PRINCIPIUM

The Initiative and Institute for Interstellar Studies

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Scientia ad sidera
Knowledge to the stars

Editorial

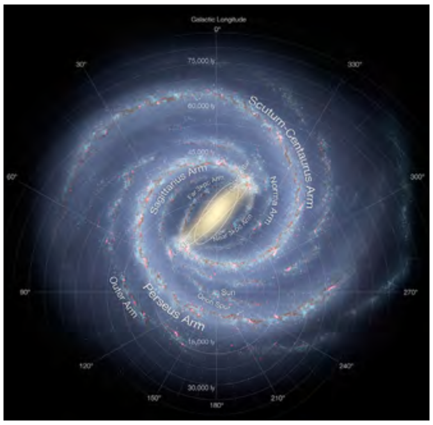
Welcome to issue 32 of Principium, the quarterly magazine of i4is, the Initiative and Institute for Interstellar Studies.

Our lead feature this time is *AMiTe Treffpunkt - A proposal for communication between Kardashev Type IIb civilisations* by David Gahan. David is a physicist and entrepreneur-engineer. He has always been fascinated with matters interstellar and here he builds speculation about very distant matters on relatively near-term technology. It's an eye-opener!

Slightly less distant but equally intriguing is Michel Lamontagne's *Worldship and self replicating systems*. Here the co-designer of the Icarus Firefly interstellar probe revisits his thinking on what may be our only route to human interstellar.

Our front cover image is a NASA visualisation of an exoplanet, *Hubble Pins Down Weird Exoplanet with Far-Flung Orbit*. The back cover image is a striking image of the veteran 250 foot dish at Jodrell Bank, taken by one of its staff, Dr Anthony Holloway. Much more about both inside the back cover.

As promised we have the second set of reports by multiple writers on the International Astronautical Congress 2020. We have 17 items of *Interstellar News* including a more detailed than usual look at the latest Interstellar edition of the Journal of the British Interplanetary Society. Max Daniels brings us more policy analysis with implications for our long term space activities, the US-led Artemis accords. We have a News Feature on the Starshot Downlink Webinar preceding their request for proposals for communications system research and development.



Spiral Arms of our home galaxy

See page 8

Professor Alan Aylward of University College London runs a very sceptical eye over the ideas of Professor Avi Loeb of Harvard about the interstellar object 1I/'Oumuamua in *An Interstellar Visitor: sorting the fact from the speculation.*

The regular Members Page includes summary of our recent Newsletters to members and *Become an i4is member* features a précis of Adam Hibberd's talk for members and a listing of new videos of our talks.

Our next issue, May 2021, will include a book review of *The Generation Starship in SF* by Simone Caroti (postponed from this issue) and of Avi Loeb's book, *Extraterrestrial* following on from the critique of Loeb's ideas by Alan Aylward in this issue.

Michel Lamontagne will expand on the theme of the self-replicating factory from his Worldship piece in this issue and Adam Hibberd will explain some *Practicalities and Difficulties of a Mission to 1I/'Oumuamua*.

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

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More in *The i4is Members Page* - page 65

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Please print and display our posters - we have new versions in this issue our: general poster on pages 24 (black background) and 44 (white)- and student posters on pages 49 (black) and 4 (white).

All our poster variants at -

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

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AMiTe Treffpunkt - A proposal for communication between Kardashev Type IIb civilisations

LEAD FEATURE

David F Gahan

In this paper David Gahan suggests that advanced and very long-lived civilisations might meet and communicate at an agreed meeting point. He uses a published model, the Daedalus probe, as a benchmark to consider how this might be achieved.

The author would like to thank Adam Crowl for useful discussions.

Abstract

This paper proposes the 'AMiTe' point - the Andromeda/Milky-Way Treffpunkt - as a meeting point of civilisations driven by a shared motive. It takes the basic Local Group geometries as its starting point and discusses whether 'Kardashev Type IIb civilisations' would find any absolute impediments to sending probes there to make contact. It is based on published analyses of interstellar mission profiles, communication and energy budgets.

The proposal is to model a 59 million-year mission comprising 1,000,000 Daedalus-class [1] 'Ships of the Line', forming a chain of communication at a nominal 4.19 light-year inter-ship separation. This line, extended in space and time, would attempt to make contact with a similar line, travelling anti-parallel or parallel in the region of AMiTe, sent by long-lived, overlapping and similarly motivated Type IIb civilisations (to be defined in this paper). These could be from either M31 Andromeda or our own galaxy. The extragalactic meeting point is proposed in order to solve the 'uniqueness' problem of where to go looking.

Introduction and Motivation

This paper is in direct response to comments on the 'Infinite Monkey Cage, UFO Special' broadcast 17/2/20 [2]:

- "If civilisations don't overlap, we will never meet the aliens." Dr Maggie Aderin-Pocock
- "The question is how close the nearest civilisation (is at present); I think the answer may be outside the Milky Way and therefore forever inaccessible." Professor Brian Cox

The paper posits a treffpunkt, watering-hole or poste-restante as a place for civilisations to meet. Recognising the useful work of Michael Hippke [3] on interstellar communications, this paper will adopt the German language word for meeting point, 'Treffpunkt' (so useful in German airports pre mobile phone), and refer to the unique point as the Andromeda/Milky-Way Treffpunkt or AMiTe (which could be pronounced 'Amity').

The paper takes as axiomatic that civilisations similar to ours would proceed from identical motivations to find each other, ie simple curiosity. If they develop the 'Treffpunkt' concept and conclude that a proposal to meet at AMiTe is both logical and technologically possible then it may already have been attempted many times by civilisations arising in, and over the long lifetimes of the Milky Way, Andromeda - and Triangulum - galaxies.

NB: given the extensive range of this paper, commonly accepted or uncontroversial numbers are sourced from Wikipedia unless otherwise stated.

[1] See *Project Daedalus – A Beginners' Guide,* Patrick J Mahon in Principium 24, February 2019, page 30.

[2] www.bbc.co.uk/programmes/m000ffzg *The Infinite Monkey Cage* is a BBC Radio 4 comedy/pop science series hosted by University of Manchester physicist Brian Cox and comedian Robin Ince, running for more than ten years as of this issue. Maggie Aderin-Pocock is one of the current hosts of *The Sky at Night*, a monthly astronomy BBC TV programme television since 1957.

[3] Hippke's publications include - *Interstellar Communication Network. I. Overview and Assumptions,* The Astronomical Journal, Volume 159, Number 3, preprint arxiv.org/abs/1912.02616 - *Interstellar communication. II. Application to the solar gravitational lens*, Acta Astronautica, Volume 142, January 2018, Pages 64-74, preprint arxiv.org/abs/1706.05570 - more via scholar.google.com/ "Interstellar communication".

A Unique Meeting Point / Water-Hole / Poste-Restante / Treffpunkt

Our galaxy contains between 100 and 400 billion stars and at least that many planets. The difficulties of other civilisations finding evidence of our existence ‘at home’ is the converse of us finding them at theirs. It is the contention of this paper that only at an obvious Treffpunkt, watering-hole or poste-restante, will the needles emerge from the cosmic haystack.

The only clearly unique location within the Milky Way galaxy is the galactic centre (GC). The stars in the innermost 10,000 light-years form a bulge containing the GC, an intensely busy radiation environment including the Sagittarius A* supermassive black hole of 4.1 million solar masses. Any space probe would have to pass through the most complex navigational and gravitational path to get there, with the highest extinction path for any return signals. The GC thus appears to be a poor choice for a galactic Treffpunkt as being too complex and dynamical a challenge.

Within the immediate environs, the Large Magellanic Cloud (LMC, fourth largest member of the Local Group) provides an alternative, defining a point of galactic longitude which only slowly varies in time.

However, over the timescale of millions of years which may be necessary for civilisations to succeed in an encounter, the position (eg of the mid-point) will vary, thus blurring the target. Furthermore, the LMC currently lies on the opposite side of the GC from us and getting there presents a navigational and dynamical challenge. However, the mid-point between the LMC and the Small Magellanic Cloud (SMC) may be a logical choice for civilisations in that part of the cosmos; they are in a stable relationship and are gravitationally connected by a tenuous gas-bridge.

As an alternative, the neighbouring Andromeda Galaxy, containing an estimated one trillion stars, is much the most obvious other member of our Local Group. The mid-point between the two galaxies represents a unique location in the Group, for aeons in the past and aeons in the future. We will refer to this as the AMiTe Point or just ‘AMiTe’. The line connecting the Milky Way GC (Sgr A*), AMiTe and the M31 GC will be the ‘AMiTe Line’ which also defines the Interaction Cylinder, to be discussed later.

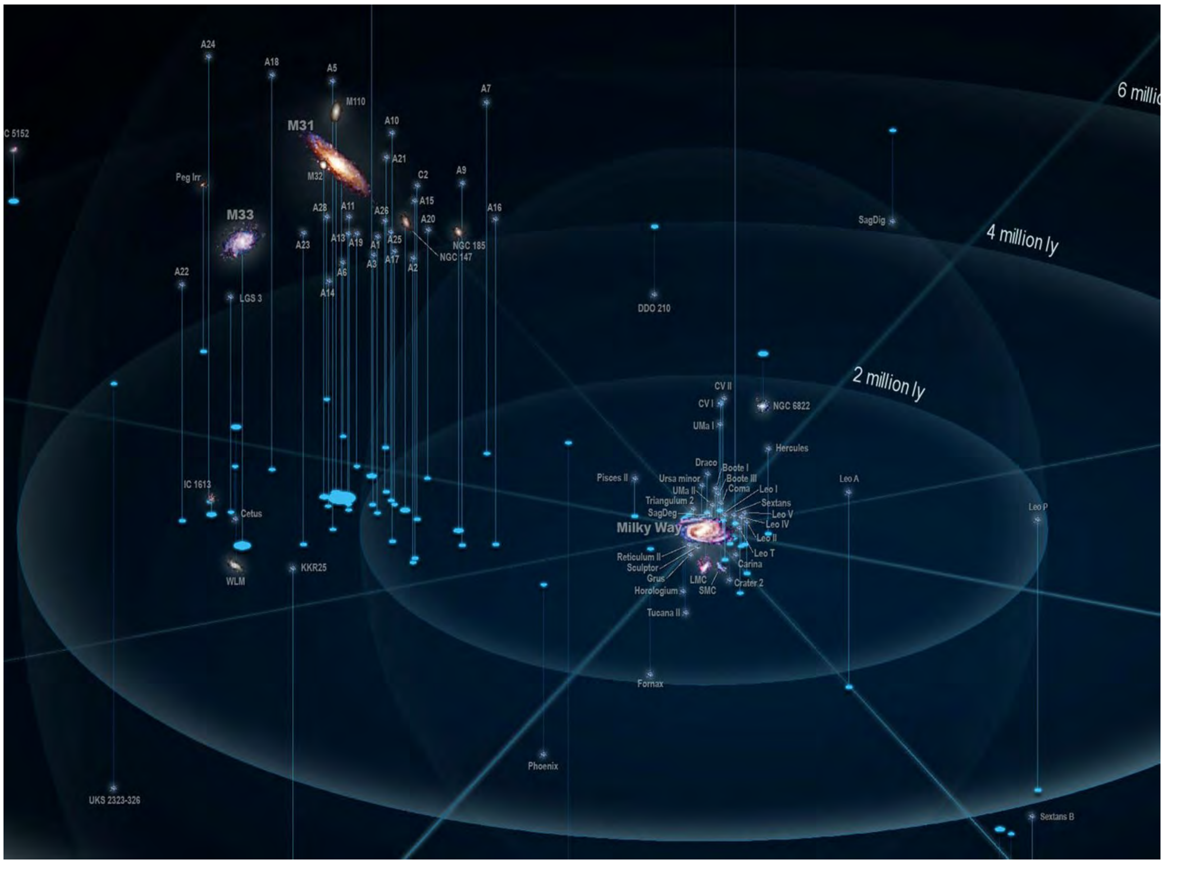


Figure 1 The Local Group and AMiTe Point (‘upside-down’ with galactic south at top)

Original graphic: Antonio Ciccolella / Wikimedia Commons

NB: Zero Galactic longitude is approximated by the Sculptor dwarf galaxy ‘near’ the LMC, so the Solar System is on the opposite side of the GC from this.

Removing the Time Constraint: Type-IIb Civilisations

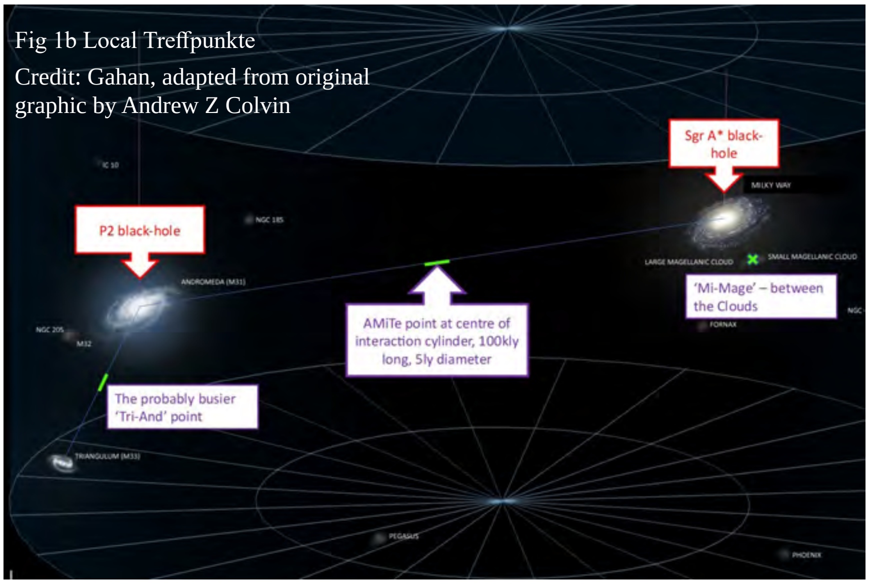


Fig 1b Local Treffpunkte
Credit: Gahan, adapted from original graphic by Andrew Z Colvin

The Drake equation requires a value for the longevity, L, of candidate civilisations. Drake's original estimates included a lower bound of 1,000 years [1]. Recent commentators have suggested values as short as 420 years [1], in part as an explanation of why 'they' haven't found us (the Fermi paradox). The author of this paper proposed an effective value for L based on an extrapolation of current endogenously (socially) driven human Total Fertility Rate (TFR) trends. Taking future trend TFR to be 1.6 (>40 states currently at or below this level, also the average of high-income countries, 2018 figures [2]), a peak population of 10 billion in 2100, and using three generations per 100 years, gives a constant logarithmic decline. In engineering terms, this is a factor of -1dB per generation or -3dB per ~100 years, ie a halving in the number being born. Figure 2 shows this extrapolated reduction to a level where arbitrary reasons might lead to the temporary extinction, technological disengagement or hibernation of the human race. A recent academic publication [3] has suggested that the absolute decline will start earlier than the author's model but did not extrapolate to the logical conclusion of maintained 1.6 fertility. No economic or socio-dynamic reasons why the decline (or change in TFR trend) will be arrested/reversed have been proposed.

A dwindling towards possible 'extinction', for instance ~5-6,000 CE, leaves plenty of time for our descendants to make every effort on currently envisaged SETI efforts and (if unsuccessful) consider very long-lived missions such as AMiTe. It seems entirely possible that they would consider a 'new start' for humanity in the future, either when the planet has been renewed or an alien race has been found with whom to commune, and make provisions for that. There would therefore also be time to perfect a robotic guardian/caretaker capability and biological sciences capable of effecting the new start. This could happen several times. With reference to the Kardashev scale, we may call a periodically 'hibernating' species plus its robotic caretakers a 'Type IIb' civilisation. For a Type IIb civilisation, with the entire resources of the Solar System at its disposal (Kardashev Type II), timespans of tens of millions of years required to send an AMiTe mission may be perfectly acceptable in order to achieve the Prime Directive decreed by the founding controlling human authority: 'Find other Civilisations!' This Type IIb concept removes any obvious time constraint on achieving that directive.

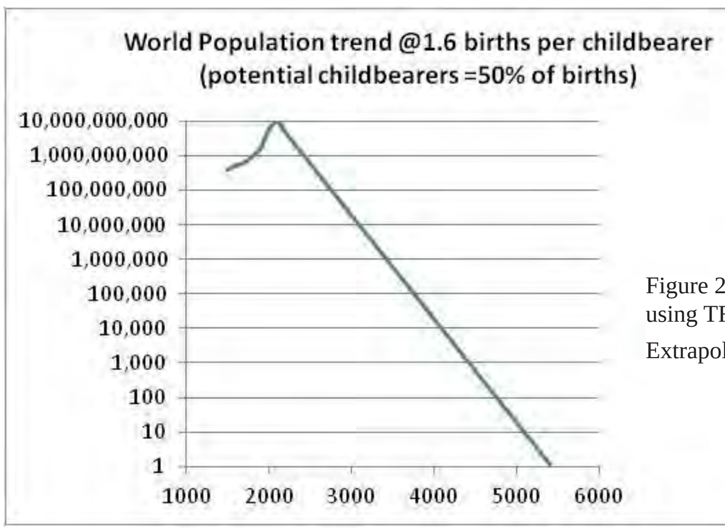


Figure 2. Historic growth of world population then decline over time, using TFR of 1.6 due to social factors.

Extrapolation/image by the author D Gahan

[1] The Drake Equation en.wikipedia.org/wiki/Drake_equation and *The Origin of the Drake Equation*, Drake & Sobel astrosociety.org/file_download/inline/58ee6041-5f61-4f88-8b15-d2d3d22ab83d

[2] Sovereign states by total fertility rate - en.wikipedia.org/wiki/List_of_sovereign_states_and_dependencies_by_total_fertility_rate.

[3] *Global population in 2100*, The Lancet, www.thelancet.com/infographics/population-forecast. Extract from Vollset SE, Goren E, Yuan. C-W. *Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study.* The Lancet 2020. Published online July 14. www.sciencedirect.com/science/article/pii/S0140673620306772.

Indeed, if galactic civilisations flower only rarely and briefly [1], a timescale of 60 million years (MY) may not be unreasonable. It represents one-tenth of the time since the Cambrian Explosion origin of complex life and is similar to the length of the Cenozoic geological era, since the extinction of the dinosaurs. From dynamical considerations of the Sun's position and orbit in the Milky Way, this admittedly long timescale may also be considered reasonable.

Our Position in the Milky Way: A Good Time to Go

Milky Way Data (from Wikipedia [2])	
Diameter	Stellar disk: 170–200 kly (thousand light years); dark-matter halo: ~1.9 Mly (million light years)
Thickness of thin stellar disk	~2 kly, average ~1 kly
Number of stars	100-400 billion $(1–4)\times10^{11}$
Sun's distance to Galactic Centre	25.6–27.1 kly
Sun's distance North of galactic plane	16–98 ly
Sun's Galactic Rotation Period	240 MY (million years)
Sun's orbital velocity	~220 km/s
Velocity vector angle with respect to Andromeda	31.7 degrees (longitudinal only)
Escape velocity at Sun's position	550 km/s

From Wikipedia [2]: "Perhaps, the Milky Way may contain ten billion white dwarfs, a billion neutron stars, and a hundred million stellar black holes. Filling the space between the stars is a disk of gas and dust: the interstellar medium."

From the foregoing it will be seen that navigation within the disk of the galaxy is much more complicated than out-of-disk. Leaving the comparatively thin disk of the galaxy would reduce the amount of fuel needed for course corrections to avoid hazards. A distance of 1-2 kly (depending on angle) is 0.1 to 0.2% of the distance to AMiTe and so, during this portion of the voyage, could be navigated at lower committed speed with navigational information being passed backwards along the chain. Escape velocity is 2.6% of the (to be proposed) cruise speed and so can be neglected. Gravitational attraction of the outer disk, in particular the Perseus arm (Figure 3), may in fact assist the planned trajectory. It should be taken into account, together with navigational hazards from smaller, satellite galaxies and intervening masses in a future, more detailed analysis.

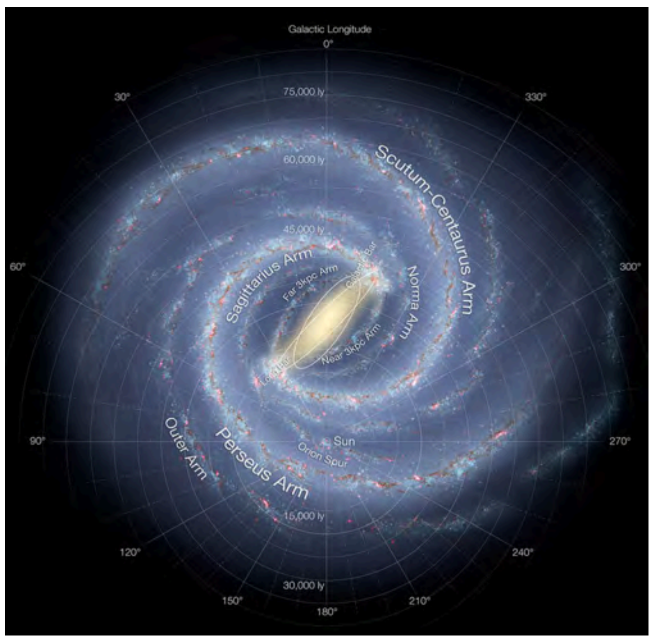


Figure 3 Spiral Arms of our home galaxy.

Credit: NASA/JPL-Caltech/ESO/R. Hurt www.eso.org/public/images/eso1339e/.

Our Solar System currently lies in an unusually propitious relationship (except for distance) with M31 Andromeda for our civilisation to consider a mission to AMiTe. In Figure 3, the galactic coordinate direction to M31 is along the 120° (actually 121.7°) galactic longitude line, through the final 's' of 'Perseus', about 10 diameters in this direction. The galactic latitude of M31 is -21°. For a description of galactic coordinates, see [3].

[1] *A Statistical Estimation of the Occurrence of Extraterrestrial Intelligence in the Milky Way Galaxy*, Xiang Cai, Jonathan H. Jiang, Kristen A. Fahy, Yuk L. Yung arxiv.org/abs/2012.07902.

[2] Milky Way en.wikipedia.org/wiki/Milky_Way.

[3] Galactic Coordinate - en.wikipedia.org/wiki/Galactic_coordinate_system main article and item #2 on 'talk' page en.wikipedia.org/wiki/Talk:Galactic_coordinate_system.

A description of the dynamics of the Solar System's motion towards M31 Andromeda is given by 'SyntheticET', a contributor to the Wikipedia page on Galactic Coordinates (cited above): -

"If the galaxy were a carousel on a moving train, Andromeda's Galaxy would be dead ahead on the tracks and your horse would be moving 31.17° to the right relative to the train. At the present time Andromeda and the Galactic Centre are 121.17° apart along the Galactic Equator. About 19 MY ago Andromeda and the GC were 90° from each other and Earth was moving fastest toward M31. 65 MY ago when the dinosaurs disappeared M31 was in 'conjunction' with the Galactic Centre. The Milky Way Galaxy itself is moving in its entirety toward Andromeda. The Sun and nearby stars are moving and at a point in Galactic orbit somewhat past 90° from the GC. The two velocities - Galactic and Solar - add vectorially. At this time the Sun is 31.17° past the point where the velocity dead ahead is greatest."

With the Sun's rotation period around the GC being ~240 MY, our closest approach to M31 will be in about 40 MY. The following 60 MY are therefore 'a Good Time to Go' in this direction, minimising distance but also avoiding the intervention of the GC which could disrupt the tenuous communication line. Type IIb civilisations on the opposite side of the GC from us may choose to wait another ½ rotation before attempting the AMiTe point.

As given above, the galactic latitude of M31 Andromeda is -21.57 (note galactic +90° in Coma Berenices). The Sun's position at 16–98 light years (ly) north of the galactic plane, of 1-2 kly thickness, means slightly more of the thickness of the plane to traverse before emerging into less populated regions, but this seems one of the lesser concerns. The relatively high out-of-plane latitude of M31 seems favourable to minimise travel within the populated disk (versus travel to the GC).

Definition of the AMiTe Treffpunkt from both viewpoints

The distance to M31 is 2.54 ± 0.11 Mly (uncertainty of 0.11Mly depending on definitions) [1], therefore distance to AMiTe is around 1.27 Mly. It is taken as a given that civilisations in both galaxies would independently and unambiguously define their own GCs based on the 'sheet anchor' roles played by their respective black holes. These would be extrapolated to a space/time coordinate based on time-of-flight mission profiles, assumed for the purposes of this paper to be broadly similar (errors to be calculated).

