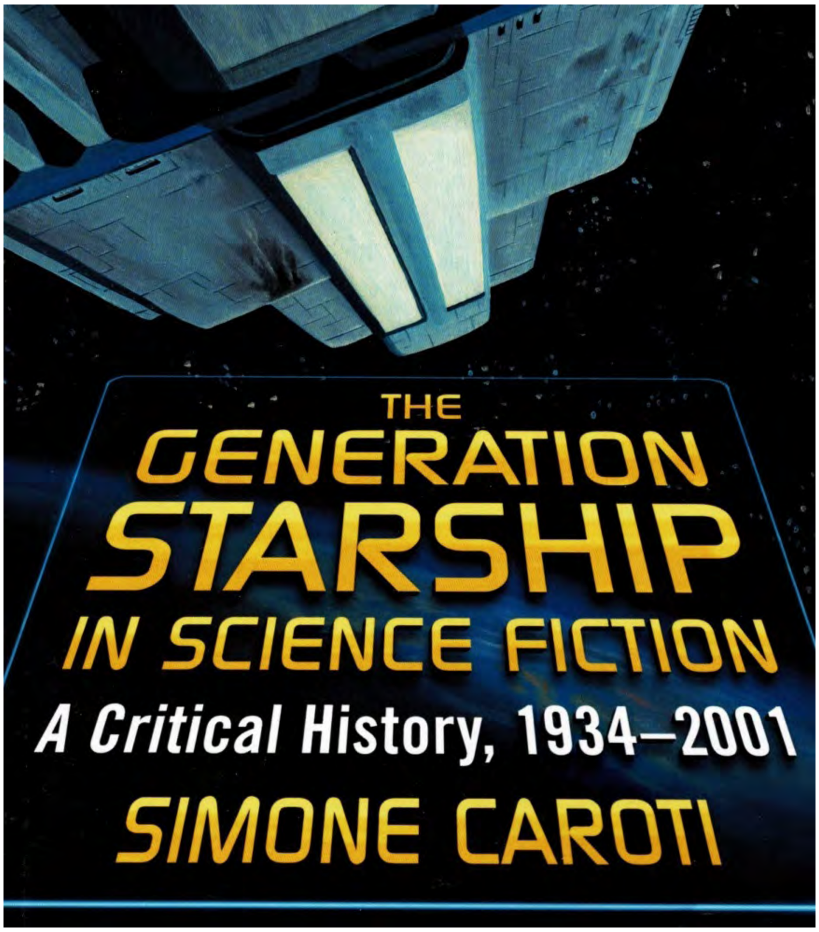
[1] See *A Few Notes on The Culture* by Iain M Banks, www.vavatch.co.uk/books/banks/cultnote.htm

[2] Evaluation of Technological/Social and Political Projections for the Next 300 Years and Implications for an Interstellar Mission, A M Hein, JBIS, v65, 2012

[3] Future Geopolitical Scenarios, Their Dominant Schools of Thought and the Impact Thereof on the Promotion of Deep Space Exploration, F Ceyssens et al. (2014), JBIS, 67

NEXT ISSUE

Worldships - a new study - Michel Lamontagne



Book Review: The Generation Starship in SF by Simone Caroti
71st International Astronautical Congress 2020:
The Interstellar Report - Part 2 of 2

Cover Images

Front Cover

Our front cover is a worldship interior envisaged by Michel Lamontagne. The fleet of four ships, each built for 10,000 people, appeared on our last cover. Here you can see one of the four contra-rotating sections of a worldship. The idea of a rotating station to provide a gravity-like environment for humans dates back to Tsiolkovsky and Von Braun, the Stanford Torus and the ideas of Gerard K O'Neill - *The High Frontier: Human Colonies in Space* (1977). This Worldship has a diameter of 5 km and a length of 20 km, with about 15 km of that as habitat. Each Worldship's dry mass is about 2 billion tonnes.

Back Cover

First Ever Image of a Multi-Planet System around a Sun-like Star Captured by ESO Telescope

The European Southern Observatory's Very Large Telescope (ESO's VLT) has taken the first ever image of a young, Sun-like star accompanied by two giant exoplanets. Images of systems with multiple exoplanets are extremely rare, and — until now — astronomers had never directly observed more than one planet orbiting a star similar to the Sun. The observations can help astronomers understand how planets formed and evolved around our own Sun. (Credit: ESO www.eso.org/public/news/eso2011/ and www.eso.org/public/images/eso2011a/)

Mission

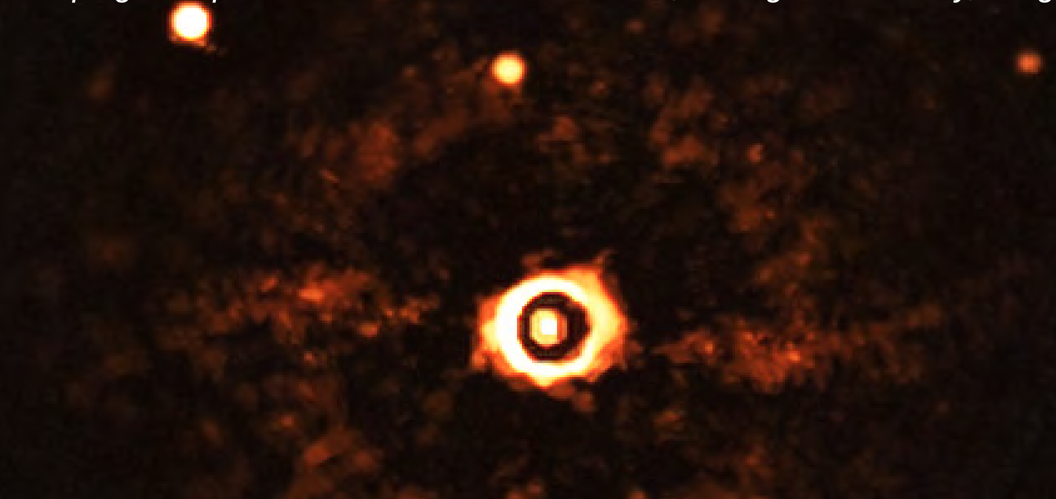
The mission of the Initiative for Interstellar Studies is to foster and promote education, knowledge and technical capabilities which lead to designs, technologies or enterprise that will enable the construction and launch of interstellar spacecraft.

Vision

We aspire towards an optimistic future for humans on Earth and in space. Our bold vision is to be an organisation that is central to catalysing the conditions in society over the next century to enable robotic and human exploration of the frontier beyond our Solar System and to other stars, as part of a long-term enduring strategy and towards a sustainable space-based economy.

Values

To demonstrate inspiring leadership and ethical governance, to initiate visionary and bold programmes co-operating with partners inclusively, to be objective in our assessments yet keeping an open mind to alternative solutions, acting with honesty, integrity and scientific rigour.



Editor: John I Davies
Deputy Editors: Patrick J Mahon, Andreas M Hein
Layout / Proofing: John I Davies, Carol Wright, Lindsay A Wakeman

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The Institute for Interstellar Studies was incorporated in 2014 as a non-profit corporation in the State of Tennessee, USA.

Front cover: Worldship interior
Credit: Michel Lamontagne
Back cover: First Ever Image of a MultiPlanet System around a SunLike Star, Credit: ESO/Bohn et al.

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Scientia ad sidera
Knowledge to the stars