We know where to find our own GC, Sagittarius A*, a black hole of 4.1 M solar masses; we presume that counterparts from M31 know this equally well. Any orbit of Sgr A* relative to the aggregate barycentre would introduce uncertainty over time. However, observations from home-system based telescopes at both ends of the chain during time-of-flight would allow for corrections. This would be spatial information but in the most logical timeframe or 'epoch'. The space coordinate of AMiTe for mission considerations would be the exact half-way spatial point between the best observed positions of the Galactic Centres, but the time coordinate would (probably) be 2.54 MY before AMiTe's notional present to allow for round-trip times for correction information. M31 is inclined at 13° relative to the line of sight to Earth, therefore M31 civilisations would have ample opportunities to observe the Milky Way and the long term location of Sgr A*, and send the latest estimates.

Images from the Hubble Space Telescope (2005) [2] of the Andromeda Galaxy's inner nucleus showed two concentrations. The dimmer concentration, designated P2, contains a black hole measured at 1.1–2.3 × 10^8 solar masses. The brighter concentration, P1, is offset from P2 by 4.9 ly; this separation distance could be among the considerations for a scaling rule for the target volume. Taking the location of both the black holes as the accepted GCs, it is proposed that the location of the AMiTe could be defined to a very few light years in a logically reasonable reference frame. In the absence of a more detailed mathematical treatment, we will consider an AMiTe uncertainty of +/-2.5 ly in X,Y,Z for the communications challenges, or a volume 5 ly in diameter.

An alternative scaling factor for the target volume would be the average interstellar distances in the vicinity of civilisations attempting this mission (assuming galactic disk, not core or globular cluster). In the case of the Solar System, this is approximately 5-6 ly, consistent with a stellar density of 0.004 stars per cubic lightyear [3].

[1] Andromeda Galaxy - Wikipedia, Distance Estimate en.wikipedia.org/wiki/Andromeda_Galaxy#Distance_estimate

[2] Andromeda Galaxy - Wikipedia, Nucleus, en.wikipedia.org/wiki/Andromeda_Galaxy#Nucleus

[3] Stellar density - Wikipedia en.wikipedia.org/wiki/Stellar_density

Once the midpoint has been determined, there is also an opportunity to define a cylindrical corridor along the AMiTe Line and centred on the midpoint. This Interaction Cylinder we might propose (for illustrative purposes) to be 5 ly diameter x 100 kly long. This would allow longer interaction times for fleets of probes. Figure 4 illustrates the scale length of the interaction cylinder around the AMiTe point (width not-to-scale) together with other Local Group 'Treffpunkte'. Before considering communications strategies, we will examine the nature of the probes.

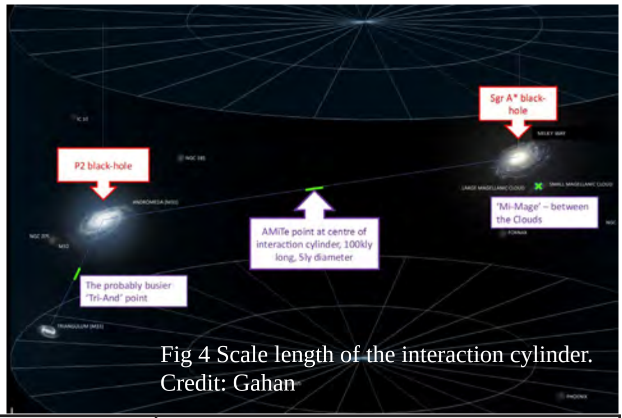


Fig 4 Scale length of the interaction cylinder. Credit: Gahan

Nature of the Probes

Project Daedalus [1] remains the benchmark 'heavy-ship' model in the literature and is referenced by most studies, including the in-progress 'Project Icarus' , see the 2011/2016 review of fusion based propulsion by K F Long [2]. Its respectability on the grounds of the laws of physics has not been formally challenged but Long notes that its performance is at the 'outer extreme' of parameters such as specific power (MW/kg).

Daedalus Target Capabilities:	First stage:	Second stage:
Empty mass:	1,690 tonnes (at staging)	980 tonnes (at cruise speed)
Propellant mass:	46,000 tonnes	4,000 tonnes
Engine burn time:	2.05 years	1.76 years
Thrust:	7,540,000 newtons	663,000 newtons
Engine exhaust velocity:	10,600,000 m/s	9,210,000 m/s
Final velocity:	0.071 c	0.12 c

However, we can join the other studies by quoting the projected capabilities and using those as an initial model for the energetics of the mission. Both Daedalus (and Project Longshot [3]) take the Pulsed Fusion Microexplosion Drive [4] as the only technology likely to yield sufficient specific thrust with feasible amounts of reaction mass. The system concept is to fire high energy beams at small fusionable pellets that will implode and be magnetically channelled out the nozzle. The projected specific impulse (I_{sp}) is 10^6 seconds. Long raises some specific concerns noted by the Icarus team on the uniformity of the inertial confinement fusion compression based on more recent ICF [5] studies. The Icarus team considered alternative drive schemes which could in the future be considered for a more realistic AMiTe study.

Daedalus (and Longshot) selected helium-3/deuterium (He-3/H-2) as the fuel since yielding no neutrons or a low flux of neutrons, which would otherwise irradiate the entire spacecraft over the 50-100 year transits. Availability of helium-3, very rare on earth (and only 0.0002% occurrence vs He-4), was flagged as a problem. The possibility of mining the atmosphere of Jupiter was proposed; this may be a suitable task for a robotic 'guardian' civilisation based on our or other moons. Saturn was not proposed, despite having an outer atmosphere of 3.25% (total) helium by volume, compared with 8-12% for Jupiter, but with a lower escape velocity. Such mining would consume a lot of energy, but much fusionable deuterium would also be obtained. For the purposes of this paper, we assume that sufficient fuel can be collected once every 59 years (time taken for the Sun, Jupiter and Saturn to return to the same configuration). We take this 59 year interval as a possible launch frequency. Future studies may decide that He-3 is not required, possibly relaxing some constraints including the proposed launch interval.

[1] A. Bond & A.R. Martin, *Project Daedalus – Final Report,* JBIS, pp.S5-S7, 1978, also *Project Daedalus – A Beginners' Guide,* Patrick J Mahon, in Principium | Issue 24 | February 2019, page 30 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/

[2] *Project Icarus: Specific Power for Interstellar Mission using Inertial Confinement Fusion Propulsion* JBIS Vol 69 pp190-194, 2016, static1.squarespace.com/static/565a1ea9e4b0f0c1a0216d38/t/5855d2106a49634cd5552c84/1482019348621/190-194+%281%29.pdf

[3] en.wikisource.org/wiki/Project_Longshot/Spacecraft_Systems#3.1

[4] Inertial Confinement Fusion - nuclear fusion initiated by heating and compressing a fuel target using lasers as in the US National Ignition Facility (NIF) lasers.llnl.gov/science/pursuit-of-ignition.

[5] Project Icarus:Development of Fusion Based Space Propulsion for Interstellar Missions JBIS Vol. 69 pp 289-294, 2016.

Project Longshot acknowledged that a fuel injection in a system that must run for 100 years continuously, without repair would be problematic; however the AMiTe mission profile is far more demanding and requires ship operation for millions of years. While the majority of the extra-galactic part of the mission will be in cruise mode, the mission profile would require a minor course correction (1-2% delta-v) after ~96% of mission time and therefore a healthy propulsion system with some remaining fuel. In 'Longshot', a fission reactor is available for constant power for the communications lasers. Since AMiTe requires power for the lasers over very long (but not necessarily continuous) periods, and then also to re-start the main drive for at least one course correction, either an alternate fusion reactor mode or a small additional fission reactor (if mass-efficient) would be required, perhaps taking advantage of the extraordinarily long half-life of U-235 (703.8 million years).

Entering Kardashev Type II (and then IIb) stages, human civilisation will have thousands of years before attempting an AMiTe mission to develop and perfect starship technologies as proposed for Icarus and Daedalus. These and the required communications chain technologies could be perfected during hundreds of visits to nearby stars. Taking for the moment an assumption that successful missions over some thousands of years will enable the numerical performance goals at the Stage1 / Stage2 transition of Daedalus to be realised, it follows that 'Daedalus-class' starships can at least be despatched towards AMiTe to attempt contact.

Energetics

To estimate the ongoing communications power requirements, the energetics of Project Longshot are instructive. Longshot was designed "with existing technology in mind" and maintains communications with earth from the Alpha Centauri system (see Communications). The power plant is a 'long-lived' fission reactor "initially generating 300 kilowatts". The Longshot mission reactor would be used initially to power the ICF [1] fusion lasers, the ongoing ship-control needs and then, during encounter, the full power would be used for a 250 kW communications laser back to Earth. During cruise phase (most of the journey) the Longshot laser would be used at a much lower power for sending data about the interstellar medium or (more relevant for AMiTe) 'keep alive' tracking signals for ships up and down the line.

While AMiTe mission profiles seem to rule out a fission reactor as sole energy source (because 'always on' over extended timescales), the power budget of 250/300 kW calculated by Longshot designers is a useful benchmark. For the whole mission energy budget, taking Daedalus as a model and comparing the available energy budget with the requirements for communications over an 'Alpha Centauri' distance of 4.37 ly:

Daedalus Class ship on AMiTe Mission:		
Cruise velocity	0.071c	Cruise velocity = Daedalus 1st stage terminal
Mass at 0.071c	6,670 tonnes	Daedalus 1st /2nd stage plus 2nd stage fuel
Required fuel to 0.071c	46,000 tonnes	If propulsion system is feasible
Available fuel mass at 0.071c	4,000 tonnes	Used by Daedalus 2nd stage to achieve 0.12c
Kinetic energy at 0.071c	1.51E+21 J	Simple ½ mv2
Energy in 4,000 tonnes	1.32E+20 J	Simple 4/46 calculation; need to model efficiency for power plant (non-drive) uses
Distance to half-way point plus 50 kly	1,320,000 ly	(0.5*2.54 Mly) + 50 kly; would be somewhat longer due to path curvature, but not much
Time at 0.071c	18.6 MY	Note, this permits 100 kly of anti-parallel path
Available energy/time (W) for 18.6 MY	224 kW	Approximately 2x power of a London bus,

Thus modifying the Daedalus mission profile to achieve an extra-galactic cruise velocity of 0.071c by a mass of 6,670 tonnes including 4,000 tonnes of convertible fusion fuel the probe would have sufficient 'energy' on board to be equivalent to a time-averaged shipboard power of ~225 kW for 18.6 MY for all communications and detection purposes. This power/energy budget over mission life, being within 10% of 'Longshot' power requirements is a serendipitous conclusion from the adapted Daedalus numbers; even being within a factor of 10 would be encouraging. Energy conversion efficiencies will be much lower than the primary drive but much more advanced mission modelling may permit a more realistic profile.

[1] inertial confinement fusion. en.wikipedia.org/wiki/Inertial_confinement_fusion

See Rob Swinney's introduction to ICF at ISU Strasbourg in *2.12 M8-ISR-L12 Advanced Propulsion Systems 2* summarised in Principium 31 November 2020 page 79 and his earlier *Extreme Deep Space Exploration: A Personal Perspective* Principium 25 May 2019 page 24.

The energy requirement for a final course correction along the 'AMiTe Line' would represent a delta- v of 1-2% (actually maximum now at 1.8% for a straight course, due to the current position of M31 at galactic longitude of ~121 deg). While this must be budgeted, the energy could be saved by reducing cruise velocity to 0.0697c, so not significant overall.

While the above assumes that the power conversion rate of ~224 kW would be 'always-on' during the entire mission, the search phase part of the mission lasts for less than 10% of the journey travelled (100 kly in 1.32 Mly). There may be an opportunity to save energy during the 'quiet' part of the cruise where mostly keep-alive data will be sent/received. However, this depends on power-plant design.

Communications: The Chain

There are two clear communications challenges:

(1) AMiTe Treffpunkt to Solar System chain and inter-ship communications, including (when found) with 'ET'.

(2) First Contact, 'We're Here' signalling.

We will address these in the order above, since (1) constrains (2).

Using Project Longshot as a communications model [1] for an Alpha Centauri mission within the disk of the Milky Way, we take this link-length to be the standard link-length for the entire chain. To paraphrase the Longshot scheme:

> "The major challenges for the communications system are at the range of 4.3 light-years (4.1 x 10^{16} metres - the maximum transmission range). A data rate at about 1 kilobit per second must be maintained, since all probe instrumentation is returning data. The only type of communications system capable of the necessary directivity and data rate is a high-power laser using pulse code modulation (PCM)."

Low background noise from the target system is necessary for a low power level, so a laser wavelength of 0.532 microns was chosen by Longshot. Radiation of this wavelength is almost totally absorbed by the outer atmospheres of K and G type stars such as Alpha Centauri, leaving a hole in the absorption spectrum (no transmitted radiation). (NB Doppler shift at velocities of 0.045-0.071c will change this). Laser radiation of this wavelength can then be produced by a frequency-doubled diode-pumped YAG laser with an optical attachment to provide a large initial aperture.

The Longshot transmitter aperture is 2 metres in diameter with receiving mirrors (solar system) of 24 metres diameter. The spreading angle is 1.22*lambda divided by the aperture diameter, or 3.25 x 10^{-7} radians (0.067 arc-seconds. At 4.3 light-years, the spreading results in a footprint radius of 13.4 million kilometres, 8.9% of an astronomical unit). Both the pointing accuracy of the laser mount and the attitude determination capability of the probe must be within 0.067 arc-seconds so very low error laser mounts and star trackers are required. (NB for AMiTe, we will consider send/receive optics of 10 m diameter).

A total input power of 250 kilowatts is needed for each laser that is transmitting. With an assumption of a 20% lasing efficiency, the transmitted power is 50 kilowatts. If the power is distributed isotropically over an area of 5.64 x 10^{20} square metres (the area subtended by the laser beam when it reaches the target distance), the power density is 8.87 x 10^{-17} watts per square metre, or 222 photons per square metre per second. For a 24 metre diameter mirror (area of 452.4 square metres), the received power level is 4.01 x 10^{-14} watts, or 100,000 photons per second. Using the assumption that a digital pulse 'on' level is 100 photons, the receiver sees 1000 pulses per second. So, data rate at maximum range for 'Longshot' was 1 kbit/s. Compare with the NASA probe 'New Horizons' which achieved a data rate of 1 kbit/s at P = 13 W (radio frequency) from Pluto, and transmitted a total of 50 Gbits over the course of 15 months.

Longshot posits six 250 kilowatt lasers, operating at 'slightly different' wavelengths (although not clear if this is consistent with the reactor power). The estimated weight of the communications lasers is 2 metric tons. If we retain the 4.3 ly range for communications, the above worked example shows that communications could be maintained along a chain using ~250 kW of peak power for the required mission length. The principal assumptions we will change are the diameter of the sending (2 m: diffraction limited) and receiving (24m: satellite based) optics. The number of received photons in the scheme scales as the

[1] Project Longshot Communications System Design en.wikisource.org/wiki/Project_Longshot/Spacecraft_Systems#3.4

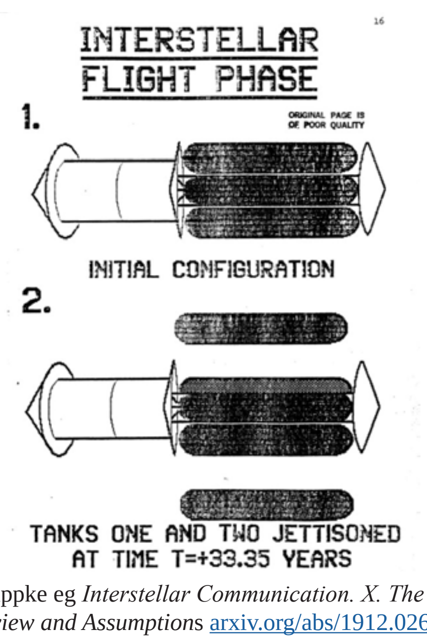
product of the optics diameters squared, ie $(D_{send} \times D_{rec})^2$. For our mission, we'll assume (as does Hippke [1]) 10 m diameter send optics which improves divergence by a factor of 52 and 10 m receive optics reducing light collection efficiency by 2.42. The net change is an improvement by a factor of ~4. Technologically, the compensating improvement due to larger send optics may be harder to achieve than the countervailing reduction in receive area but we will take this modified Longshot model and scaled numbers as an indication that a ~4.3 ly ship separation (in the extra-galactic cruise phase) gives reasonable communication bandwidth. According to Hippke [1], the time to transmit 1PB = 10^{15} bytes, 'the information content of a human brain' at 1 kb/s would be 250 thousand years, not long by the AMiTe mission scale.

At 4.3 ly *2 round-trip times, pointing feedback would require continuous but low bandwidth monitoring, especially in trajectories affected by nearby stars during traverse of the galactic disk. Lower data rate signals at higher divergence could be sent to avoid losing contact and inter-ship distances kept smaller due to lower speeds. Outside the galactic plane there would be greater predictability and perhaps ability to compensate if a ship 'falls silent' by missing out a link in the chain, so 4.3 ly separation is retained for modelling. Links to next-but-one ships at lower data rates should be possible.

Thus, the chain of communication is proposed to be Daedalus-class 'ships of the line', using 532 nm and 10 m optics. We modify the inter-ship separation (during the extra-galactic cruise) to 4.19 ly, the modified distance comes from allowing for one launch every 59 years and assuming a 'Daedalus' cruise velocity of 0.071c). The line can tolerate a few fall-outs but must be largely maintained for secure data-transfer back to Earth for 40-60 MY, ie up to one million ships.

Hippke in his thoughtful series has also examined extreme distance communications at optical wavelengths [1]. Assuming that laser physics for all civilisations converge on the most efficient technology, Hippke discusses wavelengths including Nd:YAG (1,064 nm), its second harmonic (532 nm), and also at the sum frequency and/or second harmonic generation of Nd:YAG and Nd:YLF laser lines eg 393.8 nm (near Fraunhofer CaK); for known Doppler shifts, these can be observed through a narrow filter for long-chain communications. From extinction considerations, and for strong signals, he concludes that shorter optical wavelengths such as 532 nm are optimal for distances up to ~ kiloparsecs (kpc) ~3,000 ly.

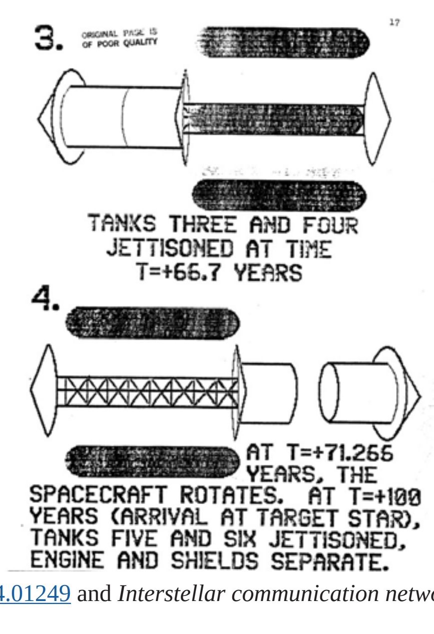
These extreme distances are dependent on high power pulses and high bit/photon efficiency, and so are quoted here to put bounds on signalling distance. Hippke gives an analysis of extreme distance (kiloparsec [2]) point-to-point signalling using Megajoule pulsed lasers and concludes that a 1 MJ laser outshines a host star (eg the Sun) by a factor of 10^4 during a pulse if the wavelength is known, independent of distance. However, for an AMiTe mission, the line connecting the GCs terminates on the bright and extended areas of the galactic cores and so this calculation needs to be verified against the GC brightness over extended spectral bands owing to Doppler uncertainty (due to ship velocity).



Longshot vehicle configuration from *Project Longshot: An unmanned probe to Alpha Centauri*, ntrs.nasa.gov/citations/19890007533

Credit: NASA / Beals et al, US Naval Academy Annapolis, 1988

NOTE: There is some doubt about the relative size of the fuel tanks, based on the calculations in the study.



[1] Hippke eg *Interstellar Communication. X. The Colors Of Optical Seti* - arxiv.org/abs/1804.01249 and *Interstellar communication network. I. Overview and Assumptions* arxiv.org/abs/1912.02616

[2] One thousand parsecs. A parsec is about 3.26 light-years. It is the distance at which an astronomical unit subtends an angle of one arcsecond. It thus relates directly to astronometry using the Earth's orbit as a baseline.

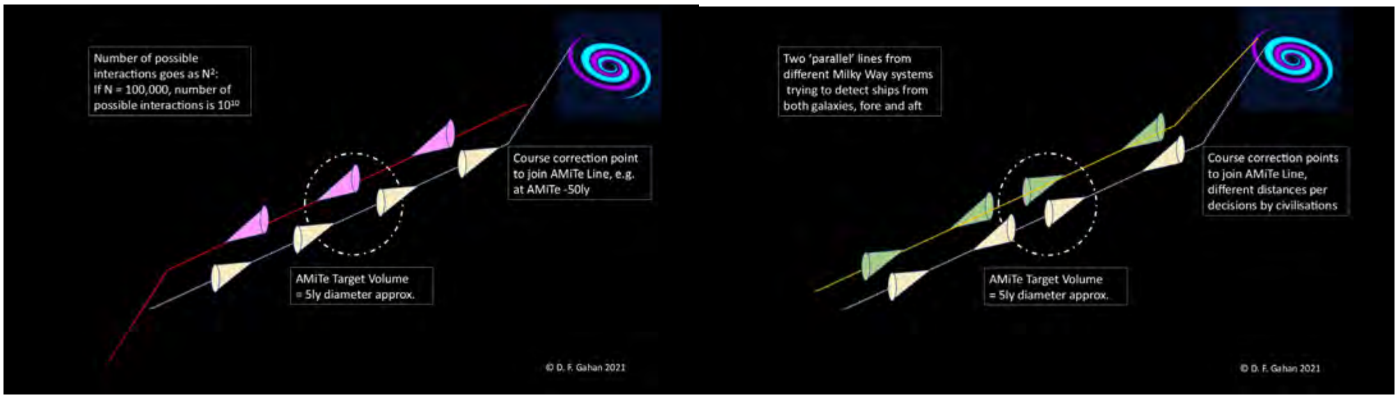


Fig 5: Interacting lines of ships attempting contact while travelling antiparallel and parallel in the vicinity of AMiTe: Lines from Andromeda and Milky Way conducting forward searches (a); Lines searching both forward and backward can detect probes from their galaxy of origin (b).

Credit: Gahan / Local Group montage

Credit: galaxy icon – Vectorstock,

The importance of N for 'First Contact'

From the above, it will be seen that we are trying to establish contacts between two putative lines of ships, anti-parallel or parallel (Figure 5). If participating civilisations came to the same or similar conclusions, the main parameters might be:

- AMiTe point location: mid-point between GCs, epoch 2.54 MY before AMiTe present, uncertainty +/2.5 ly xyz
- Core target area: sphere of 4.9/5 ly diameter (scaled by AMiTe uncertainty, Andromeda central concentration separations, average stellar distances in the galactic disks)
- Desirable number of ships in target volume at any one time: one (from each line)
- Interaction cylinder length (parallel/anti-parallel trajectory from any point in approaching quadrants: unknown. 100 kly has been arbitrarily chosen for energetics calculations, ie life of probes, but multiples of 10 and 'light-years' are not obviously meaningful bases for other species
- Length of mission: ¼ of galactic rotation period: 60 MY for both
- Length of mission overlaps: unknown, depends on Drake equation parameters
- Actual velocity and separation in interaction zone: unknown, depends on arbitrary factors
- Wavelength selected: probably common, but at unknown Doppler shift

If all the arguments above concerning Type IIb civilisations, Prime Directives, uniqueness of AMiTe, technological feasibility are held to be reasonable, the problem reduces to a core Drake equation question: will two Type IIb civilisations send out missions as above which travel along antiparallel/parallel paths for a significant portion of time, and what is the probability they will communicate?

Taking the case where the only relevant Type IIb in M31 'approaching quadrant' is dephased from ours by 30 MY, eg we start sending probes now but they don't develop the capability and the intention until 30 MY in the future, and where the transit time to AMiTe is ~20 MY: many of our Daedalus ships will have no opportunity to interact. ET will only start sending ships when the first of ours is already 0.75 of the way to M31 and will be dead, per the design energy budget. Their line of ships will only reach the interaction cylinder ~50 MY in the future when we have already despatched 5/6 of the ships that will ever be sent, and 10 MY before the chain is broken at our end. This clearly gives 10 MY of interaction time.

To calculate interaction probability, we will take the length of the interaction cylinder as 100 kly, at the far end of which, all available energy has been expended on communications attempts. How many ship-ship encounter possibilities will there be over 10 MY? This is easy to calculate: three of our ships passing three of theirs gives 3*3, so goes as N-squared. With 10 MY interaction time representing over 100k ships, there are more than 10^{10} opportunities for interaction within the target area before the chain is broken. Even at very high individual probabilities of 'ships passing in the night' without communicating, the odds seem favourable. Higher numbers of participating civilisations greatly increase the possibilities of many-to-many communication.

‘We’re Here’ Signalling

At first glance, the problems for two small starships trying to find each other in a 5 ly volume appear daunting. The modelled communications over 4.3l y to Alpha Centauri depends on pointing accuracy within 0.067 arc-seconds and known wavelength, permitting narrow-band filtering.

While we have chosen 0.071c for historical reasons (Daedalus study and available calculations), the actual relative velocities of ship trajectories is unknown and Doppler shifts could be either blue for approaching ships or even slightly red, in the case of overhauling other Milky-Way outbound chains. Taking the extreme case of two probes approaching with a relative(istic) velocity of 0.2c (both ships at near Daedalus maximum velocity), signals would be significantly blue-shifted. The standard Doppler calculation shows, for wavelengths considered by Hippke:

λ-emitted (nm)	λ-received (nm) at 0.2c
1064	869
532	434
395	322

The large uncertainty in blueshift would preclude the use of fixed narrow-band filters in the initial detection phase; this would add to the difficulty of initial detection phase against the background of the bright GCs. If a sufficiently strong signal for spectral analysis, and with an unusual repetition (‘Little-Green-Men' LGM pulses [1]), Doppler shifts might be useful for positive identification. Of course, any help from blue-shift in this respect would only apply to approaching ships and be of little help in contacting outbound ships.

However, there would be no help from filtering for initial detection, and none from direction due to the geometric uncertainty of the AMiTe GC/GC line. In fact, for central line +/-2.5 ly, a ship on the periphery of the circle of uncertainty would subtend an angle of +/-30° to the centreline for a ship entering the central volume on the connecting line so could be coming from ‘anywhere’. Clearly, any reduction in assumed uncertainty would help to narrow the search volume.

Thermonuclear explosion signalling

A further possibility which can be numerically considered and perhaps quickly dismissed, is to examine the effectiveness of thermonuclear explosion signalling. Assuming that a short series of bombs equal to the largest ever exploded could survive an 18 MY wait and be detonated (at a suitable distance behind the probe) while crossing the calculated AMiTe point and at timed intervals, what is the effective detection range?

The size and mass of thermonuclear warheads is surprisingly small and a few could be accommodated, eg W88 Warhead (Trident missile), mass <360 kg, size <2 m^3, yield 2×10^{15} Joules. The half-life of the U235 (fission primary) is >700 MY and so it seems reasonable that such explosions would be possible. The light curve (spectrum vs time) of a bomb in vacuum is not readily available information but some estimate can be made of the gamma-ray yield. According to [2] the strong electromagnetic pulse (EMP) that results has several components. In the first few tenths of nanoseconds, about a tenth of a percent of the weapon yield appears as gamma rays with energies of one to three mega-electron volts. In the case of the largest H-bomb trial in the 1950s which yielded 2×10^{17} Joules, if 0.1% of this was emitted as 1 MeV gamma rays, the photon yield would be 1.25×10^{27} photons. Such energetic particles yield multiple detection events and can be used to extract directional information (as happens eg in the Large Hadron Collider detector stations). However, this requires a lot of detector area electronics. The gamma photon yield is small when spread over eg a sphere radius 1 ly (1.26×10^{33} sq m) and at least two explosions would need to be detected, with good directional data and same energy to distinguish from random cosmic events. If a ship only used explosive signalling at the AMiTe point then probabilities are increased as N (number of ships) rather than N^2. This at present seems unpromising and an example of the difficulty of isotropic signalling at light-year distances, the ‘wastefulness’ of this method coming from most energy being lost as the kinetic energy of an expanding sphere of gas. More consideration may be warranted if an estimate could be made of the light curve of the cooling sphere.

[1] Jocelyn Bell Burnell, *Discoverer of pulsars (aka Little Green Men) reflects on the process of discovery and being a female pioneer,* news.cornell.edu/stories/2006/07/jocelyn-bell-burnell-reflects-discovery-pulsars

[2] Fission bomb yields en.wikipedia.org/wiki/High-altitude_nuclear_explosion referencing *Electromagnetic compatibility (EMC) - Part 2: Environment - Section 9: Description of HEMP environment - Radiated disturbance. Basic EMC publication* webstore.iec.ch/publication/4141 (paywalled)

As mentioned, the AMiTe Line connecting the GCs terminates on the bright and extended areas of the galactic cores. M31 has an 'Absolute Magnitude' in the visible of –21.5 (at the notional 10 parsecs); the apparent magnitude at AMiTe would be +1.5 (using ½ way distance of 389 kpc, the inverse square law and taking logs to base 100 and applying to the 'absolute'); compare this with +3.4 apparent magnitude at Earth's surface on a fine autumn/winter's night. Detailed photometric calculations would be needed to determine the effective range of a blue-shifted source at a particular power/divergence/pulse-length vs either the bright galaxy or the 'sky' around it. The bright nucleus visible with the naked eye on earth has an angular extent of about 0.5° and so would be around 1° from AMiTe. Any defect in the spaceships' courses from the 'perfect' AMiTe Line would mostly remove them from optical overlap with the bright background galaxies, but these areas would be more 'in view' from further back in the interaction cylinder.

Consider the area illuminated by a low divergence cone. This is really very small compared with the possible cross-sectional 'uncertainty area' of a 5 ly disk. At 4.3 light-years, the spreading of 'Longshot' (2 m send lens) signals results in a footprint radius of 13.4 million kilometres, or 8.9% of an Astronomical Unit (AU). With 10 m receive optics, this would still support a bandwidth of over 100 bit/sec, plenty for LGM signalling. 10 m send optics could, of course, be defocused to give the above divergence angle, or greater. Assuming the radius of 9% of an AU at 4.3 ly (~10% of AU at 5 ly) this represents a tiny fraction of a 5 ly disk (3.6×10^{-15}) or about 10^{-13} of a 1 ly diameter disk. If it takes a ship around 60 years to cross the volume, the average crossing time of two anti-parallel ships would be 30 years, about 10^{9} one-second timeslots over a 60° full-angle cone if the beam could be scanned/rastered, and assuming wide-angle defocused receiving optics. However, even this number of time-slots and area coverage over the whole area to scan, we fall short of covering the full target area by a factor of 10k to 250k. The N- squared factor of (eg) 10^{10} would therefore be needed to improve the odds. Higher spreads with weaker signals would also do this, limited by S/N performance, but should still allow reception of an unmistakeable LGM signal by a ship in the cone (and possibly up to twice or more the distance down the chain). There are many variables in signalling, search and trajectory patterns and it may be up to the optical SETI (O-SETI) research community to suggest a more considered approach to give a higher probability of any pair of ships communicating.

High energy pulse signalling may also be an option with ships starting to send high energy pulses as soon as they are on the interaction line, ie at AMiTe - 50 kly. At ~4 ly spacing along a 100 kly line, there would be of the order of 25,000 ships all sending high energy pulses forward, at low repetition rate, but with identical Doppler shifts which could have considerable range (remembering the maximum range calculated by Hippke of up to 3 kpc (~10,000 ly), in ideal filtered conditions).

After Contact: What Next?

This can mainly be left to the imagination. Once initial detection had been made within the interaction zone, trajectories would be calculated and passed up and down the line. Remaining fuel would be used to achieve closer approach and higher bandwidth communication at a precisely defined and filtered wavelength. 'Conventional' SETI thinking, AI and machine learning would establish communications protocols which would enable data downloads to commence. Once all on-board data had been exchanged, some ships might use remaining fuel to divert towards suitable home systems in the target galaxy, enabling recovery (and possible artefact transfer) by separate, later launched 'docking' missions.

Project Counterparts

The 'Treffpunkt' concept relies on other civilisations drawing the same conclusions about the merits of AMiTe as a unique meeting point and, following long study and practical experience, arriving at a broadly similar mission profile. Absolute details such as probe velocity and spacing may be influenced by home-system details eg orbital periods of suitable gas giants and availability of He-3. Missions from both galaxies can be considered as equally likely and most probably from the 'approaching quadrants'; lengths of mission (we propose 59 MY) may be influenced by favourable/unfavourable position in the approaching quadrant.

It is not impossible that ships approaching from M31 Type IIb civilisations may already have perfected the techniques having had previous success. After all, they have the advantage of the much nearer and more convenient M33 Triangulum galaxy (3rd largest in Local Group), which defines a 'Tri-And' Point at their mid-point. This would require much less time and energy to reach, improving the odds thereby. A single contact at the AMiTe point might therefore not only be with a single species but with a trans-galactic 'community' stretching back possibly billions of years.

Summary and Future Work

Mission Profile: Saturn, in a 5:2 orbital resonance with Jupiter, may be a convenient He-3 mining and jump- off point for 'Daedalus-class' starships. Returning to the same relative positioning with Jupiter every 59 years (two orbits), the best conditions for accomplishing a Jupiter Oberth manoeuvre (if useful) and launching along the same trajectory as previous ships would pertain. Future analysis may choose Jupiter but we use the 59 year interval which hopefully would give enough time to extract the He-3 portion of the fuel, and for the construction of the spaceship, eg on the Moon, Titan etc (see Daedalus concept, Figure 6).

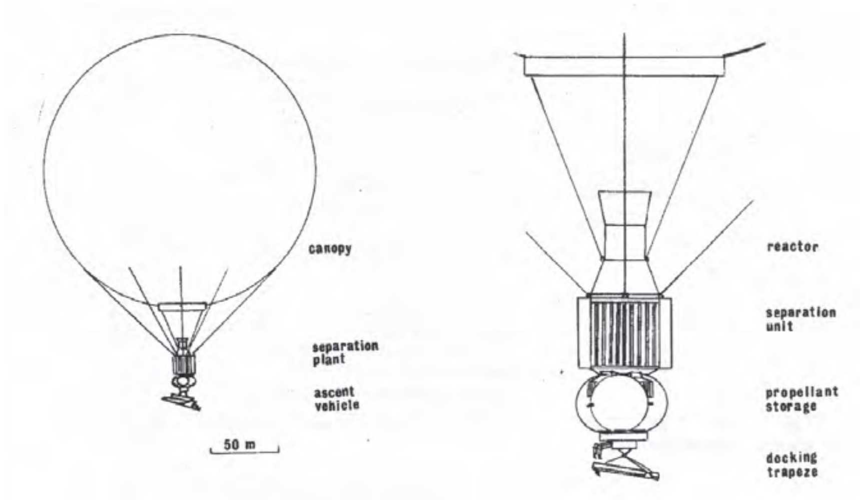


Fig 6. Daedalus Study: Proposed He-3 mining

(Original caption: Fig. 2. Jupiter aerostat factory
(a) overall scheme, with the ascent, vehicle docked
(b) detail of the factory complex)

Credit: *Project Daedalus: Propellant Acquisition Techniques* RC Parkinson

BIS *Project Daedalus - Final Report*, pp. S83-889, 1978.

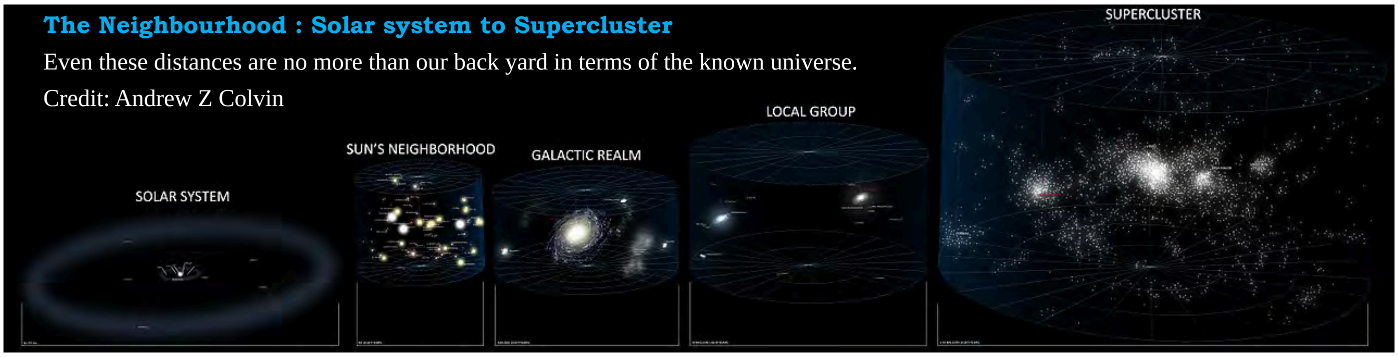
Ships would be launched every 59 years and attain a speed of 0.045c (Longshot) in the galactic disk, relaying navigational information and being tracked back along the line. Hopefully, a 'free trajectory' could be established outside the disk and then an acceleration to a cruise at 0.071c, in energy saving mode, towards a point at AMiTe minus 50 kly. At this point a final burn would occur to correct the vector along the GC-AMiTe-GC line, using latest data of AMiTe position passed up the line from Earth. Communication attempts could begin.

Note, the number of proposed ships at 1 million is not in itself extravagant compared with the number of automobiles in existence; this includes 200 million SUVs at the time of writing. The critical resource is assumed to be He-3 as has been noted elsewhere. Even the extremely long timescale is less that some of the proposals for L in the Drake equation and so AMiTe could be considered even by very long lived Kardashev IIa civilisations if other means had not been met with success.

This initial proposal is consistent (on the whole) with numbers published in previous proposals (Daedalus, Longshot) and reasonably foreseeable technologies. Further assessment is required especially on propulsion and power-plant aspects and also on mission profile. Even if the numbers derived from Daedalus still look 'optimistic', there may be a way of closing the gap (more fuel, more mass). At its core, the problem reduces to, "can a 2-way communications package with a nominal 4.3 ly range be accelerated to 5-7%c with enough convertible energy to last ~20 million years?". Practical experience of missions to nearby stars over the next few centuries would test the technology. The communications requirements appears consistent with current O-SETI proposals but in this case we propose a new challenge: finding a needle in a 5 ly haystack. This aspect could clearly benefit from more analysis.

The proposal has been careful not to draw on any radically new technologies requiring the capabilities of an 'advanced civilisation', eg antimatter confinement. If such things are possible then we should consider studying the AMiTe point for signs that ET has long-since established a communications station there.

The desirability of the project is a moot point; it may only become attractive in the far-future as 'the last one standing' after other methods have been considered. Like many SETI proposals, it has a timescale longer by far than a human lifetime, or indeed the lifetime of any extant human civilisation, but the tantalising possibility that other civilisations have already used this method may prompt further study and perhaps alternative proposals.



The Neighbourhood : Solar system to Supercluster
Even these distances are no more than our back yard in terms of the known universe.
Credit: Andrew Z Colvin

Further reading

This supplements earlier footnotes.

ESA

ESA Advanced Concepts Team: Interstellar Workshop 20-21 June 2019
www.esa.int/gsp/ACT/news/2019-02-04-interstellar_exploration_workshop/

Michael Hippke

ui.adsabs.harvard.edu/search/q=author%3A%22Hippke%2C%20Michael%22&sort=citation_count%20desc%2C%20bibcode%20desc
Interstellar Communication Network. I. Overview and Assumptions / II. Deep space nodes with gravitational lensing.
Interstellar communication. I. Maximized data rate for lightweight space-probes / III. Optimal frequency to maximize data rate / IV. Benchmarking information carriers / V. Introduction to photon information efficiency (in bits per photon) / VI. Searching X-ray spectra for narrowband communication / VII. Benchmarking inscribed matter probes / VIII. Hard limits on the number of bits per photon / IX. Message decontamination is impossible.

Civilisation lengths

The Lancet: Global population in 2100 www.thelancet.com/infographics/population-forecast

BIS Project Daedalus

A Bond & A R Martin, "Project Daedalus – Final Report", British Interplanetary Society, 1978 - bis-space.com/shop/product/project-daedalus-demonstrating-the-engineering-feasibility-of-interstellar-travel/

Project Longshot

Spacecraft Systems: 3.4 Communications System Design
en.wikisource.org/wiki/Project_Longshot/Spacecraft_Systems#3.4

Doppler calculations

Georgia State University, Physics & Astronomy - *Hyperphysics* - hyperphysics.phy-astr.gsu.edu/hbase/index.html
Low Speed Doppler Shift / Doppler Expression Expansion / Doppler Calculation
hyperphysics.phy-astr.gsu.edu/hbase/Relativ/reldop3.html

About The Author

David F Gahan is a physicist, engineer and tech-entrepreneur, graduating from Imperial College London in 1984 (BSc Physics). He is the co-inventor of the world's highest temperature commercially available pressure/temperature sensor (1,000 Celsius, fibre-optic based), and was the Founder and CEO of Oxsensis Ltd (oxsensis.com/), which developed the sensor for gas-turbine aero and power applications and worldwide deployment. He has been CEO/CTO and occupied senior commercial positions in a number of companies and specialises in the development of technical/business opportunities in the physics based industries, from start-ups to major international enterprises in UK, France and USA. Sectors including energy, telecoms, displays and semiconductor equipment.

He now consults in technology development, innovation, change management, visioning, and company and process development. He has a side-line in classical composition, based on the writings of Charles Darwin, which led to a string-quartet performance at the Oxford Museum of Natural History in 2015.

Interstellar News

John I Davies reports on recent developments in interstellar studies

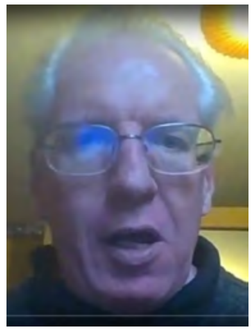
Initiative for Interstellar Studies AGM

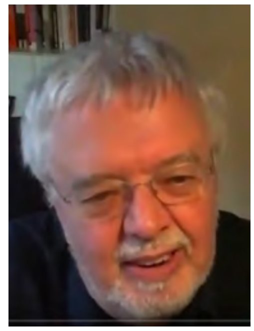
The UK-registered component of i4is, the Initiative for Interstellar Studies, held its statutory Annual General Meeting on Sunday 15 November 2020. We followed this with a gathering of members and a little long distance conviviality. Our membership is worldwide so it's unlikely that we would ever be able to be together in the same place but we hope to make this a more face-to-face opportunity once the world recovers from the present emergency.

Avi Loeb nails his colours to the mast

The name of Harvard Professor Avi Loeb will be familiar to Principium readers. He is both chair of the Advisory Committee for the Breakthrough Starshot Initiative and principal advocate of the possibility of an intelligent origin for the interstellar object (ISO), 1I/'Oumuamua. He has now reinforced his position in the latter by publishing a book, *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth*, Houghton Mifflin Harcourt (HMH) 2020 (www.hmhbooks.com/shop/books/Extraterrestrial/9780358274551). His views are not universally well-received and we include a new contrary analysis of his ideas, *An Interstellar Visitor: sorting the fact from the speculation*, by UCL Professor Emeritus Alan Aylward, elsewhere in this issue. i4is is, of course, interested in determining the nature of this ISO and this interest will grow if we find no similar ISOs in the next few years. We'll be reviewing the Loeb book in a future issue of Principium.

[1] for example- *A Telescope at the Solar Gravitational Lens: Problems and Solutions*, Geoff Landis 2018 ntrs.nasa.gov/citations/20180002197.





Patrick and John on 2020 in Principium and i4is

The editor and deputy editor of Principium, John Davies and Patrick Mahon recorded a video chat reviewing the year 2020 in Principium and i4is. It's on our website at -

i4is.org/videos/john-patrick-discuss-principium/

Starshot to the Solar Gravitational Focus

James Benford is a founder of modern Interstellar Studies and he continues to bring ideas to the subject. His recent contribution to Paul Gilster's Centauri Dreams summarises his thinking, with Greg Matloff - another pioneer of our subject - on the use of the Starshot technology (laser propelled chipsat spacecraft) to reach the Solar Gravitational Lens, *Beamer Technology for Reaching the Solar Gravity Focus Line* (www.centauri-dreams.org/2021/01/01/beamer-technology-for-reaching-the-solar-gravity-focus-line/). He stresses the incremental approach to the development of large beamers, both optical and microwave and the importance of achieving cost-effectiveness through such an approach. He also mentions the advantages of intentional emission of material from sails' to add to the impulse generated by the beam and the contribution of Roman Kezerashvili and his team. Greg and Roman are both at New York City College of Technology which hosted our first Foundations of Interstellar Studies Symposium in 2017. The advantages of the Solar Gravitational Focus as the lens of an immensely powerful telescope have been much discussed[1] but the focus line is hundreds of astronomical units away so reaching it is a challenge fit for our most advanced propulsion thinking.

Centauri Dreams (www.centauri-dreams.org/) is always a prime source for interstellar studies.

Exploration of trans-Neptunian objects using the Direct Fusion Drive

Acta Astronautica, Volume 178, January 2021, publishes a paper by a team from New York City College of Technology / City University of New York and Politecnico di Torino suggesting a fusion propelled probe beyond Neptune using the D-^{3}He nuclear fusion reaction (www.sciencedirect.com/science/article/pii/S0094576520305610), the Direct Fusion Drive. This builds on the Princeton Field Reversed Configuration idea and ideas going back at least as far as 1989 - Chapman et al, *Fusion Space Propulsion with a Field Reversed Configuration*, Fusion Technology 15 (2P2B) (1989) 1154–1159 (no open publication found).

The Acta Astronautica paper aims for missions to reach some trans-Neptunian objects such as Makemake, Eris and Haumea in less than 10 years with a payload mass of at least 1500 kg.

Genetic evolution on worldships

Frédéric Marin is the lead author of a paper, *Genetic evolution of a multi-generational population in the context of interstellar space travels -- Part I: Genetic evolution under the neutral selection hypothesis* with Camille Beluffi and Frédéric Fischer (arxiv.org/abs/2102.01508). This gives further results from their developing agent based Monte Carlo software, HERITAGE, modelling the whole human genome showing that centuries-long deep space travel has small but unavoidable effects on the genetic composition/diversity of travelling populations meaning substantial genetic differentiation on longer time-scales. They assume an annual equivalent dose of cosmic rays similar to the Earth radioactivity background.

Principium readers may remember Dr Marin's contribution to last year's i4is master's elective for the International Space University, M8-ISR-L14 Worldship Population Dynamics, reported in Principium 31, November 2020 page 84 with presentation and video in the members area of the i4is website. He has also published on this subject in JBIS and ESA's Acta Futura.

JHU APL Interstellar Probe Study Webinars

The team at Johns Hopkins University Applied Physics Laboratory report their work on their "Super Voyager" to the heliopause and beyond, the Interstellar Probe Study. You can reach them on YouTube or via interstellarprobe.jhuapl.edu/. This work can deliver both science results from beyond our Solar System and technologies applicable to missions including ISO interception.

The i4is Talk Series - 2020 and 2021

i4is is delivering a series of talks on interstellar topics. Some of these are **Open** to all and others are for i4is members only.

Members can see past talks via the members' page i4is.org/members/ and the presentations as PDFs at i4is.org/members/member-events/. Register for future talks by email to talks@i4is.org.

The talks are -

2021 Series

26th January — John Davies — The Interstellar Downlink — **Open**

2nd February — Olivia Borgue — Advanced Propulsion 2 (Nuclear etc)

9th February — Adam Hibberd — 'Optimum Interplanetary Trajectory Software', from Interplanetary to Interstellar

16th February — Robert G Kennedy III — Assuring Humanity's Interstellar Mission Capability for Posterity, or, Learning from Bronze Age Mistakes

23th February — Dan Fries — Interstellar Travel using Einsteinian Physics — **Open**

More in preparation

2020 Series

27th October — Rob Swinney — Introduction to Interstellar Studies

3rd November — Marshall Eubanks — Missions to Interstellar Objects - an i4is Initiative — **Open**

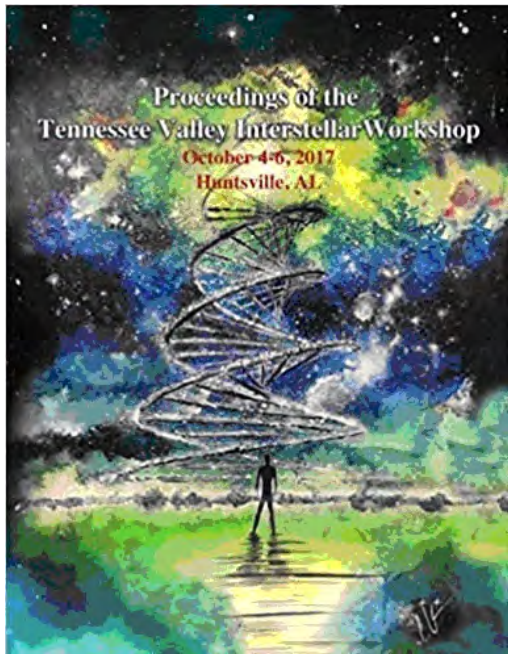
10th November — Dr Andreas Hein — Worldship Design

17th November — Dan Fries — An Introduction to Advanced Propulsion

24th November — Robert Swinney — Interstellar Precursor Missions

1st December — Patrick Mahon — Science Fiction Interstellar Starships — **Open**

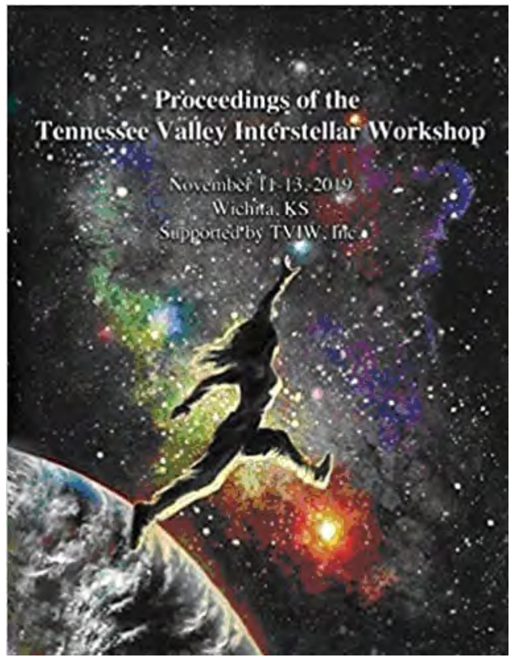
TVIW / IRG 2017 and 2019 proceedings published



Our colleagues in the Interstellar Research Group (IRG) announce publication of the proceedings of the the Tennessee Valley Interstellar Workshop symposia in 2017 and 2019. See 2017 (www.amazon.com.au/Proceedings-Tennessee-Interstellar-Workshop-Huntsville/dp/B08JDXBJPD) and 2019 (www.goodreads.com/book/show/56195469-proceedings-of-the-tennessee-valley-interstellar-workshop). i4is will be working with IRG to deliver the 7th Interstellar Symposium in September 2021 (irg.space/irg-2021/) at the Tucson Marriott, University Park, Arizona, and worldwide.

Slow Down!

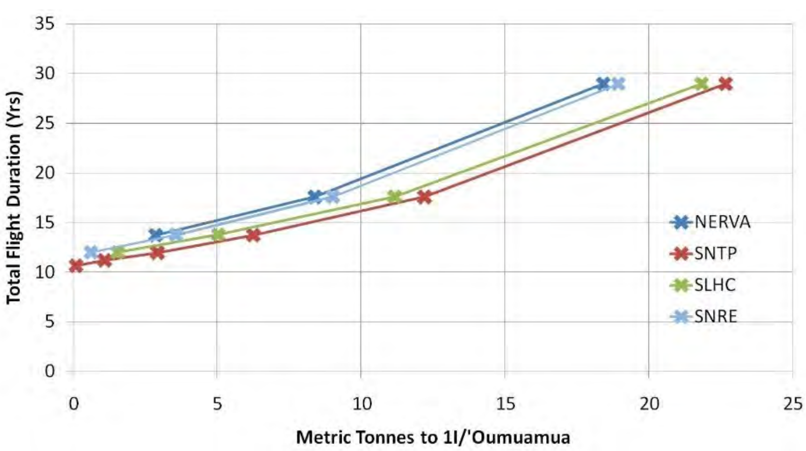
As Al Jackson and Adam Hibberd reported from IAC 202 in our last issue, P31, pages 48 and 49, Kush Kumar Sharma of the International Space University (ISU) reported on an ISU study *Feasibility assessment of deceleration technologies for interstellar probes*. This is now in the public domain at www.researchgate.net/publication/348187503 including discussions, stats, and author profiles for this publication.



The benefits of rendezvous over flyby have clearly been shown in Solar System exploration but the challenges of decelerating from substantial fractions of the speed of light are considerable. First studies (BIS Daedalus and Breakthrough Starshot current plans) inevitably are flybys but later work (Icarus Firefly and other Icarus studies) attempt rendezvous. This is clearly an area "for further study". Our i4is colleague Tishtrya Mehta examined an earlier idea by Prof Claudius Gros in *"Slow down!": How to park an interstellar rocket* in Principium 21, May 2018 page 3.

Catching an ISO using Nuclear Thermal Rockets (NTRs)

As reported in P30, page 58, the i4is Project Lyra team have been working on concept for an intercept mission to the interstellar object (ISO), 1I/'Oumuamua using Nuclear Thermal Propulsion (NTP). This is now being published in Acta Astronautica, *Project Lyra: Catching 1I/'Oumuamua–Using Nuclear Thermal Rockets*, Volume 179, Feb 2021, Pages 594-603, Adam Hibberd, Andreas M Hein. The team has looked at a laser propelled mission but they point out that although no real missions have yet used NTP, R&D in the US (the Rover/NERVA programs) gives a higher Technology Readiness Level (TRL) than laser push. The paper has four proposed NTRs and five trajectory scenarios. Probe mass could be several tons with mission durations less than 15 years (open publication: arxiv.org/abs/2008.05435).



Trajectory scenario (4) with Liquid Hydrogen, LH_2 propellant. - LEO to 1I/'Oumuamua via Jupiter. Launch in Year 2031. Total Flight Duration vs Payload Mass for 4 Different NTR Engines.

Credit: Hibberd / Hein / i4is

Getting around in the neighbourhood

It has long been pointed out that, with patience, the energy required to get around the Solar System can be small if the major gravity wells (planets and the Sun) are avoided. This is sometimes referred to as the "Interplanetary Transport Network". An interesting new perspective on this appeared in Science Advances, *The arches of chaos in the Solar System* (advances.sciencemag.org/content/advances/6/48/eabd1313.full.pdf) by researchers Todorović, Wu and Rosengren of Belgrade Astronomical Observatory, University of Arizona and UC San Diego. Interstellar objects (ISOs), targets in the outer Solar System and the nearby stars are of course, not confined to the ecliptic plane [1] so these "easy" paths may not be helpful but they may have value in getting close to useful places from which missions can advantageously set out (or just "boldly go"!).

Software to the Stars

Our i4is Project Lyra colleague, Adam Hibberd, gave a talk to the BIS West Midlands branch in November, as reported in the latest issue of the BIS monthly, Spaceflight (Vol 63 March 2021 SpaceFlight page 46). His Optimum Interplanetary Trajectory Software (OITS) has supported Project Lyra work since he joined the team in 2017. Naturally he mainly talked about missions to the ISO 1I/'Oumuamua showing a series of options culminating with a mission launching on 9 June 2030, reaching an intermediate manoeuvre on 25 November 2031, cycling back to an Earth barycentre for a slingshot on 17 April 2033, followed by a slingshot around the Jupiter barycentre on 12 July 2034, a fall back towards the Sun for a Solar Oberth manoeuvre on 24 February 2036, and finally a rendezvous with ‘Oumuamua on 29 July 2052. BIS West Midlands has a high proportion of professional rocket engineers and it looks as if contributions were enthusiastic and lively!

Are galactic nuclei wormholes, not big black holes?

The above proposition looks like something from the wackier end of the UK popular press but it is in a paper in the very respectable Monthly Notices of the Royal Astronomical Society. The paper is - *Search for wormhole candidates in active galactic nuclei: radiation from colliding accreting flows*, Monthly Notices of the RAS, Volume: 498, Issue: 1, July 2020, authors Piotrovich, Krasnikov, Buliga and Natsvlishvili of the Central Astronomical Observatory at Pulkovo, Saint-Petersburg (open publication: arxiv.org/abs/2008.09411). Their hypothesis is that the observed active galactic nuclei (AGNs) are wormhole mouths rather than supermassive black holes, as currently theorised. They cite earlier suggestions that such wormholes do exist and suggest that they may emit gamma radiation as a result of a collision of accreting flows inside the wormholes. This radiation has a distinctive spectrum much different from those of jets or accretion disks of AGNs.

This is a strictly astrophysical suggestion and it would be interesting to hear a reaction from Kip Thorne given his interesting speculations in support of the film, *Interstellar*, as reviewed by Keith Cooper in Principium 9, page 19. See also i4is Senior Researcher Remo Garattini's report *News Feature: Wormholes, Energy Conditions and Time Machines - at Marcel Grossmann: the third time*, in Principium 22 page 44 and reports from our second Foundations of Interstellar Studies workshop of presentations by Remo Garattini and Francisco Lobo in Principium 26 page 14.

Space Science and Technology from GoSpaceWatch

UK-based GoSpaceWatch offers online lectures, gospacewatch.co.uk, which complement our own, i4is.org/talks, and BIS, www.bis-space.com/events/. All are available both live and recorded.

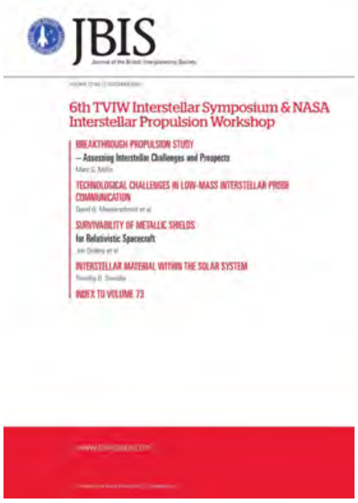
IRG Updates

Our colleagues at the Interstellar Research Group continue to provide a regular stream of interesting links. Just a few amongst the ones which have caught our eye include -

- *Android Noahs and embryo Arks: ectogenesis in global catastrophe survival and space colonization*, Matthew R Edwards, International Journal of Astrobiology, Cambridge University Press, February 2021.
- *Bridge To The Stars: A Mission Concept And Policy To Enable An Inner Solar System Encounter With An Interstellar Object*, Kristie Llera, 14th Europlanet Science Congress 2020.
- *Modeling Rendezvous Trajectories to Objects of Interstellar Origin*, Martha Njuguna, California State University scholarworks.calstate.edu/concern/theses/3197xr742.

Recent Interstellar papers in JBIS

[1] en.wikipedia.org/wiki/Ecliptic#Plane_of_the_Solar_System



JBIS Vol 73 No.12 December 2020 - 6th TVIW Interstellar Symposium & NASA Interstellar Propulsion Workshop

INTRODUCTION	Les Johnson	Program Chair, 6th TVIW Interstellar Symposium & NASA Interstellar Propulsion Workshop, November 2019	Les Johnson (NASA) introduces papers from the 6th Interstellar Symposium (TVIW/IRG, Wichita State University, Ad Astra Kansas in conjunction with NASA's Interstellar Propulsion Workshop).
Breakthrough Propulsion Study – Assessing Interstellar Challenges and Prospects	Marc G Millis	Ohio Aerospace Institute	Marc Millis on progress toward developing a consistent evaluation system for interstellar propulsion. See NASA report *Breakthrough Propulsion Study Assessing Interstellar Flight Challenges and Prospects*, 2018 ntrs.nasa.gov/api/citations/20180006480/downloads/20180006480.pdf.
Technological Challenges in Low-Mass Interstellar Probe Communication	David G Messerschmitt, Philip Lubin & Ian Morrison	University of California at Berkeley, University of California at Santa Barbara, International Centre for Radio Astronomy Research, Curtin University, Australia	David Messerschmitt et al on the interstellar downlink. More about this paper in *The Interstellar Downlink - Principles and Current Work* in Principium 31, November 2020, pages 28-42 - and at - i4is.org/wp-content/uploads/2021/02/jid_20210201_principium.pdf.
Survivability of Metallic Shields for Relativistic Spacecraft	Jon Drobny, Alexander N Cohen, Davide Curreli, Philip Lubin, Maria G Pelizzo & Maxim Umansky	University of Illinois at Urbana Champaign, University of California - Santa Barbara, Consiglio Nazionale delle Ricerche - Istituto di Fotonica e Nanotecnologie Italy, Lawrence Livermore National Laboratory	Jon Drobny et al confront the challenges of collision with the interstellar medium (ISM) noting the similarity with those observed in plasma-facing components in fusion reactors.
Interstellar Material within the Solar System	Timothy D Swindle	University of Arizona, Tucson	Timothy Swindle considers what interstellar material may be found in the Solar System from the tiny, <1 micrometre, to the recent ISOs, 'Oumuamua and Borisov - and the spacecraft which detected smaller particles (eg Stardust and Cassini) to the missions which may reach ISOs including the various i4is Project Lyra studies and the planned ESA Comet Interceptor.

KEEP AN EYE ON OUR FACEBOOK PAGE

Our Facebook page at - www.facebook.com/InterstellarInstitute - is the place for up to date announcements of our work and of interstellar studies in general. It's a lively forum much used by our own Facebookers and others active in our subject area.

If you prefer a more professionally focussed social network then our LinkedIn group provides this - www.linkedin.com/groups/4640147

The Artemis Accords: what comes after the Moon?

Max Daniels

Max gave us Territory in Outer Space in Principium 24, examining the political and legal issues of exploration and settlement in space. Here he discusses the Artemis Accords, named after the new NASA moon landing programme, to regulate the new "race to Moon" and its implications beyond our big natural satellite.

The Artemis Accords' virtual signing ceremony, October 2020. Source: NASA (youtu.be/PkVxAJpb3Bk) see also - NASA, International Partners Advance Cooperation with First Signings of Artemis Accords (www.nasa.gov/press-release/nasa-international-partners-advance-cooperation-with-first-signings-of-artemis-accords).

The Artemis Accords [1] are a series of principles signed bilaterally by the US and its international partners. The aim is to ensure those operating in space use the same rulebook. They represent a push by the U.S. to make space activities happen, ruffling a few feathers by sidestepping existing multilateral channels. Looking further afield, they will also probably mark the beginning of a new space divide. If countries want to make these discussions more international, they will have to step up.

First, a brief overview of the Accords. The aim is to achieve a sustainable and 'robust' presence on the Moon, and to develop forms of best practice when operating in space.

There are several 'principles' underpinning the Accords: peaceful purposes; transparency; interoperability; emergency assistance; the registration of space objects; release of scientific data; the protection of heritage; space resources; deconfliction of activities; and orbital debris and spacecraft disposal. Some recall existing international law or practice; others are more novel or more controversial.

The final Accords were published and signed by NASA and space agencies from seven other countries in October 2020: Australia, Canada, Japan, Luxembourg, Italy, the UK and the UAE [2]. At the time of writing, Ukraine and Brazil had subsequently added their signatures.

[1] *The Artemis Accords Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids For Peaceful Purposes* nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf.

[2] US and seven other countries sign NASA's Artemis Accords to set rules for exploring the Moon - NASA's biggest partner, Russia, is not on the list - theverge.com/2020/10/13/21507204/nasa-artemis-accords-8-countries-moon-outer-space-treaty.

Forging ahead, but not alone

Dr Kai-Uwe Schrogl
Credit: IISL

The US has emphasised the compatibility of the Accords with existing international agreements. The 'Outer Space Treaty' (OST) is mentioned 13 times in the seven pages of the agreements, while signatories have affirmed the "importance of compliance with… the OST".

Unlike the OST, they are not a new Treaty or legally binding, but have been agreed bilaterally. This has irked some in the space policy community. Dr Kai-Uwe Schrogl, President of the International Institute of Space Law (IISL), insisted that the Accords are, "not appreciated as particularly democratic", as they began as high-level political dialogue rather than as a co-signed working paper presented to the Legal Subcommittee of UNCOPUOS [1]. It was at this UN body in March 2020 that the use of space resources was going to be discussed, before the meeting was postponed [2].

Elsewhere, the Hague International Space Resources Governance Working Group adopted its 'building blocks' for the governance of resource extraction in November 2019 [3]. This does not represent a treaty either, but had more states and organisations involved in their drafting.

The differing approaches reflect tension in European approaches to space. As a political agreement the Accords are matters of foreign policy, and so have been considered by individual states. While some European countries typically prefer working through multilateral organisations such as UNCOPUOS, Italy, Luxembourg and the UK have gone around this to join the US [4]. The Accords have laid bare diverging paths in European policy, forged already with the likes of Luxembourg encouraging the extraction of space resources.

This is a dilemma shared by Australia. Section 10 of the Accords encourages the extraction and utilisation of resources in space, "in a manner that complies with the Outer Space Treaty." The OST, for its part, makes no mention of resource extraction, which was instead accounted for in the Moon Agreement (1979) signed by 18 states. This declared resources 'the common heritage of [hu]mankind', a framework that its supporters argue would have led to a fairer distribution of lunar resources [5].

Instead, the Moon Agreement has little legal bearing. It has been signed by few states whose number includes none of the major space powers. Keen to promote commercial activities in space, the US has said it will, "object to any attempt by any other state or international organisation to treat the Moon Agreement as reflecting or otherwise expressing customary international law."[6] The problem here is that Australia has signed both, which is a legal contradiction. It is a scenario that other countries will face as the US seeks to gain consensus around its policies in outer space.

The issue has been parked to one side for now. The Australian Space Agency was keen to stress how useful the Accords would be to the development of the Australian space sector as part of a post-COVID-19 recovery. This tension will remain going forward, however, and commentators have warned that, "Australia needs to decide what it values more – an outer space shared by all, or the profits from possible mining deals that come from a more exclusive approach to space."[7]

[1] #SpaceWatchGL Interviews – Kai-Uwe Schrogl: "We must not overrate the Artemis Accords" spacewatch.global/2020/11/spacewatchgl-interviews-kai-uwe-schrogl-we-must-not-overrate-the-artemis-accords/

[2] Report of the Legal Subcommittee on its fifty-eighth session, held in Vienna from 1 to 12 April 2019, para. 278: undocs.org/A/AC.105/1203

[3] Building Blocks for the Development of an International Framework on Space Resource Activities November 2019 www.universiteitleiden.nl/binaries/content/assets/rechtsgeleerdheid/instituut-voor-publiekrecht/lucht--en-ruimterecht/space-resources/bb-thissrwg--cover.pdf

[4] ESPI Brief 46: Artemis Accords: What Implications for Europe? espi.or.at/news/espi-brief-46-artemis-accords-what-implications-for-europe

[5] The Artemis Accords: repeating the mistakes of the Age of Exploration thespacereview.com/article/3975/1

[6] Executive Order on Encouraging International Support for the Recovery and Use of Space Resources - Infrastructure & Technology - Issued on: April 6, 2020 - "By the authority vested in me as President by the Constitution...." www.whitehouse.gov/presidential-actions/executive-order-encouraging-international-support-recovery-use-space-resources/

[7] Australia has long valued an outer space shared by all. Mining profits could change this theconversation.com/australia-has-long-valued-an-outer-space-shared-by-all-mining-profits-could-change-this-137405

Safety zones: a grab on territory?

Another aspect of the Accords with long-term effects on space policy is the concept of safety zones. Situated within the 'Deconfliction of activities' section, the aim is to avoid harmful interference with others' activities on the surface of a celestial body. This would occur through the provision of publicly available information on the location and general nature of operations.

The details need to be ironed out, including whether it would be area-based, some type of a 'code of conduct', or functioning more on sector-by-sector or policy-by-policy bases. There are also questions about who would decide these regulations, how enforcement would work, and whether they would draw on other examples of area-based management.

NASA have argued that safety zones are necessary, practical, and comply with existing international law by implementing Article IX of the OST[1]. Operators working in proximity would require some form of area-based coordination as lunar regolith and dust is blown up by landing craft that could disrupt others.

This is recognised in other international spaces. On the high seas, the UN Convention on the Law of the Sea (UNCLOS) allows safety zones of up to 500 m radius around artificial islands and manmade installations[2]. Crucially, states cannot claim sovereignty, either over territorial waters or of the resources in the water column or the seabed [3].

Parties to the United Nations Convention on the Law of the Sea.

Source: UNEP/GRID-Arendal, 2009 - on p.8 of *Continental shelf: the last maritime zone.*

United Nations Environment Programme (2009) wedocs.unep.org/handle/20.500.11822/8584

Note: As of January 2021 the UK is not an EU member

To take a possible model for the safety zones, a network of Antarctic Specially Protected Areas has been developed to protect scientific research or conservation within certain geographically defined areas. These do not involve national appropriation, as they are proposed and agreed by all signatories to the Antarctic Treaty System, with support from expert committees. Space lawyers have argued that it cannot be national appropriation as this is prohibited by OST Art II, while Art XII allows states to inspect each other's bases – again as happens in Antarctica[4].

Critics have said that safety zones would "exclude other actors" and make the US the, "de facto gatekeeper to the Moon, asteroids, and other celestial bodies." [5] This seems an exaggeration, as there are practical needs for the coordination of in-space activities. Crucial to the other examples listed is that they are managed through internationally agreed mechanisms – such as the UN, or bodies within the Antarctic Treaty System framework. The Artemis Accords have instead sidestepped the equivalent bodies in space policy, including the UN.

[1] Beyond Earth Institute (beyondearth.org) Artemis Accords: A Model for Space Settlement International Protocols? youtu.be/_JyrtAT2JgM

[2] SpaceWatchGL Opinion: *The Artemis Accords' Proposed "Safety Zones" On The Moon A Good Start* spacewatch.global/2020/05/spacewatchgl-opinion-the-artemis-accords-on-bringing-safety-zones-to-the-moon-and-some-expectations/

[3] *United Nations Convention on the Law of the Sea*, UNCLOS (1982), Art 60 (4) un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf, *Article 60 Artificial islands, installations and structures in the exclusive economic zone,* page 45.

[4] *Spacewatchgl Feature: The Space Law Context of the Artemis Accords* -

(Part 1) spacewatch.global/2020/05/spacewatchgl-feature-the-space-law-context-of-the-artemis-accords-part-1/

(Part 2) spacewatch.global/2020/05/spacewatchgl-feature-the-space-law-context-of-the-artemis-accords-part-2/

[5] US policy puts the safe development of space at risk science.sciencemag.org/content/370/6513/174?rss=1

UNilateralism?

Herein lies the problem. The Artemis Accords are clearly an attempt at spurring agreement on how to operate in outer space, and there is much emphasis on keeping to existing international law[1]. They have not, however, sought international buy-in beyond countries already close to the US, with none from Africa or South America (until Brazil) [2]. NASA do not seem bothered about this: at a Space Court Foundation roundtable, the agency's Mike Gold outlined how their space programmes are going to happen, with or without partners[3].

One of those partners could have been Russia, although the country has refused to sign the agreements. The Director General of Roscosmos Dmitry Rogozin compared their proposals to the 2003 invasion of Iraq when they were first released. The other major space actor is China, but who have also refused to sign (although US law would have forbidden their participation anyway [4]). Through its mouthpiece The Global Times, it referred to China as a 'space rival' to the US, with the latter waging a 'Cold War' against China and Russia [5]. It also labelled the agreements as, "an 'Enclosure Movement' in pursuit of colonisation and claiming sovereignty over the Moon."

Going beyond the Moon and Mars

It is still too early to see the effects of the Artemis Accords. We remain far away from a crowded lunar surface, let alone interplanetary or even interstellar operations. Their impact on the policies and international law that shape these will only be seen after this decade's developments in space, which includes the possible crewed return of humanity to the Moon and, later, Mars.

This is novel legal and political territory. While they are not legally binding, the Accords are the most serious attempt at practical guidelines for activities on the Moon and beyond. Importantly, they have forced the issue, and are an attempt to put in place a US-centric framework, particularly around interoperability and the extraction of resources.

Space-related activities will continue apace regardless. The growing sophistication of the private sector complements the entry of 'new' nations into space, such as Israel and the UAE. The fact that Brazil and Ukraine are signatories indicates their long-term space ambitions, as much as their contemporary politics.

The agreements have highlighted contrasting approaches to space that reflect different geopolitical outlooks [6]. They will not change the fundamentals toward space policy – of a distanced Russia and alternative route taken by China. It could lead, however, to competing spaces in which we discuss space policy, with a new group of states that have made international agreements outside of bodies such as UNCOPUOS. As we operate in space and travel ever further afield, it is harder to see projects that will represent all of humanity.

The Artemis Accords have clearly placed greater urgency on resolving the more complicated issues in space policy. To those who dislike operating outside conventional channels, this should be a wake-up call to come to some agreement; or lose relevance as countries press ahead on their own.

[1] U.S. space policy: An international model science.sciencemag.org/content/370/6520/1045.2.full

[2] Artemis Accords: why many countries are refusing to sign Moon exploration agreement theconversation.com/artemis-accords-why-many-countries-are-refusing-to-sign-moon-exploration-agreement-148134

[3] Space Court Foundation (www.spacecourtfoundation.org): SCV3 | Round-Table: Artemis Accords and the Future of Space Governance | Special Guest Mike Gold www.youtube.com/watch?v=Hnl6cP3ACRc

[4] Do NASA's Lunar Exploration Rules Violate Space Law? The Artemis Accords—NASA guidelines supposedly designed to regulate global cooperation on the moon—may serve to circumvent preexisting international treaties www.scientificamerican.com/article/do-nasas-lunar-exploration-rules-violate-space-law/

[5] Trump administration's 'Artemis Accords' expose political agenda of moon colonization, show Cold War mentality against space rivals: observers www.globaltimes.cn/content/1187654.shtml

[6] Artemis Accords: A Step Toward International Cooperation or Further Competition? www.lawfareblog.com/artemis-accords-step-toward-international-cooperation-or-further-competition

About the Author

Max Daniels works in communications and public affairs for an NHS Foundation Trust. He was previously a Parliamentary Officer in the UK House of Commons. Max has an MA in Geopolitics, Territory and Security from King's College London, specialising in the political geography of outer space. He holds a BA in Geography from the University of Durham.

Worldship and self replicating systems

Michel Lamontagne

Michel Lamontagne is a bit of a "Renaissance Man" - visionary, artist and practical engineer. He was the co-leader, with Robert Freeland III, of the Icarus Firefly design study for an interstellar probe propelled by Z-pinch fusion, see *To the Stars in a Century: Z-Pinch fusion & Firefly Icarus* by Patrick Mahon in Principium 22. He is a renowned imaginer of both spacecraft, including Firefly on the cover of Principium 22, a worldship fleet on the cover of Principium 30 and a worldship interior on the cover of our last issue P31. Here he considers the requirements for worldships and a worldship-building society and concludes that worldships can be a relatively early part of a society beginning to occupy the solar system with little impact on its economies or ecosystems.

More about Michel in the brief bio at the end of this article. All otherwise uncredited images here are, of course, credited to Michel Lamontagne.

Summary

The recent publication of Worldships, Feasibility and Rationale, by A Hein et al [1] has redefined some of main parameters of Worldship design, in particular a target population reduced from 100,000 [2] to 3,000, and raised the issue of their viability as an interstellar settlement system. In two other recent papers, Hein, Borgue et al also explore the ideas of self replicating probes and of the artificial Intelligence required for Interstellar vehicles [3][4]. We suggest that these ideas can be combined into a proposal to build Worldships using self replicating factories. This should reduce the cost of Worldships considerably, making them more interesting for a future interplanetary civilisation. The Worldships, due to their large mass, can themselves carry self replicating factories, allowing for the construction of new Worldships and space settlements at the target star system, rather than attempting to terraform any eventual planets found there. This increases the available targets for Worldships to practically every single star in the sky.

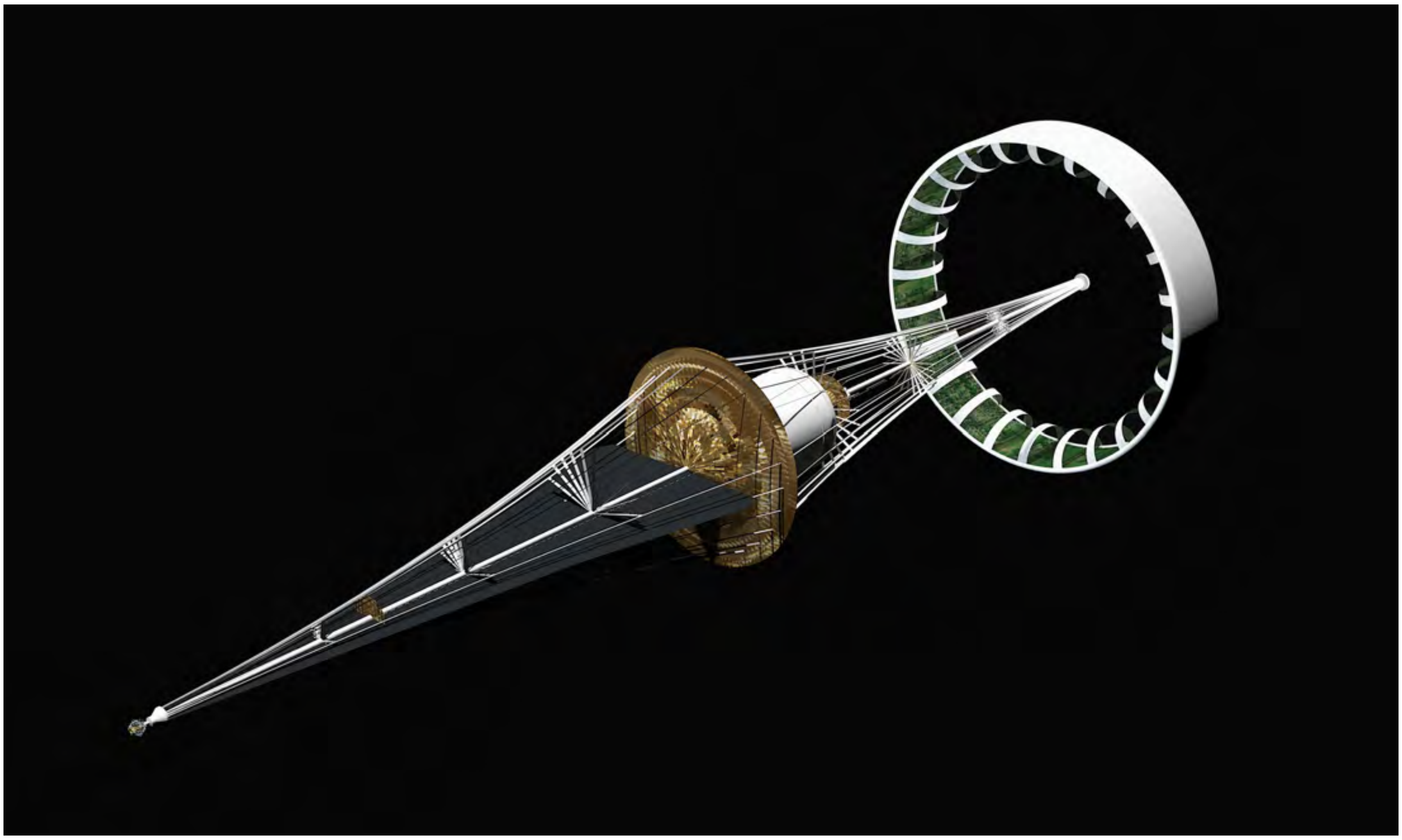


Image 1- Worldship with rotating habitat

Worldship parameters

For this article, we chose an average travel velocity of 1% of the speed of light, giving a travel time of 100x the distance in light years. So 430 years to Alpha Centauri. As proposed by Hein et al [1] the minimum acceptable target population for communities to survive such a trip is 1,000 individuals per community, with a total population of 3-4,000 people in one or more Worldship(s). Many small ships are more secure than a single large ship. With the minimum population of 1,000, the 3 or 4 vessels in the Worldship fleet would mass about 12 million tonnes each. Fusion propulsion with an exhaust velocity of 10,000,000 m/s using deuterium or deuterium/He-3 gives us a mass ratio Vo/Vf of 3.3:1. This includes all the propellant required for a continuous thrust system, with both acceleration and deceleration. The Worldship habitats are the main mass of the ship, with over 98% of the ship's mass, mostly in the form of radiation shielding and structural components. A large part of the habitat mass is also taken up by the biome in the habitat, mostly in the air, soil and water. The human passengers represent only about 100 tonnes, a tiny fraction of the vehicle's mass.

Worldship description

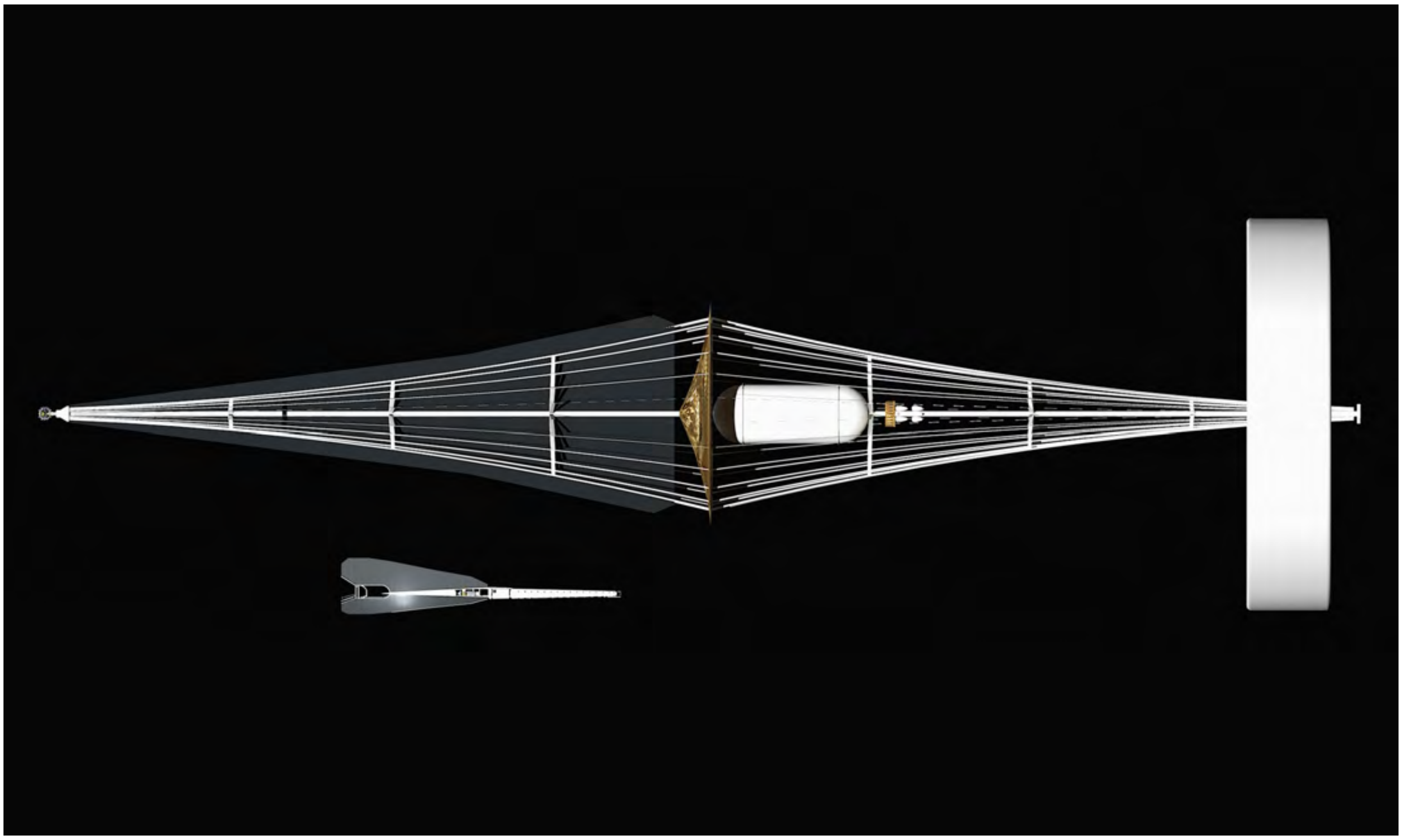


Image 2- Worldship and Firefly*

The Worldship is a large structure, about 4 km in length. The fusion drive occupies one end, while the habitat, a rotating torus 1,200 m in diameter, is at the other end. The radiation shield protects the ship from neutrons escaping from the drive chamber. Radiators dissipate the heat from the radiation shield. Heat from the various drive elements such as the nozzle structure, fusion drivers, magnetic confinement system and shock absorbers is rejected by lower temperature radiators in the same area.

Following the radiators, a multilayer insulation shield protects the habitat and the propellant tanks from the heat emitted by the radiators. The tanks hold liquid deuterium, or a combination of deuterium and helium3, depending on the type of fusion drive used. A technical area follows, housing workshops, the exploration vehicles required to visit eventual planets at destination and to correspond with other vehicles in the Worldship fleet. A large number of self replicating factories, quite analogous to fruits on a branch, lead to the habitat.

* The Icarus Firefly vehicle is an uncrewed probe; the result of the Icarus Firefly study by Robert Freeland and Michel Lamontagne - see next page and *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 - also i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/.

The habitat is composed of two levels: a radiation protected floor with a 5,000 kg/m^2 mineral shield, where the passengers live and sleep, and a large park/biome with much lower radiation protection, where the passengers can experience a more natural setting and look outside the ship. However, the park is a highly maintained area, closer to a botanical garden than a wilderness. The food production and maintenance systems are located on the radiation protected floor. A lightweight, transparent Whipple* shield covers the front of the vehicle.

The main structure of the ship is a hyperboloid tower. The habitat is linked to the tower using cables that are invisible at the scale of the image.

A number of Worldships would travel together. These would probably have variations in design, both for psychological reasons and for protection through diversity.

Icarus Firefly [5][6], shown in image 2 for scale, is a Sprinter type fusion Starship close to the original Daedalus design, but using a different engine configuration. The Worldship torus is similar to, but much smaller than, the original O'Neil Toroidal Space Colony†, itself designed for 10,000 people.

The Worldship proposed here is not a stable structure. However, nothing on the Worldship will be static. The Worldship is a truly dynamic system, that requires constant governance. The problem of maintaining the correct attitude for the Worldship will be trivial compared to the problem of maintaining all the internal systems in operation for centuries. As it is continuously operating, the Worldship cannot break down and coast for centuries, as so often shown in fiction. Its operation is a part of the society's make-up. Rather like a city is part of a society. The illusion of the stable and eternal ecosystem cannot be sustained, just as the neglect of the Earth's ecosystem has shown itself to be non sustainable.

The Interplanetary Society

The constructability of Worldships depends entirely on the capacities of the society that will build them. Although our present planetary society would be incapable of building such a vehicle as it cannot yet build the drive for it or the closed ecological systems required; an Interplanetary Society should acquire the capability. And perhaps acquire it earlier than later in its development. In our Solar System, Martian colonization and Space Settlements, as recently revitalized by Elon Musk in the first case and Jeff Bezos in the second, offer possibly complementary paths forward towards developing the elements required for a Worldship.

Martian colonization

All recent Mars exploration plans [7][8] include the use of In Situ Resource Utilisation (ISRU) to produce propellant and water for the Mars exploration bases and return vehicles. Most early base concepts also include the use of martian regolith to create radiation shielding, and the eventual development of other Martian resources such as Iron/Steel, Glass, plastics and some form of concrete.

The colonization of Mars should be a large scale experiment that will help define the requirements for a workable Worldship. Mars provides an interesting environment, half way between the Earth and a Space Settlement. There is no biome, but there are tremendous energy, water and mineral resources that will serve as stabilisers in the development of life bearing infrastructures for Space. Mars will require compact food production systems, pressurized habitats, high rates of communication and artificial environments that can all later be applied to Worldships. The rate at which Martian regolith can be converted into soil will give the expected growth rate for living soils in space habitats. The isolation of the initial small Martian communities will serve as examples for the isolated communities in the Worldships. The present SpaceX plans[8] call for robotic exploration and preparation of a proof of concept ISRU fuel production plant. This can be seen as a precursor of the work that will be required to build Space Settlements. And as a precursor to the mode of operation of a Worldship as it reaches a new Star system.

* Fred Whipple proposed a multi-layer shield for spacecraft in 1947. Such shields are now widespread in spacecraft engineering practice, see -*Meteorites and space travel* - Whipple, F L, Astronomical Journal, Vol. 52, p. 131, 1947

† The High Frontier: Human Colonies in Space, Gerard K O'Neill, William Morrow and Company 1976. 2001 Edition - Collector's Guide Publishing. Available from bookshop.org

Image 3- An Early Martian settlement. Propellant production on Mars may be a first step in In Situ resources development.

Space settlements

The original O'Neill space colonization[9] paradigm was: Use a space colony (The Stanford Torus) to produce solar power satellites. Finance the construction of the colony with the future revenue from the power satellites. The objective was the occupation of space, the means was power satellites. This could be changed to: Use solar powered self replicating factories to produce affordable Space habitats. Sell the 'land' on the habitat to produce revenue and bring about the occupation of space. Real Estate rather than energy would be the ultimate driver. Affordable Space Habitats require very low costs for transportation and energy. The lowest costs for these come from In Situ resources, most likely from the Moon[9], and low cost energy from power satellites or lunar surface arrays. Space habitats near the Earth, rather than in the asteroids, would benefit hugely from then Earth's resources and industrial base, possibly requiring less technological progress than Mars colonization. However, the development of self replicating factories to reduce costs would certainly help in the development of technologies usable by Worldships, in particular once Space Settlements start reaching out towards the Asteroids for raw materials.

Image 4- A SpaceX Starship docked at an early Space Settlement, Kalpana 2, design by Al Globus(10)

Fusion drives

Space Settlements in the solar system may be interested in moving from their initial construction point to other parts of the solar system. Due to their large mass, this will be practically impossible using chemical or even nuclear propulsion. This might offer an interesting market for the development of large and powerful fusion drives. These fusion 'tugboats' could move from settlement to settlement, providing deltaV on demand. These fusion engines could then naturally evolve into the powerhouses required for Worldships.

Worldship society

A stable society

Worldships are often portrayed in fiction as low energy, stable agrarian societies. However, to accomplish their mission to move from one star to another, a Worldship requires a drive that produces thousands of times the energy a typical habitat requires. For example, our model Worldship requires about 0.3 GW for the habitat, but the drive power is 100,000 GW. Due to the Coulomb barrier in fusion reactions, the energy required to ignite a Starship's fusion drive is a large fraction of the power of the drive itself. Therefore, a fusion Starship must have a power system capable of handling a significant portion of its drive output. For our Worldship, the driver power will be in the order of 10,000 GW. Deriving a small portion of this power to run the habitat ecosystem becomes a trivial exercise, and all inhabitants of a Worldship should have at their disposal a few orders of magnitude more power than any person living on the Earth today. Therefore, it may be best to plan on having a very urban society, with high technological complexity. Since these types of societies are recent we have little experience with their durability, but they do seem more compatible with the available power levels and with the operation of the Worldship. It also seems counterproductive to have a crew of humans spending their time laboring in an agricultural setting while the ship requires attention and supervision.

It is likely that the inhabitants of the Worldships will themselves come from similar space settlements in the Solar system. Living in a space settlement should already be a way of life for the inhabitants of the Worldship. This cancels the founder's dilemma, where the initial enthusiasm that motivated the first generation is lost by the new generation that doesn't necessarily share the initial vision. The Interstellar voyage is then no longer an exceptional and restrictive move, but something akin to business as usual, perhaps with some different circumstances but largely with the same living conditions as before.

The best solution then is to have no founders at all. The operation of the Worldship is a continuation of the operations of the Space Settlements. The only limitation should be some limitations of resources. If these are not perceptible for the length of a trip, then the Worldship society will not feel that it is travelling. Some Space Settlements will already be remote from Earth. When Space Settlements are built in the resource rich asteroid belt, or around Mars, their communication delays will grow to 45 minutes or more. This is enough to create a local community. The Worldship distance will just be a question of degree.

The inhabitants of the Worldship will eventually need to construct a large industrial base at the target star system. As the Worldship itself is an industrial product, it would seem logical for the settlers to be an industrial society, rather than an agrarian society. This favors the inclusions of unfinished elements in the Starships, perhaps even including 'raw' starships in the exploration flotilla, that can be built and modified as the flotilla proceeds towards its target, as proposed by Summerford[11]. This also favors the active participation of the settlers in the maintenance of the Worldships, rather than being mere passengers in an all enveloping technological cocoon.

The lower limit of 3-4,000 people and the use of 'small' Worldships does not mean that the Worldship fleet needs to be that small. The Worldship fleet might be significantly larger, and a larger population would definitively help to stabilize the society by creating more diversity and opportunities. The vision of a mass optimised system operating on a minimum budget may be typical of a governmental agency, and seeing NASA operating for decades in this mode may give the impression that it is the only way. But for a society that has significantly excess production capacities, travelling in style would certainly be the better way to go. In any case, the flotilla concept allows for places to visit. Flotillas set up a large distance away, a few light minutes for example, would replicate the way of life of Space Settlements in the solar system.

The large fleet of smaller ships also answers the problem of the dangerous psychopath, or idiot caretaker. Their reach is necessarily limited. And for those who would like to see the world burn, destroying a single Worldship should be enough of an accomplishment. Staying in contact with the larger domain of Solar system civilisation also means that the problem of the rare genius is solved, up to a point. The genius on Earth can exercise his influence all the way to the Worldship through communications.

Communications vs isolation

The crew of the Worldship, although isolated, will not really be alone. The parent society will have some interest in this distant child, and communications, although slow, will be possible.

Peter Milne [12] has shown that an Interstellar Spacecraft could maintain a 20 gigabits/sec communication with Earth for interstellar distances with a few Megawatts of transmission power. High frequency microwaves in the 20 GHz range with a bandwidth of a few GHz would be sufficient, and laser transmission might offer an even better transmission system. The most enabling technology would be a large transmitter/receiving in the solar system, rather than the system at the Worldship itself. So a Worldship could communicate continuously with the parent world and any other Worldship in a interplanetary convoy. In fact, due to the large mass of the habitat, a Worldship can have a significant mass fraction allocated to secondary systems, and a Worldship could easily dedicate a few GW to a laser sail system capable of driving bidirectional lightsails, such as those defined by Lubin for Project Starshot[13], between the Worldship and the solar system. As Project Starshot aims to create a vehicle moving at 20% of the speed of light, this would allow for the transmission of small quantities of material between the Earth and the Worldship, if needed, while the Worldship was still travelling. Due to the large fuel requirements of a Worldship, it should even be possible to reserve an amount sufficient to refuel a few Sprinter starships such as Firefly, that would require only 22,000 tonnes of propellant out of the more than 26,000,000 tonnes the Worldship would start out with. This would allow delivery of payloads in the 100 tonne range to the Worldship.

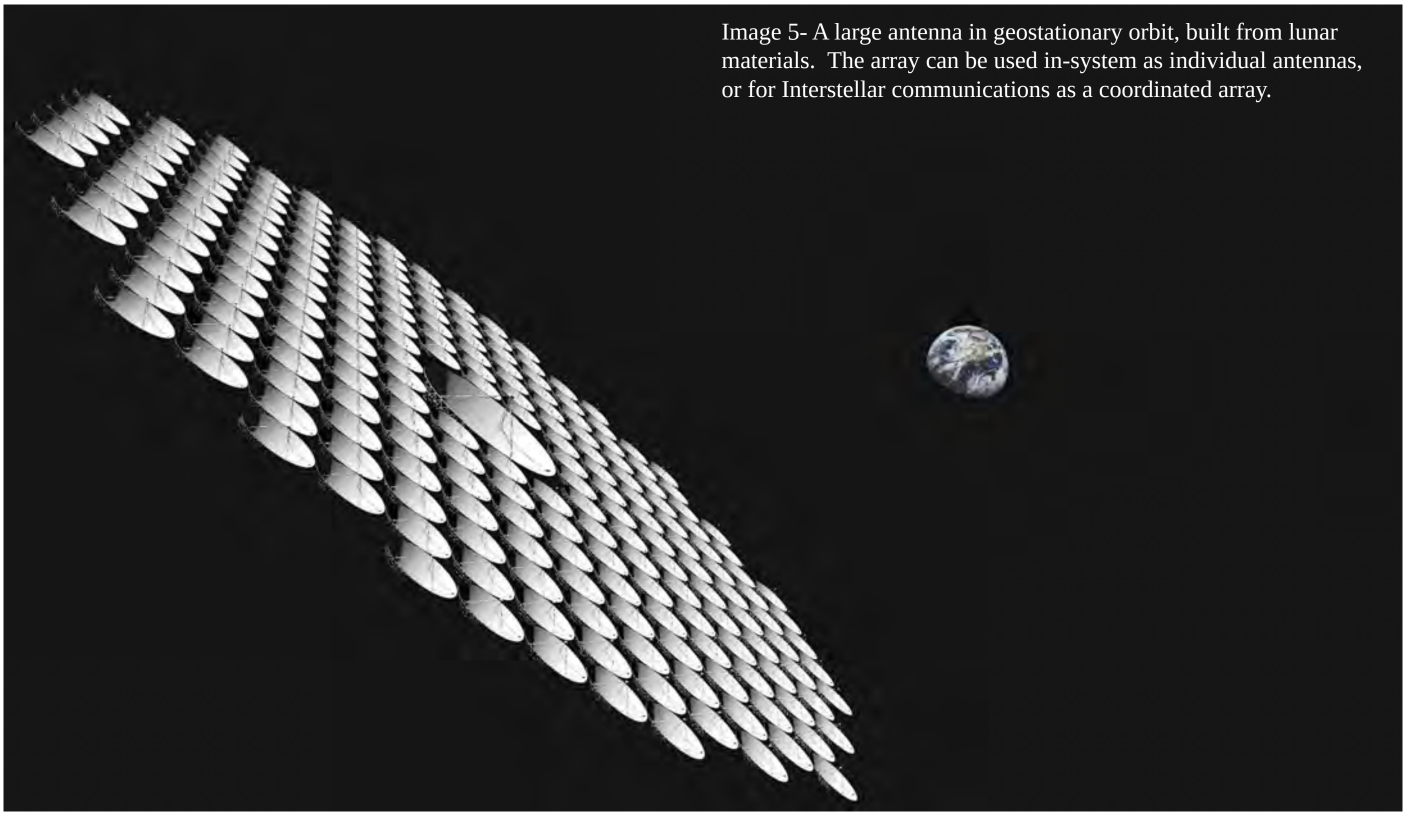


Image 5- A large antenna in geostationary orbit, built from lunar materials. The array can be used in-system as individual antennas, or for Interstellar communications as a coordinated array.

As far as the antenna in the solar system is concerned, large arrays of multiple antennas should be relatively simple to construct, and be in use in the solar system for interplanetary communications long before the first Worldship departs.

Worldship construction

Construction method and costs

The cost of a Worldship to an Interplanetary society seems large at first glance. However, a large part of that cost may be eliminated using the concept of self replicating factories[3]. In particular self replicating factories can produce propellant extraction systems and structural fabrication systems for very low cost with little human intervention, leaving the final small but complex systems, such as the computers and engines,

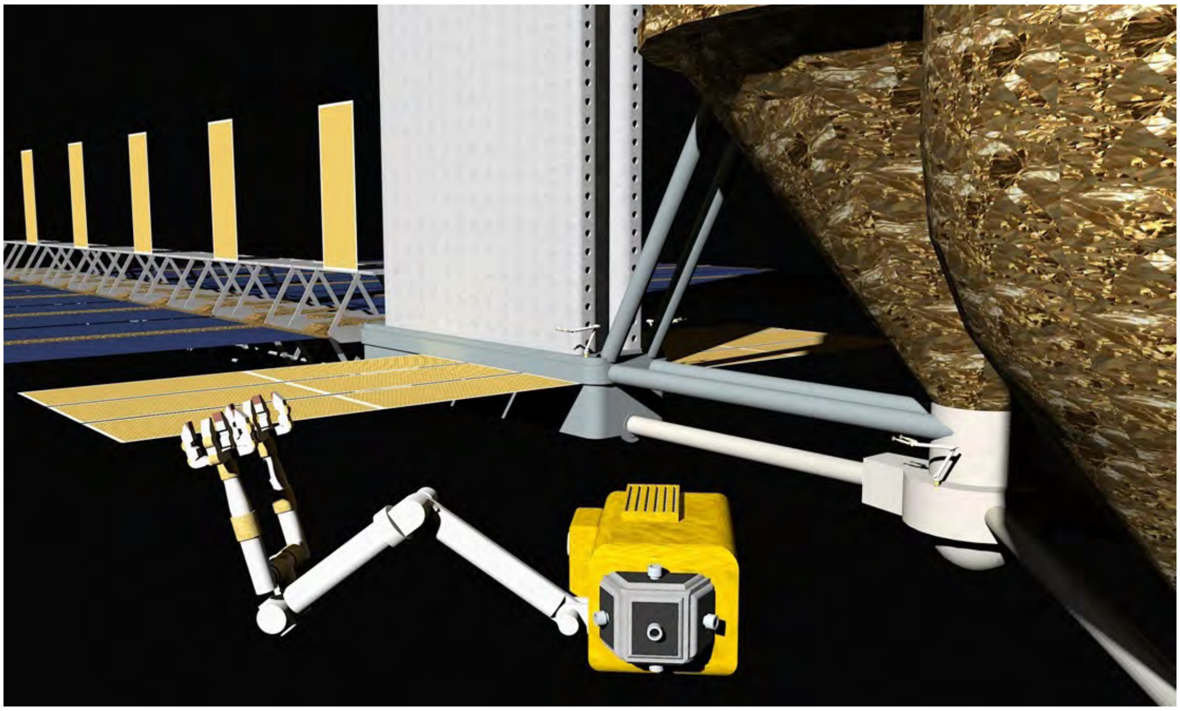


Image 6- A beam maker. Solar power is used to sinter lunar or asteroid regolith into monolithic beams, assembled using post tensioned cables. A small autonomous maintenance robot is in the foreground.

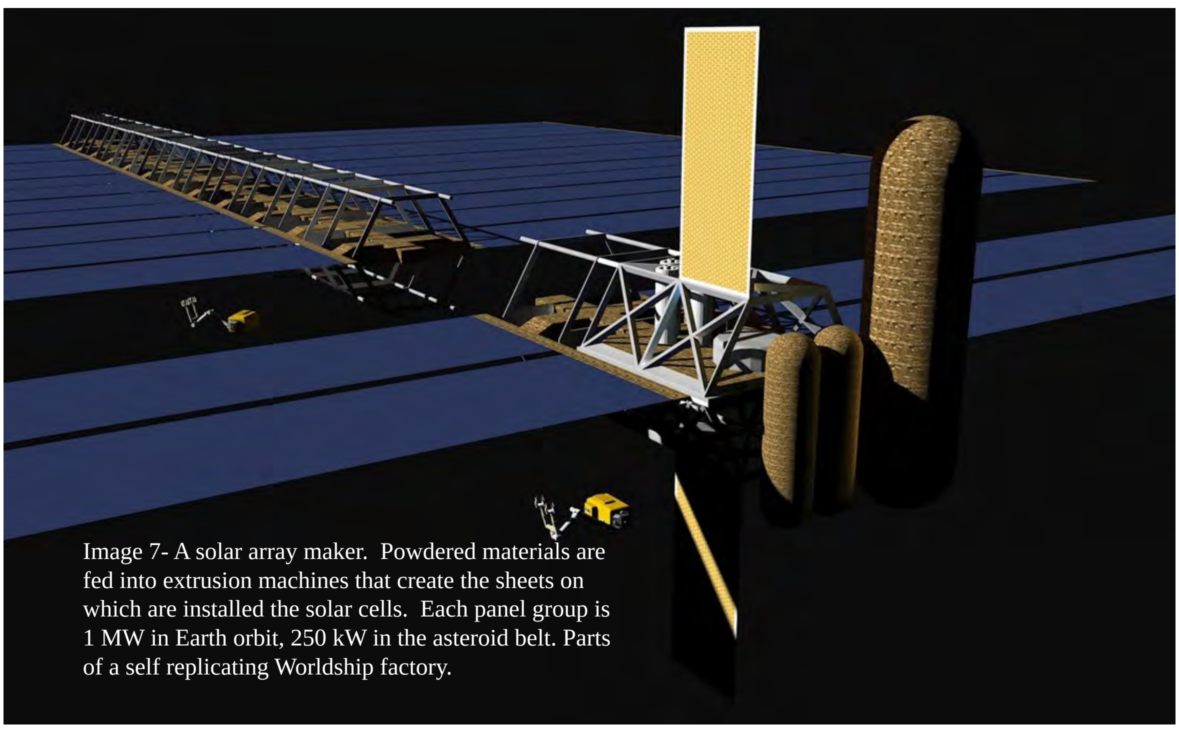


Image 7- A solar array maker. Powdered materials are fed into extrusion machines that create the sheets on which are installed the solar cells. Each panel group is 1 MW in Earth orbit, 250 kW in the asteroid belt. Parts of a self replicating Worldship factory.

to be built by humans. Totally or partially self replicating machines would allow humanity to use a larger fraction of the solar energy output without necessarily increasing the size of the economy to match the available energy increase. The same way humanity already uses the energy embodied by self replicating plants for their growth, without actually controlling or paying for that energy in the economic system.

The two main parts of a Worldship are the habitat and the drive. Most of the habitat is ‘simple’’ mass: radiation shielding (probably some form of sintered regolith or concrete), structural elements (Aluminium, steel or composites), an internal atmosphere, water and soil. This particular worldship design also has a large amount of glass for the park. A very small part of the overall habitat mass is more complex materials, such as living organisms, lighting and controls of life supports systems and food production systems.

The drive part is more complex and high maintenance, with high temperature materials, computers, workshops and the fusion engine itself. The radiation shield, by far the largest part of the mass of the Worldship, requires no maintenance at all.

Most of the mass of the Worldship also has low embodied energy. While concrete has an embodied energy of about 1 MJ/kg and steel is in the order of 30 MJ/kg[14], the energy in computer equipment and other complex systems is more in the order of 4000-7000 MJ/kg. Using low embodied energy materials reduces the cost of the Worldship considerably. The complex, sophisticated part of the Worldship may be in the order of one hundred thousand tonnes of the approximately twelve million tonnes vehicle, perhaps one thousands of the mass. So only that small portion of the Worldship is expensive to build. The rest of the Worldship should be rather cheap.

Energy and material costs

The ecosystem of the Earth has stored over millions of years tremendous amounts of solar energy in the form of gas, oil and coal. And every year stores huge amounts of energy in plants and trees. To the point that that energy seems free. In the same way, solar powered factories can produce and store energy in elements such as mineral beams, metallic structures and propellant depots that can be used to build Worldships or space settlements. The energy costs for extracting and using fossil fuels or natural materials are generally the only one accounted for in the operations of a society. An interplanetary Society might act in the same way, using prepared resources but, in a sense, not paying for them, as they would be the results of a production environment that supplies them without requiring payment in any form.

Maintenance

The Worldships will be complex systems, with numerous parts and subsystems. For a small crew of a few thousand, even when trained in technology, most maintenance will need to be automated, carried out by robotic equipment or self healing systems. Ecological systems will also require maintenance, and although this might be seen as a kind of farming, the small size of the community might mean that no more than a dozen people would be actively involved in agriculture.

Maintenance on the worldship would also be helped by the presence of at least one large self replicating factory, that by definition will be able to carry out any number of complex construction, and by extension repair, operations. However, the presence of a human crew reduces significantly the artificial intelligence required by the factory, reducing it from the level of a quasi self aware ‘agent’ to a rather more accessible level of semi autonomous operations.

On a Worldship there will be no externalities, except for the tremendous amount of power available from the drive. Although a materially closed system, the Worldship habitat has much more energy available than the original Earth habitat. And although missing the tremendous material reservoir that a planet represents, the Worldship should be able to make up this absence by the availability of an equally large energy supply. The Worldship will also benefit from the information storage capabilities of computer systems. Every single element of the Worldship, every component, part or system will be completely described in the Worldship’s data banks, and include the entire procedure required to fabricate it. And the Worldship will carry the equipment necessary to carry out that task. The only exception will be the biological systems, whose complexity will still be greater than the complexity of the machine carrying them. Over the centuries of travel, it is likely that most of the working elements of the ship will need to be replaced. Rather like the ship of Theseus, but one that will draw most of its new components from the old ones, rather than from the environment.

Recycling

As it has no access to external material resources, the Worldship will need to recycle everything. As the Earth already does with its many cycles: water, oxygen, nitrogen, calcium and carbon. Beyond standard systems already used on Earth or the ISS, the large amounts of energy available on the Worldship can be used to break down complex debris into its component atoms using high temperature and plasma furnaces. The individuals elements can then be separated. The limited time required for the trip may also allow for the storage of some primary materials, such as Rare Earths. Using as a basis of reference the average use of under 1 kg per person per year today on Earth, the Worldship could start out with 500 tonnes of Rare Earth storage and survive on 500 years with that stockpile. On a similar basis, with the worldwide production of platinum at about 200 tonnes per year, the Worldship could set out with 100 kg of platinum and never be expected to have to recycle any of it.

The Worldship itself will need to have recycling build into its design, rather as modern electronic equipment and vehicles are starting to have. And the Worldship biosphere will also do its part in recycling, with the possibility of non biological support if the equilibrium is lost.

With losses inevitable in any system, the Worldship should start its trip with reserves of critical material. The CHON (Carbon, Hydrogen, Oxygen and Nitrogen) elements are likely the most critical. Water in particular is a critical resource, and it might be good to replace some of the radiation shield with a water shield.

Resource extraction

Although there are no resources available in deep space, a Worldship will require resource extraction systems at both the beginning and the end of its voyage. A Worldship with in situ resources extraction systems will also have extensive exploration capabilities. These will be adjusted depending on the discoveries made at the target Star system. After all, the Worldship is not only a mode of travel, it is a habitat that would be expected to be lived in and change, both before and after the arrival at the target star system. And although the Worldship is somewhat like a seed during its travel time, the culture it transports will want to flower, just like any living organism, when it reaches a place that allows for growth by providing resources. As the development of an Interstellar Society that is capable of producing a Worldship requires in-situ robotic production techniques to develop, these will be available for the Worldship itself. The most important ones being the means of extracting large volume items such as gases, liquids and primary metals and minerals.

Although a Worldship is a large machine, it must be remembered that at 11 million tonnes, mostly built from a material that is very close to concrete, it is only twice the mass of, for example, the Daniel-Johnson hydroelectric dam[15]. That was built using a small part of the resources of a relatively small nation in the 1960s.

Daniel-Johnson Dam and Manic-5 Generating Station

Credit: hydroquebec.com

Self replicating factories

The concept of self replicating factories can be worked into the concept of Worldships and into the concept of a future solar system wide economy.

What is the difference between a self replicating factory and people, that are also self replicating? First, the length of a generation should be significantly shorter: Most complex projects in construction today are done in about two years. This is an order of magnitude less than the time required per human generation. Machines also have much simpler power systems, with electricity being able to power equipment directly, rather than the more complex system of growing food and eating used by humans. Machines can survive in vacuum, while humans can't. And of course humans are infinitely more flexible than machines, being able to run a kilometre, knit a sweater or write a poem, while self replicating machines are limited to a very specific number of tasks. Also, humans are fully self replicating, while it is likely that for a long time self replicating factories will have some number of externally provided parts. In a sense, these parts will act like a growth limiter, or vitamins[2], with the absence of the part making the completion of the machine impossible. A self replicating factory is much closer to a tree than to a human.

The self replicating factories would be used to create the simple, but massive, parts of the Worldship. The main elements ranked by mass would be:

- Deuterium (and He-3) propellant
- Regolith beams for radiation protection and basic habitat structure
- Steel/carbon fibre cables for the hoop and pressure stresses in the rotating habitat
- Glass elements for the habitat
- Sand and clays for the soil of the habitat
- Water for the habitat
- Structural extrusions for the tower structure
- Nitrogen for the habitat atmosphere
- Oxygen for the habitat atmosphere
- Hydrocarbon sealants
- Extruded sheets for tanks, radiators and radiation shields

Computers, controls, power systems, organisms for the soil, farms and the crew would probably come from Earth or from existing space settlements.

The degree of self replication is critical in the design of the mission. If fully self replicating systems exist at the departure of the mission, Sprinter starships carrying self replicating machines can be sent at the same time as the Worldship flotilla departs. The Sprinters will arrive centuries before the Worldships, and the self replicating machines will have ample time to create multiple habitats, and perhaps begin to seed them with simple life forms. In fact, the self replicating machines should be able to build habitats faster than the human populations is likely to expand. So the paradox of the fast Sprinter ships versus the slow Worldships can be avoided; it doesn't matter if later ships are faster than the Worldships, the factories can build enough space for all*.

Image 8- A Worldship and large sprinter ship with the same basic design. As most of the mass of the Worldship is in the habitat, removing it, while keeping everything else identical, allows the sprinter to arrive at the target star in ¼ of the time the Worldship requires. It could then use self replicating factories to build habitats into which the Worldship population could expand on arrival.

* en.wikipedia.org/wiki/Interstellar_travel#Wait_calculation

Factory arrangement

The elements required for a self replicating factory are described by Hein[2] and others.

- Resource extraction and refining
- Chemical processing
- Casting, sheet metal rolling and extrusion molding
- Additive manufacturing
- Conventional tooling
- CAD-CAM-AI
- Semi autonomous robots

If a factory is able to produce 100 solar units per year, after 20 years it will have produced 2,000 solar units.

With exponential growth: $x(t)=x(0)*2(t/T)$ where t is the time, T is the doubling time and x is the initial number of factories. If it takes 2 years to build a factory, after 19 years one factory will have produced $1*2(20/2)=512$ factories. If these then turn to produce solar panels, they will build 51,200 solar units in the following year.

Some of the elements required for the self replicating factory may not be easily available at the target star system and it might be necessary to use supplies brought from Earth for closure. Rare Earths metals, nuclear materials and generally any materials in low concentrations may be hard to process in reasonable times.

Although additive manufacturing is very flexible, it is also quite slow. Conventional extrusion and casting will be advantageous for large structural items of sheet metal parts and would be included in the factory.

The self replicating factory can also adjust its configuration and in particular modify its mineral processing facilities depending on what is found at the target solar system. The supplies brought from Earth can be arranged into the required configuration as observed in situ. For example, free flying ice crushing equipment for small (km sized) icy moons, or rovers and more substantial diggers for larger rocky moons.

The factory would be used to build other specialised factories, such as solar cell makers and regolith beam makers. It would only duplicate itself if the rate of progress using a single factory was too slow.

A common objection to the self replicating factory idea is that the production chain is too complex. An example often used is the production of microprocessors and the cost of microprocessor plants, or Fabs, that is ever increasing and reaches billions of dollars. The recent development of the minimal Fab technology[16], that allows for small runs of complex microprocessors is a solution to that problem that should be applicable to self replicating factories.

The most important chain that is needed is probably the steel production one. Steel castings lead to metal machine tools that can produce precise elements for further fabrication. Iron ore reduction methods using methane rather than coal would allow for steel production wherever water and CO_2 can be found in the solar system.

It is important to note that the self replicating machines described here do not create themselves Ex nihilo. They require an existing self replicating machine that can already provide the array of precision tools required to build and maintain the new precision tools, and a tremendous store of knowledge in its computers. In a sense, the self replicating factory is the smallest unit of the self perpetuating technological society that is possible.

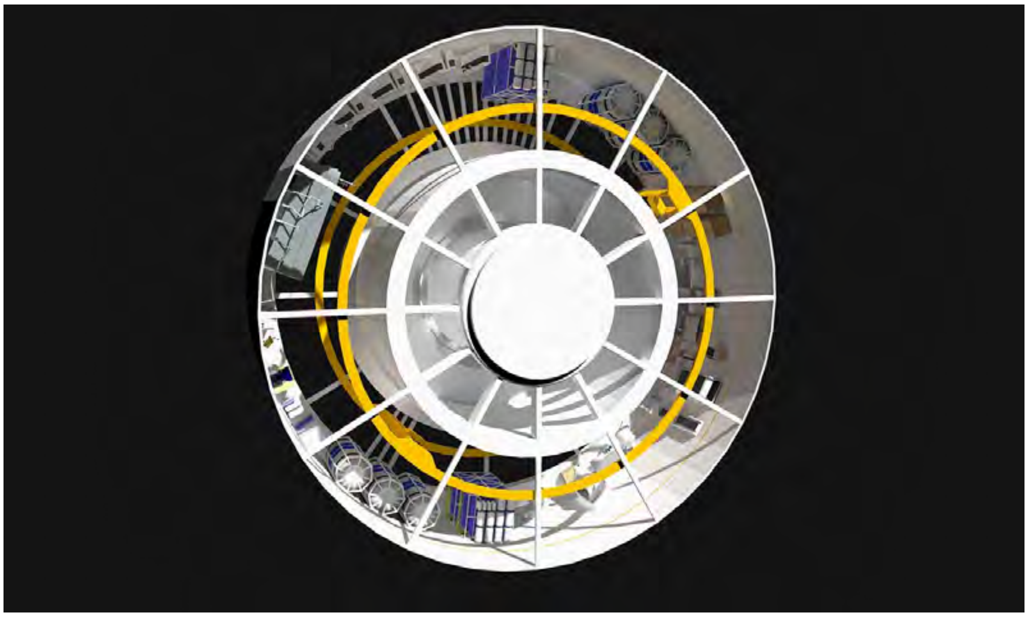


Image 9 - A self replicating factory, showing the production section. A half completed beam maker (see image 6) is shown at left.

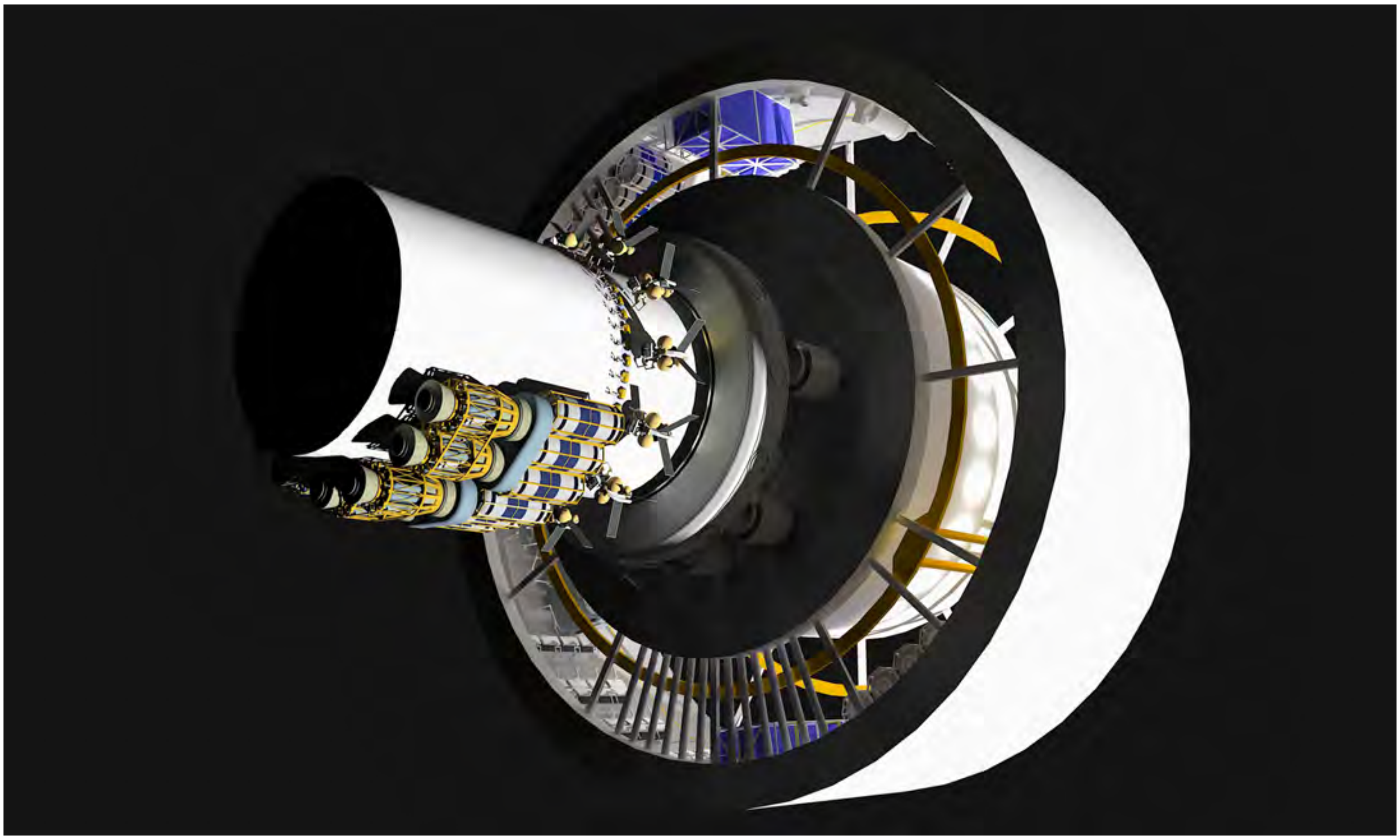


Image 10- Another view, showing the resource extraction equipment built for operations on a small ice moon or asteroid

Worldship Ecology

Building a sustainable ecology

The small size of the habitats that result from the populations proposed by Hein & all are unlikely to be able to sustain stable ecologies. The entire living area of the Worldship is just above 1.6 km², while the habitat required for a single apex predator, such as a Siberian tiger, is over 1,000 km². The upper layer of soil and water ultimately required to support the tiger's ecosystem would mass from 300 to 1,000 times more than the mass of the Worldship. However, the Worldship doesn't need to have a truly sustainable ecology, it just needs to have an ecology that can survive until a sufficiently large habitat can be recreated at the target star system. And these habitats do not need to be filled with humans. It is entirely possible to produce space habitats that serve only a local ecology. The human population can grow much more slowly than the livable space available. And the Worldships can carry all the information required for much larger ecological systems than those they themselves can sustain. They will probably need to carry frozen samples of the larger animals that the small Worldship ecologies will not be able to support.

In the solar system, the Earth will provide a stable ecological reservoir to act as a backup for the space settlements. In the new settlements around other star systems, if there are no habitable planets to serve as ecological reservoirs, it will be the task of the settlers to create sufficient space to provide these reservoirs. These will probably take the form of the larger types of space habitats, or of swarms of smaller ones.

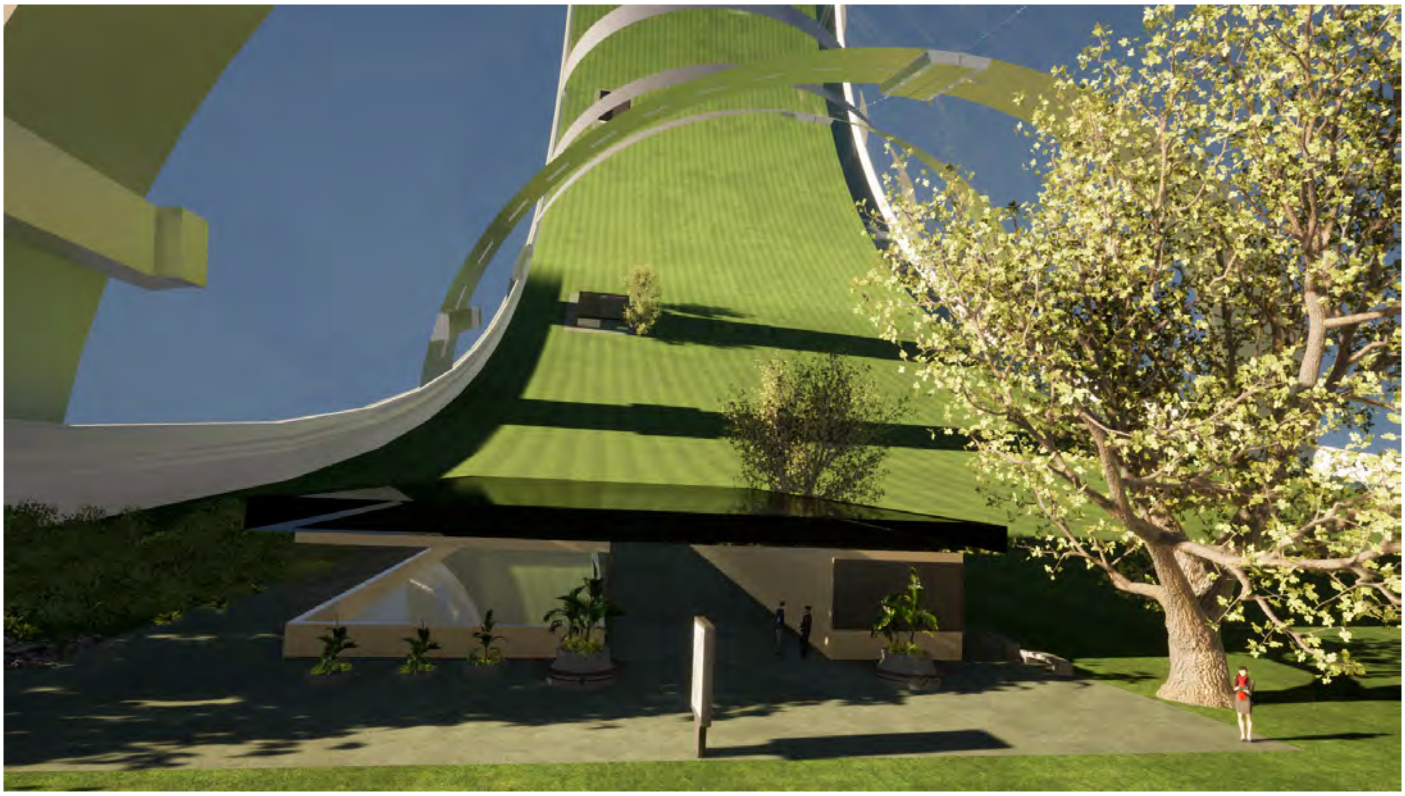


Image 11 - Interior of the Worldship forest habitat

It is also important to note than once a star system is reached new ships will continue to come along from Earth, to enrich the ecology and help create the larger system required for stable life.

In the 2015 TVIW paper by Cobbs [17], three separate biomes were suggested: Ocean, Grassland and Temperate forest, to provide maximum diversity. These could be implemented in three different Worldships. These would not be used as food sources to support the human population, as they would be much too small, rather they would serve as biological reservoirs to provide a base population to populate space habitats built at destination. The well known failure of Biosphere 2, with just over one hectare of area, sets a lower size for an independent biome. By necessity, space settlements in the solar System will have served as base design to test the stability of small ecosystems before the Worldships set out, and that the 240+ hectares proposed here for the Worldship flotilla will have been proven to be sufficient.

The energy required for an ecology on Earth is simply the solar constant, divided by the night and day cycle and with some losses from the planet's albedo. This is approximately 300 W/m² (1,300 W/m² divided by two for night and day and again by two for the spherical form of the Earth, plus some losses here and there). So a space Settlement, or a Worldship, simply needs to provide 300 W/m² of light to any surface capable of sustaining life, with gravity, air, water and soil plus a number of trace elements. Life will take care of the rest.

And to provide a self sustaining ecology at the target system, rather than depending on the presence of an habitable planet, with all the dangers and problems that terraforming may present, it seems likely that the Worldship will carry a number of the self sustaining technologies that helped build it, as well as some of the more sophisticated elements required for the construction of the space settlements. In fact that may be the true defining factor for the size of Worldships: At the target systems, these need to provide the technological basis and the intellectual capacity required to create new space settlements.

Discussion

The very existence of Worldships or of an Interplanetary society may well depend on the nature of an eventual technological singularity, that might render moot the whole idea in Interstellar Travel, or otherwise create opportunities that cannot be envisioned today other than by Science Fiction.

At the scale of an Interplanetary Society, Worldships should be tiny objects.

Self replication and AI may be much harder than expected.

The ecological system may self destruct through instability, destroying the main value of the Worldship concept.

It may be impossible to maintain a technological society over five centuries.

The three generation paradigm, also know as from Shirtsleeves to shirtsleeves in three generations*, or the founder's dilemma, may all make the long term survival of a Worldship impossible.

Althought the ships described in this essay are fusion powered, Antimatter powered ships might provide an interesting alternative. Antimatter is not an energy source, it is simply the ultimate battery. But in a solar system where self replicating factories can produce solar power satellites in tremendous amounts, manufacturing the antimatter using that solar power should be possible.

Conclusion

Using methods developed for the exploration and occupation of the Solar System, notably self replicating factories, it should be possible to build Worldships for a small part of the budget of an Interplanetary Society. By increasing the available energy and resources beyond the usually understood bounds of the economy using self replicating factories, Worldship might be less expensive than expected. The main analogy being that a mechanical 'ecosystem' would provide external resources that could be used at a cost that excluded most of the energy and material required to generate these resources, the same way Earth societies still use plants and trees from the planetary ecosystem without accounting for the work of the ecosystem to create these resources.

Image-12 Worldship habitat, looking down towards the engine radiator thermal shield and the fuel tank.

* Editor's Note: Known as "rags to rags in three generations" during my childhood in industrial Lancashire. eg Braithwaite worked hard and created Braithwaite and Son, his son had it cushy and thought his own son should become a "gentleman". Instead he become a waster.

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About the Author

Michel Lamontagne is one of the two principal developers, with Robert Freeland, of the Firefly interstellar probe design for Project Icarus. Michel is a French Canadian living near Montreal. He works as a mechanical engineer, mainly in building systems: plumbing and HVAC. He's been a member of Icarus Interstellar for five years, mostly working on the Firefly study. As you will see from the illustrations here, and his cover are for P22, P30 and P31, Michel is an artist as well as an engineer. He mostly worked in comic art in his earlier years; you can find examples of this earlier work (up till 2014) on the web site: sites.google.com/site/bdespace/Home - use the side menu for most images. His more recent work is on Deviant Art: www. deviantart.com/michel-lamontagne/gallery/.

JOIN I4IS ON A JOURNEY TO THE STARS!

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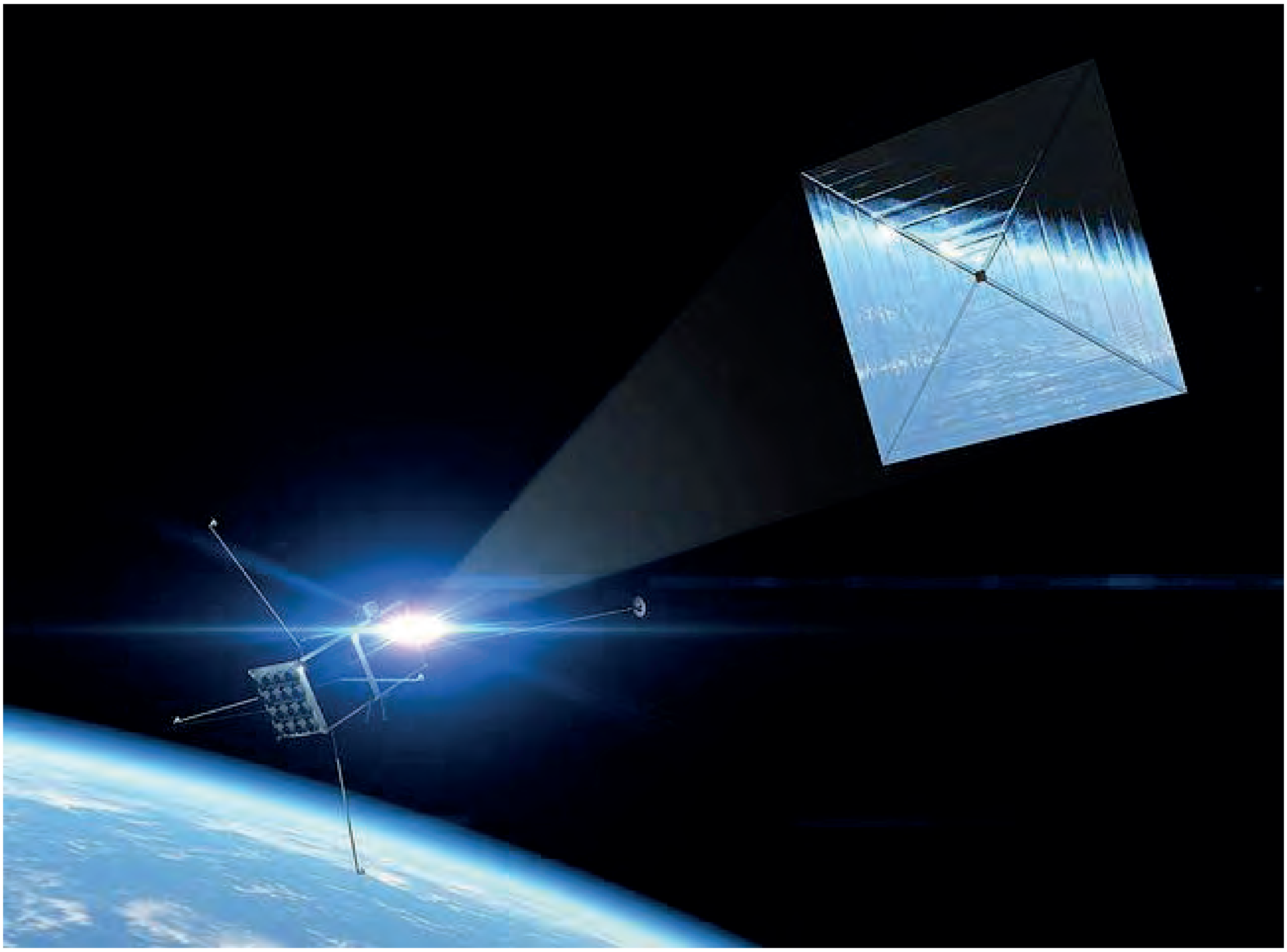


The Initiative for Interstellar Studies (i4is) has launched a membership scheme intended to build an active community of space enthusiasts whose sights are set firmly on the stars. We are an interstellar advocacy organisation which:

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

Join us and get:

- early access to select Principium articles before publicly released;
- member exclusive email newsletters featuring significant interstellar news;
- access to our growing catalogue of videos;
- participate in livestreams of i4is events and activities;
- download and read our annual report;

To find out more, see www.i4is.org/membership

News Feature: Starshot Downlink Webinar December 8 2020

Request for proposals for communications system research and development for Breakthrough Starshot project

John Davies

i4is people including Executive Director Dr Andreas Hein and Principium Editor John Davies were invited to a webinar on 8 December 2020. This was run twice at 15.00 UTC (7am PT / 8am MT / 11am ET) and 24.00 UTC (4pm PT / 5pm MT / 8 pm ET). It introduced the Request for Proposals from Breakthrough Starshot for communications system research and development for the Starshot project. Andreas and John attended the first of these and here John summarises - all verbatim quoted material is from public sources including www.starshot-asu.com.

For an introduction to the problems of the Interstellar Downlink for Starshot and similar probes see the article *The Interstellar Downlink Principles and Current Work* - in Principium 31, November 2020.

Introduction

The webinar was introduced by Professor Philip Mauskopf (Arizona State University). Pete Worden (Executive Director, Breakthrough Starshot) gave a general introduction to the Breakthrough programmes. He mentioned prize funds of $3m with early career prizes of $100k and smaller high school scholarship prizes.

Programme

James Schalkwyk (Program Manager: Breakthrough Initiatives) gave more detail on Breakthrough Starshot, characterising communications as one of the three overall challenges faced by Starshot - alongside the laser propulsion source and the sailcraft. We are 30 years from first launch and our target is 5 parsecs away. He suggested an initial goal "to try to prove that we can't" [1].

He identified three major stages for the project - technology development to 2030, prototype missions to increasingly distant objectives 2030-2040 and Alpha Centauri missions. The current (first) stage will determine the feasibility of current and future technologies to meet the requirements to successfully conduct the Alpha Centauri missions; are there any showstoppers? The first phase will be one year of small contracts to develop competing solutions addressing each of the technical challenges, further characterise the risks and identify strong teams for subsequent work. Multiple submissions are encouraged.

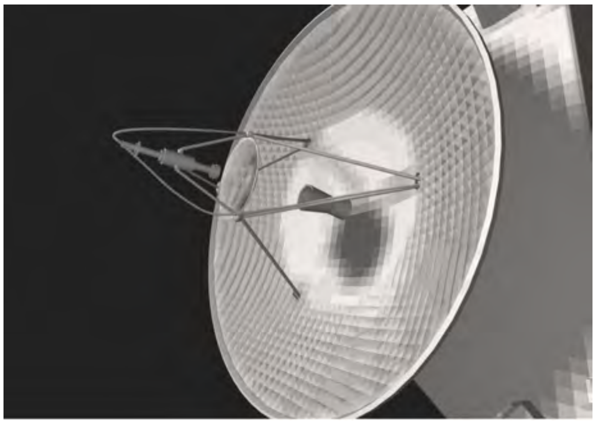


Philip Mauskopf, Pete Worden, James Schalkwyk

Credits: Arizona State University, S. Pete Worden (@worden -Twitter) and starshot-asu.com respectively

[1] Karl Popper would no doubt be pleased by this approach - see *Conjectures and Refutations: The Growth of Scientific Knowledge,* Karl Popper, 1963. Also - plato.stanford.edu/entries/popper/#ScieKnowHistPred and www.lse.ac.uk/philosophy/conjectures-and-refutations/

Communications



New Horizons main transmission dish. Note the secondary medium gain dish incoporated into the Cassegrain secondary reflector for the main dish.

Credit: Fac-tory-o / Wikipedia (commons.wikimedia.org/wiki/File:New_Horizons.stl)

Professor Philip Mauskopf of Arizona State University (ASU) is Communications Committee Chair & Technical Lead for Starshot. He introduced the technical part of the RFP for Phase 1 Communications R&D.

The Phases (www.starshot-asu.com/) are -

- RFP Release: December 1, 2020
- Pre-proposal white papers due: January 4, 2021
- Invitations to propose Issued: January 11, 2021
- Full proposals due: February 7, 2021
- Selections: February 14, 2021

Prof Mauskopf gave us a headline goal - to receive images of planets from Alpha Centauri. And a scaling of the problem - the downlink technology needs to improve on the New Horizons probe to Pluto[1] and beyond by 4-5 orders of magnitude.

The New Horizons downlink data rate was 1,000 bits per second and the data transfer took about one year - long after the flyby. The working figures for Starshot performance would accept a lower data rate, say 10 bits per second and a lower image definition (it's worth recalling at this point that the Starshot aim is to send thousands of probes - the overhead cost per probe is probably dominated by the energy cost for each firing of the gigantic propulsion laser array on Earth).

Comparing New Horizons (NH) and Starshot -

- transmitter mass - 10s of kg (NH) versus Starshot sailcraft just a gram or so
- downlink power demands - a few 10s of watts versus a few tens of milliwatts
- total downlink data - gigabytes (NH) from Pluto versus about 100 kilobytes per sailcraft

The sailcraft antenna might be similar in size if the sail can be used. However optical links are already being implemented by NASA, for example in the Psyche mission [2]. An optical link from the sailcraft would yield several orders of magnitude increase in data rate at a similar mass and power to a radio frequency (RF) transmitter like New Horizons. Mauskopf cited NASA Deep Space Optical Communication (DSOC) as the optical technology baseline (versus New Horizons for RF). Here the receiver is the venerable Palomar 200 inch (5 m) Hale reflector. Some of us can recall early images from this former heavyweight champion of optical telescopes long before the Hubble was launched. But the old beast now has superconducting electronic detectors rather then the photographic plates of its youth.

Mauskopf and the team, however, are open to all ideas for downlink technology at this stage. He provided a spreadsheet model of one type of optical communication system to allow researchers to insert their own parameters. Overall the objective is to energise the community to develop concepts for the whole downlink system and for specific components at both transmitting and receiving ends of the downlink.

Conclusion

The challenges of communication from a very low mass probe over a distance of 4 light years are as daunting as those of sending such a probe. Researchers closely affiliated to Starshot have already addressed some of these problems as summarised in Principium 31. The public website for the communications work of Breakthrough Starshot is at Arizona State University (www.starshot-asu.com/).

[1] Pluto was 30 AU from Earth at New Horizons flyby. The transmitter was 12 Watt X-band (7 GHz) via a 2.1 meter Cassegrain antenna with the NASA Deep Space Network (DSN) stations spaced around the Earth (en.wikipedia.org/wiki/New_Horizons#Telecommunications_and_data_handling.and pluto.jhuapl.edu/Learn/Resources.php#Publications).

The DSN was founded in the early 60s as the Deep Space Instrumentation Facility but it has, of course, been much upgraded since then. The main antennas at the three DSN sites (Goldstone California, Madrid Spain and Canberra Australia) are single 70 m diameter dishes. These are due for replacement by multiple 34 m diameter dishes (www.nasa.gov/directorates/heo/scan/services/networks/txt_daep_transition.html)

[2] Deep Space Optical Communication (DSOC) - www.nasa.gov/mission_pages/tdm/dsoc/index.html, www.nasa.gov/directorates/spacetech/tdm/feature/Deep_Space_Communications, en.wikipedia.org/wiki/Deep_Space_Optical_Communications

Psyche mission - www.nasa.gov/psyche, psyche.asu.edu/mission/the-spacecraft/,en.wikipedia.org/wiki/Psyche_(spacecraft)#Ground_stations_for_laser_link

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

i4is members have received two Newsletters since our last issue of Principium -

Newsletter: Advanced propulsion concepts and how to develop them 31/01/2021

- Summary of Olivia's upcoming talk on advanced propulsion on 2nd Feb
- AMiTe Treffpunkt — A proposal for communication between Kardashev Type IIb civilisations - Principium Preprint by David F Gahan
- New Videos and Presentations in the i4is Members Area!

Newsletter: i4is 2021 Talk Series announced 14/01/2021

- Summary of John's upcoming talk on the interstellar downlink on 26th Jan
- Livestream recordings now available
- Asteroid Mining: How to mine in space instead of on earth
- Project Lyra: Catching 1I/‘Oumuamua–Using Nuclear Thermal Rockets
- Interstellar Research Group: 7th Interstellar Symposium — Call for Papers
- Discover ISU: International Space University virtual open day
- New Videos and Presentations in the i4is Members Area!

Principium Preprints

Members will have had early access to articles from this issue of Principium -

- Preprint: Worldship and self replicating systems 2021-02-07
- Preprint: The Artemis Accords: what comes after the Moon? 2021-02-07
- Preprint: AMiTe Treffpunkt — A proposal for communication between Kardashev Type IIb civilisations 2021-01-31

Videos and presentations

Lots of new videos and presentations - both public and "members only" are listed in our *Become an i4is member* page in this issue. You can find them all at -

i4is.org/videos/

i4is.org/talks/

Register for future talks via the /talks/ link - both public and "members only" or just email talks@i4is.org.

Help our Education and Outreach Activities

You will see that we are increasingly reaching out to schools, astronomy societies and other groups. If you would like to think about delivering talks yourself and maybe even promoting them in your neighbourhood city or country then get in touch with Rob (rob.swinney@i4is.org) or John (john.davies:i4is.org) to talk about it. No commitment until you are ready!

Help us to grow!

Our membership is growing steadily worldwide but we can do better with your help. If you are somewhere where virus restrictions permit then print one or two of our posters from -

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

Or anywhere in the world just tell your friends and colleagues "like" us on social media, contact us with ideas. To members who have been with us for more than one year receive a single-use code that they can share with a friend, giving their friend a One Year Free Trial on their new membership of the Initiative for Interstellar Studies (i4is.org/members/free-trial/). We hope that many of you will take this up especially on behalf of the rising generation in full time education. In subsequent years their student membership will be £5, just over $6 and just under €5.

Just login and go to - i4is.org/members/free-trial/ - you will see -

Share the single-use code with a friend and they can join with a 1 year free trial.

You can either copy the code's link and share it with a friend, or give them the code and tell them to visit i4is.org/free-trial to redeem their free trial. They can sign up with any of the annual membership plans with a one year free trial. They will be charged for subsequent years after the trial period but they can cancel their subscription at any time during the trial period.

Annual Report to members

Before the next issue of Principium in May we will be sending our Annual Report to members.

You will find a link to our first report, delivered last year, at -

i4is.org/newsletter-i4is-annual-report-2019/

It covers 2019 and summarises our whole history back to our founding in 2012 -

i4is Annual Report 2019
- ***Summary .***
- ***Letter from the Executive Director***
- ***Status of the Organisation***
- ***Membership***
- ***Our Work***
  - ***Technical Projects***
    - ***Glowworm.***
    - ***Lyra***
    - ***Past Projects***
  - ***Education***
    - ***Schools***
    - ***Universities***
    - ***Outreach***
  - ***Sustainability & Enterprise***
  - ***Media***
- ***Financial.***
- ***Organisation and Administration***
- ***The Coming Year***

This year's report will be a little shorter, covering only 2020.

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.***

Our latest talk for members

Our talk series has now been running for more than three months and has proved very popular. We have a mixture of open and members-only talks. The latest members-only talk was on Tuesday 9 February 2021, Adam Hibberd on his 'Optimum Interplanetary Trajectory Software' (OITS) which has been key to mission planning for Project Lyra and other i4is studies.

Adam Hibberd gave a hands-on demonstration of his OITS package, which he developed in 2017, and has used with i4is colleagues to calculate potential trajectories for missions, especially to the interstellar object (ISO) 1I/'Oumuamua.

He started by showing a simple mission from the Earth to Mars in 2018, and after entering the two waypoints involved, and the year of departure, demonstrated that the software calculated an optimal mission profile that very closely resembled that of NASA's InSight Mars Lander, which left Earth on 5 May 2018 and landed on Mars six months later on 26 November.

The second example mission replicated the flight of the New Horizons probe, which left Earth in January 2006, flew past Jupiter for a gravity assist in February 2007, and arrived at Pluto in July 2015. The results from OITS were again very close to the real mission timings, demonstrating the validity of the OITS approach.

Adam then used the software to plan a speculative mission to the interstellar asteroid 1I/'Oumuamua. Starting from information developed in the KISS Workshop 2014, the mission profile involves several phases, including a fly-by of Earth, a reverse gravity assist at Jupiter, and a solar Oberth manoeuvre. An alternative strategy replaces the solar Oberth manoeuvre by a fly-by of an 'intermediate point' placed roughly six solar radii from the surface of the Sun, and enabled the mission to reach Oumuamua in July 2052.

Several questions followed from the audience, both about the software itself and the potential uses to which it might be put. Those interested in exploring the software for themselves were invited to visit Adam's website (www.AdamHibberd.com) and to read Adam's article in Principium issue 27, on the theory behind the software.

New videos

New videos, with slides, we have added to the website since our last issue-

John & Patrick Discuss Principium	***Highlights of Principium and i4is in 2020*** from the Editor and Deputy Editor		i4is.org/videos/john-patrick-discuss-principium/

Talk Series | i4is.org/what-we-do/education/talk-series/

Rob Swinney	***Introduction to Interstellar Studies***		i4is.org/talk-series-introduction-to-interstellar-studies/
Marshall Eubanks	***Missions to Interstellar Objects - An i4is Initiative***		i4is.org/talk-series-missions-to-interstellar-objects-an-i4is-initiative/
Andreas Hein	***Worldship Design***		i4is.org/talk-series-worldship-design/
Dan Fries	***Advanced Propulsion 1***		i4is.org/talk-series-advanced-propulsion-1/
Rob Swinney	***Interstellar Precursor Missions***		i4is.org/talk-series-interstellar-precursor-missions/
Patrick Mahon	***Boldly going where no-one has gone before: Interstellar Starships in Science Fiction***		i4is.org/talk-series-sci-fi-interstellar-starships/
John Davies	***The Interstellar Downlink***		i4is.org/talk-series-the-interstellar-downlink/

Outreach

John Davies: Interstellar Objects

John Davies	***'Oumuamua and Borisov - the unexpected and the half-expected interstellar visitors*** 15 January 2021 — York Astronomical Society, UK		i4is.org/videos/john-davies-oumuamua-and-borisov/
John Davies	***Interstellar Probes — How can we do it?*** 26 November 2020 — Cardiff Astronomical Society, UK		i4is.org/videos/john-davies-interstellar-probes-how-can-we-do-it/
John Davies	***Interstellar Objects — 'Oumuamua, Borisov and Objects in Between*** 22 October 2020 — Loughton Astronomical Society, UK		i4is.org/videos/john-davies-interstellar-objects/

And the older ones, all at - i4is.org/videos/

TVIW 2016: Advanced Electric Propulsion for Interstellar Precursor Exploration by Angelo Genovese

Interstellar Probes: How can we do it? by John Davies (08 July 2020 — Papworth Astronomy Club)

FISW2 [25 videos]

1I/'Oumuamua and 2I/Borisov — the unexpected and the half-expected interstellar visitors

ISU Interstellar Studies Module [13 videos]

Sending Ourselves to the Stars

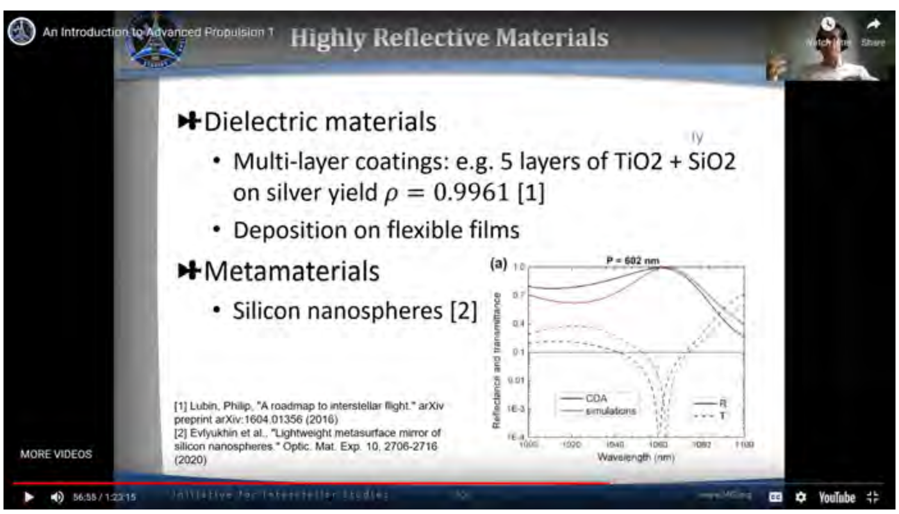
Starship Engineer [6 videos]

Project Dragonfly [5 videos]

i4is 3rd Anniversary

World Science Fiction Convention 2014

Kelvin F Long at 59th International Astronautical Congress



Dan Fries dscusses Highly Reflective Materials in his talk *Advanced Propulsion 1*, see *Talk Series* above.

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

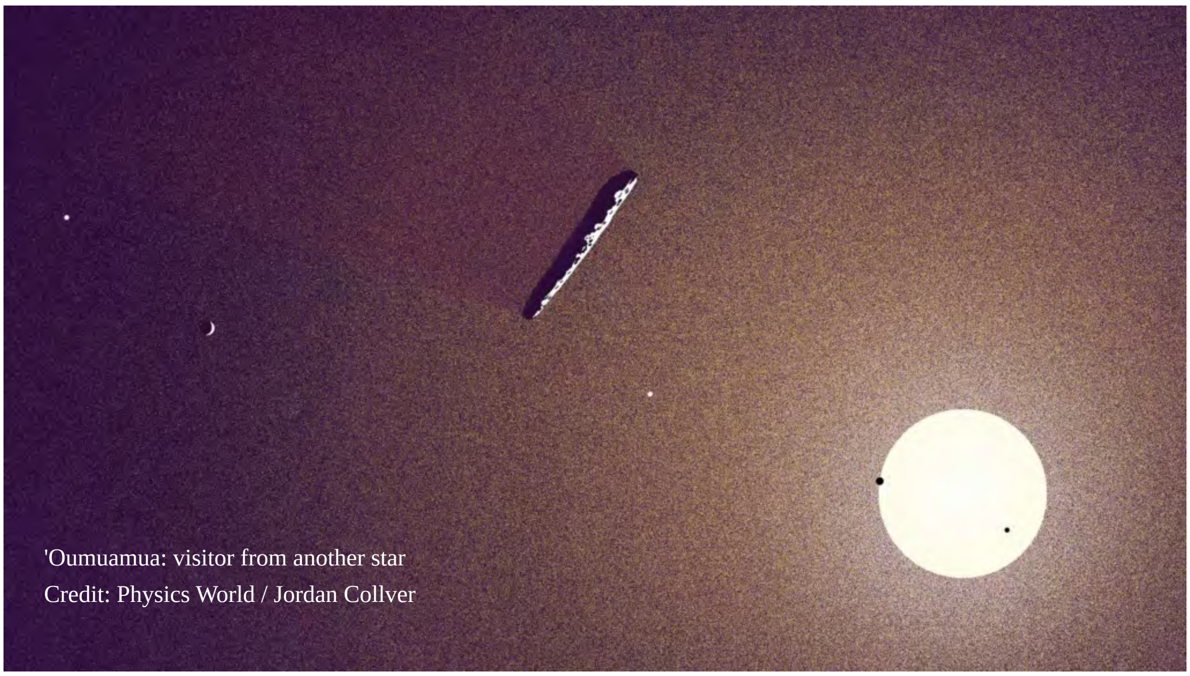
An Interstellar Visitor:

sorting the fact from the speculation

Alan Aylward

Professor Avi Loeb of Harvard University has received both brickbats and bouquets for his widely circulated thinking on the nature of the interstellar object, 1I/'Oumuamua. As Loeb's new book is published, UCL Professor Emeritus Alan Aylward delivers a closely argued contribution to the former. Principium and i4is have no set view on this fascinating object, except perhaps for an enthusiasm for a mission to find out more about it (as in numerous peer-reviewed papers by the i4is Project Lyra team and articles in Principium).

Please read on and tell us what you think. We will be reviewing Professor Loeb's book in our next issue.



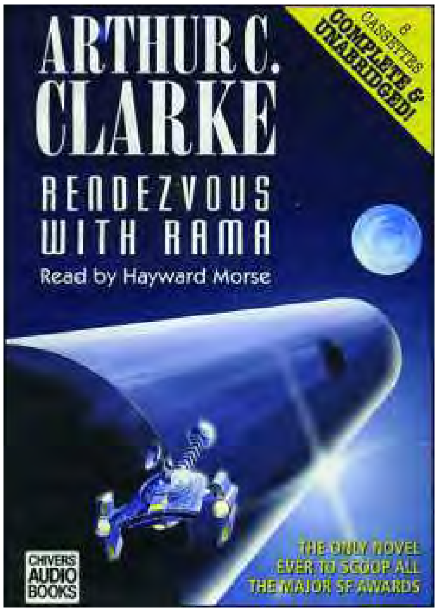
'Oumuamua: visitor from another star
Credit: Physics World / Jordan Collver

There is an unfortunate tendency in some quarters when a new, interesting phenomenon is discovered to jump to far-fetched conclusions before a proper analysis gives us the realistic explanation. I am sure that Bell and Hewish have had much time to wonder whether it was a good idea to have written LGM (Little Green Men) on the paper roll when their radio astronomy experiment detected the first pulsar, giving as it did carte blanche to an array of over-imaginative observers to take that at face value. Percival Lowell spent many fruitless years trying to convince his fellow astronomers that the straight lines he claimed to see on Mars must be the sign of a significant civilization. There were believers in Martian "Canals" right up until the time of the Mariner missions which finally showed the true face of the planet close up. Strange rock formations caught in the right light orientation on the Moon or Mars attract the imaginative into seeing alien faces or other artefacts. Even the great and good tend to sometimes drift into theories they should not have. Fred Hoyle's illustrious career was somewhat bruised by later work he did with Wickramasinghe where he claimed sudden outbreaks of disease across the world could be explained by alien microbes brought to earth with cometary

Lowell's Mars - with canals - Credit: National Martime Musuem www.rmg.co.uk/

infall. And how many remember the alien spacecraft from Epsilon Boötis transmitting to Earth as an explanation for LDEs (Long Delayed Echoes)? Astronomical phenomena seem to especially set themselves up as targets for wishful thinking. The great difference in albedo between two sides of Iapetus was long a science fantasist's play script until we actually had pictures of the moon.

The latest, previously highly-regarded scientist to dip his toe into speculative fiction is Avi (Abraham) Loeb, an astronomer from Harvard. He has become the delight of the fringe (and not-so-fringe) science scene in the last couple of years for his work on 'Oumuamua, the interstellar object seen passing through the solar system in October 2017. 'Oumuamua was certainly a revelation when it was first discovered. The first object known that was definitely on an interstellar hyperbolic trajectory, it had entered the solar system gravitational well with 26 km/s excess velocity from the direction of Lyra and it had a complex light curve that showed a 15:1 variation in brightness. The best explanation for that was that it was a highly elongated object, maybe cigar-shaped with a length 6 times its narrowest dimension, and it was spinning and coning in a semi-chaotic rotation. The interest grew even further as more detailed analysis of its trajectory showed it seemed to be accelerating slightly as it left the solar system. Despite the fact that such acceleration was not entirely unknown for small asteroids and comets this lead to some heated speculation as to its origins, no doubt fed to some extent by memory of Arthur C Clarke's sci-fi novel "Rendezvous with Rama". Without a close-up inspection of the object – by now well out of detector range – the detailed nature of it was going to take a lot of theoretical and interpretive science, if indeed it could be done at all.



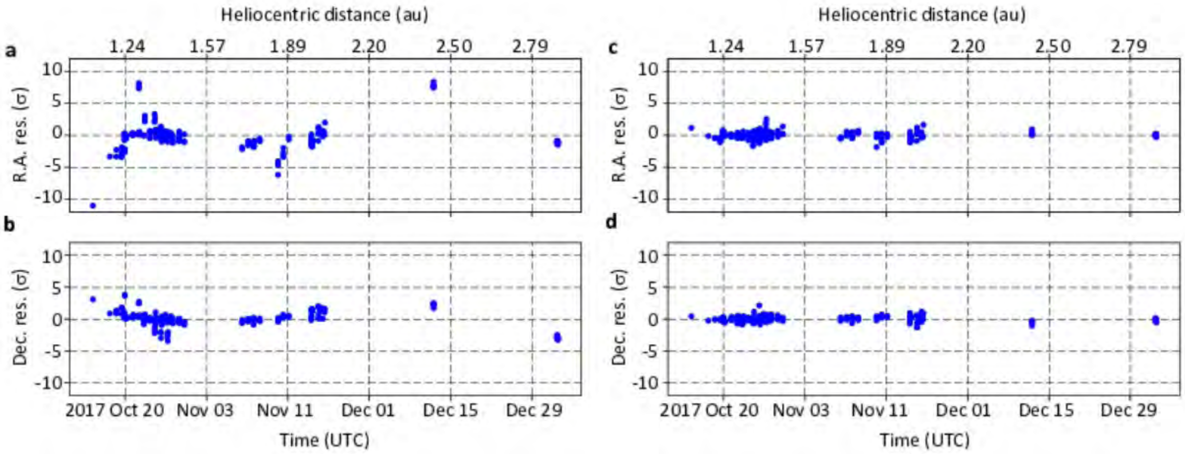
Audiobook cover of *Rendezvous with Rama*, see also *Sir Arthur C Clarke Centenary Celebrations, Thoughts on a mighty imagination and his envisaged interstellar object* by Patrick Mahon, Principium 20 February 2018.

There have been a number of papers on 'Oumuamua - a surprisingly large number considering how restricted were the observations of it, but an indication of how novel it was to have an interstellar visitor of this type. It was found by the Pan-STARRS1 survey telescope after the body had already passed perihelion and its nearest point to Earth. Because it was moving so fast and turned out to be quite small the observations that could be made were limited, but it was seen to be such an important discovery that it was observed by the ESA OGS (Optical Ground Station), CFHT (Canada France Hawaii Telescope), ESO's VLT (Very Large Telescope) and Gemini South, the latter two being 8-metre telescopes. It was also in its latter stages seen by HST (Hubble), including the final images taken in January 2018 when it became too faint to follow further.

Authors from a number of institutions lead by Marco Micheli at ESA produced a fairly comprehensive summary of the results in June 2018 concentrating on the non-gravitational acceleration ("Non-gravitational acceleration in the trajectory of 1I/2017 U1 ('Oumuamua)", Micheli et al, Nature [1]).

Their abstract summed up their findings: "After ruling out solar-radiation pressure, drag- and friction-like forces, interaction with solar wind for a highly magnetized object, and geometric effects originating from 'Oumuamua potentially being composed of several spatially separated bodies or having a pronounced offset between its photocentre and centre of mass, we find comet-like outgassing to be a physically viable explanation, provided that 'Oumuamua has thermal properties similar to comets." Although early observations had ruled out the object being a comet because they had failed to see a (visible) coma the paper said a lack of observation of what was probably water outgassing moving the body was not surprising as the acceleration seen was so low the amount of water vapour would have been below the spectroscopic detection discrimination level of even the most powerful telescopes used. There was one unusual aspect to this, which was that no CN was detected, which would have meant the CN/OH ratio in the outgassing would have been very low (a factor of 15 below solar system abundances). Also, no dust had been detected as might have been expected around the body. These do not comprise "killer" reasons for ruling out outgassing

[1] Micheli, M, Farnocchia, D, Meech, K J et al. *Non-gravitational acceleration in the trajectory of 1I/2017 U1 ('Oumuamua).* Nature 559, 223–226 (2018). Open publication: www.researchgate.net/profile/Harald_Ebeling/publication/326018112_Non-gravitational_acceleration_in_the_trajectory_of_1I2017_U1_'Oumuamua/links/5b4860a645851519b4b4a312/Non-gravitational-acceleration-in-the-trajectory-of-1I-2017-U1-Oumuamua.pdf



Micheli et al achieved a good inverse square law fit for the anomalous acceleration of 1I/'Oumuamua see -
Astrometric residuals of 'Oumuamua observations.
a, b: normalized right ascension and declination residuals against a gravity-only solution.
c, d: normalized right ascension and declination residuals against a solution that includes a non-gravitational radial acceleration $A_1 r^{-2}$
Credit (image and *caption*): Micheli et al fig 2

as the motive force for the body as the low CN/OH ratio is not entirely unknown even in solar system bodies, and if the dust released by the outgassing had been grains larger than a few hundred micrometres they would not have been detected at optical wavelengths anyway.

Some calculations by Micheli et al using a thermal outgassing model treating 'Oumuamua as a "typical" cometary nucleus showed that a relatively small outgassing from the subsolar point of the body was enough to explain the acceleration, and the best fit to the orbit perturbation was a force directed from the Sun radially outward and falling off as r^{-2} or r^{-1} as would be expected for a solar-heated release of gas from at or near the surface. Thus they conclude 'Oumuamua behaves like a miniature comet, which is consistent with the surface colour and albedo. It would have a thin insulating mantle, and slightly unusual chemical composition and dust properties, although how significant this might be was difficult to say without knowing its origin. One should stress that although there were at least 177 ground-based measurements and 30 HST observations, this was a faint and difficult to characterize body and a lot of advanced processing techniques went into the analysis, so there is some uncertainty in nearly all the parameters recovered. On the acceleration side they could rule out an impulsive acceleration - the best fit was for continuous acceleration, falling with distance, directed more or less along the sun-object line (some transverse and normal forces could make a modest improvement to the fit, but the significance was less than 1-sigma).

Following the Micheli et al paper there were a number of follow-up publications concentrating on what were considered to be inconsistencies and the unusual characteristics of the body, largely based on the differences inferred between this and "normal" solar system bodies and on the peculiar shape and dynamic behaviour of the body. It is certainly true that no bodies of this shape were known to date in the solar system. The best fit to the light curve was of a long thin body rotating to show a main 4.3 hour power maximum (assumed to be half the spin period) but with irregular flux variations, with a max/min variation of a factor of 15, which could be explained by positing an elongated shape experiencing complex non-principal axis rotation. One should note that these are noisy irregular observations and that the solution for the motion is not unique. You can get different geometries and different dynamics by, for example, having a variation of reflectivity across the surface and non-uniform structure. The accepted shape that one sees in all the popular depictions of the body is only the current best estimate of what fits the light curve - but that's not totally unique as a solution.

Soon several groups tried to find alternative explanations for what we were seeing. Seligman, Laughlin and Batygin in May 2019 produced a paper [1], which described some modelling they did to see if the Micheli et al conclusions stacked up. They created a dynamic model of the body, based on the preferred shape, assuming a nozzle-like venting of volatiles tracking the subsolar point on the body. They produced a light curve of what their model would look like to observers and concluded they could produce something that looked very close to the data obtained. They concluded the body would lose about 10% of its mass in the 100 days it was nearest the sun. Their model ellipse was 260 metres long and had an albedo of 0.1, both of which were consistent with observations. A perfect fit was not possible, as would be expected because of the uncertainties in the observations and the lack of detailed knowledge about the body shape.

Despite this sort of work some more esoteric theories started to surface about the origins of ‘Oumuamua. It was such a peculiar shape - long and thin - that maybe it was an alien spacecraft. Could it be a probe sent to gather information about our solar system? Or a failed interstellar probe that hadn’t stopped or changed course correctly when it got to its target? Why, if it was “live” did it produce the weak and ineffective acceleration that it did? The strange semi-chaotic motion would suggest that if it was a probe, its attitude control systems were rather compromised. There was some speculation about where it might have come from. It was difficult to pin-point an origin because of the uncertainty in accumulated acceleration (we know nothing of any changes that took place prior to perihelion and passing Earth). There was nothing unusual about its arrival velocity if it was “natural” as 26 km/s was about the average for the dispersion in the local galactic area. Nor was the direction of origin particularly surprising. It was mainly the unusual shape which drove the more bizarre speculation. If this was a body that was self-compacted by gravitational forces alone why did it not tear itself apart as it spun? Some groups carried out radio observations to see if it was transmitting but nothing was detected.

To address some of the speculation a group of scientists under the auspices of ISSI the International Space Science Institute (www.issibern.ch), produced a paper in Nature Astronomy in July 2019, “The Natural History of ‘Oumuamua” [2]. Recognising the limitations on the observations they conclude "the observations are consistent with a purely natural origin for 'Oumuamua". They point out that even the shape is uncertain since how the shape is interpreted depends on the specific state of rotation, including its rotation pole. It could either have a narrow elongated ellipsoid shape, or a shape more reminiscent of a flattened oval. It is almost certainly unusual, but there is nothing certain about the popular representations in the press.

The paper spent a lot of time examining criticisms of the detection based on claims the chances of a detection of a natural object were small (ie so it couldn’t be “natural”). This came down to a scientific evaluation of how many such small objects should exist in interstellar space. The ISSI team pointed out that speculation on the statistics of probabilities of things based on only one sample was poor science (we have since found a second interstellar incursor, 2I/Borisov in October 2019, so things are looking up!). The estimates of how many you expect to see are dependent on the population’s SFD (Size-Frequency Distribution) but this is almost entirely guesswork based on models of the creation mechanisms for non-solar-system bodies. Estimates can be made based on theories of production by, for example, ejection of material from stellar formation regions by Gas Giants in those systems, but all one can really say is that there is nothing in the order of magnitude estimate one gets of creation probability that rules out getting bodies entering the solar system in observable timescales.

[1] *On the Anomalous Acceleration of 1I/2017 U1 'Oumuamua*, Darryl Seligman, Gregory Laughlin and Konstantin Batygin, The Astrophysical Journal Letters, Volume 876, Number 2, May 2019 iopscience.iop.org/article/10.3847/2041-8213/ab0bb5/meta

[2] *The natural history of ‘Oumuamua*. Nature Astronomy, 3 (7). pp. 594-602. Michele T. Bannister (Astrophysics Research Centre, Queen’s University Belfast) et al. Open publication: authors.library.caltech.edu/97422/2/1907.01910.pdf

The ISSI team look at the outgassing needed to produce the acceleration seen and agree with previous work that says the Seligman et al estimates are feasible. The outgassing estimate is consistent with solar system comets of this size. And to quote: “Furthermore, when the Rosetta observations of comet 67P/Churyumov–Gerasimenko (made at comparable heliocentric distances to when ‘Oumuamua was observed) are scaled down to an ‘Oumuamua-sized object, they yield a similar outgassing rate.” They also agree with the previous comments about the lack of observation of dust not being surprising, and that the 15 times depletion in CN from the “expected” was not so far out either -in fact factors of 25 and 72 had been found in previous comets. And “The range of these ratios of volatiles in comets has recently been found to be far greater than was previously known: C/2016 R2 PanSTARRS has CO/H2O at least several orders of magnitude higher than any other measured comet, with no H2O yet conclusively detected.” So ‘Oumuamua gets to look less “special” at every turn.

The paper takes on the alien spacecraft proposition directly. By this point Avi Loeb and others had been suggesting the small acceleration could be consistent with a “solar sail” using solar radiation pressure. The ISSI team comprehensively discount this. While it fits some of the observations like the fact the body may have had a highly flattened shape, other key aspects do not fit the observations and some arguments in favour of this hypothesis are simply wrong. The key argument against is that a solar sail would have to be properly oriented with respect to the sun, but this does not fit with the observed brightness variations. It is not possible to find a geometry that can satisfy all the dynamics and observational facts. (And, they claim, in fact the best solution for the shape is an elongated ellipsoid anyway.) Other arguments about disparities in the body’s albedo and trajectory they also comprehensively dismiss. Some of the sceptics of the received version of the dynamics had produced modelling to question why the outgassing had not produced a change in the spin characteristics over the times of the observations but this has been countered by other modelling that shows the proposed accelerating jet would naturally result in NPA (non-principal axis) rotation with a light-curve amplitude and period comparable to the observations, without causing extreme spin up [1].

Despite these works all showing that the body’s characteristics could be explained by “standard” physics, a number of authors continued to question aspects of this. What about the structural integrity of such an elongated body? There were questions about the origins of the body, and some doubt cast on the acceleration mechanism seen. One more fact-based cause of concern was suggested first by Sekanina in 2019 who calculated that if the acceleration was being driven by the sublimation of H^2O ice then there was insufficient solar energy input to release it and accelerate it to the velocity that would provide the force needed. This was taken up by Seligman and Laughlin [2] who suggested that the accelerating medium was hydrogen rather than water. (There had been a suggestion in 2018 by other authors that ‘Oumuamua was partially composed of hydrogen ice.) Seligman and Laughlin built up a case that the body was composed wholly or partly of hydrogen ice and they did some detailed modelling of sublimation from geometries similar to the putative shape of ‘Oumuamua to show that the acceleration is possible. They pointed out that Hydrogen outgassing also explained why no coma had been seen around the body – hydrogen would not show one visibly.

They realised however that the biggest criticism of this model would likely be how to create a hydrogen ice body in the first instance. They suggested interstellar environments where this could have happened, though it is difficult to form hydrogen ice in most circumstances. Of course, the assumptions here can anyway be questioned. There are other possible accelerants that have lower sublimation energies than water - like Nitrogen and Neon. Also the Seligman and Laughlin paper seems to assume the same acceleration has been occurring over the full incoming trajectory, whereas it seems possible that the incoming leg could have produced heating with little release of material until the temperature in the surface layer built up enough for the outgassing needed to produce the acceleration seen on the outbound trajectory. The doubts about water supplying the acceleration also seems somewhat at odds with the statements in other papers that the outgassing from ‘Oumuamua is consistent with what is seen in solar system comets.

[1] See references in Bannister et al - 83 Rafikov (sceptic) and 64 Seligman et al (response) - open publication version - *The natural history of ‘Oumuamua*, Open publication: authors.library.caltech.edu/97422/2/1907.01910.pdf.

[2] *Evidence that 1I/2017 U1 (‘Oumuamua) was Composed of Molecular Hydrogen Ice*, Darryl Seligman and Gregory Laughlin. Astrophys J., June 2020). Open publication: arxiv.org/abs/2005.12932

The Seligman and Laughlin paper was fairly quickly criticised by Hoang and Loeb who attack not the acceleration mechanism but the possible existence of a body composed mainly of hydrogen ice. They do this on two bases. First they question whether icy grains rich in H^2 can form in dense environments because collisional heating destroys the H^2 mantle before grain growth. Secondly in travelling from the creation site - assumed to be GMCs (Giant Molecular Clouds) - the energy encountered in interstellar radiation, gas, dust and cosmic rays would destroy any small body within the time span required to reach the solar system. Their paper details the calculations to support their criticisms and basically boils down to an estimate of how long a hydrogen ice body would survive in interstellar space. Of course the survival time depends on the size of the body but they claim that a typical body entirely made of hydrogen ice would not last.

Seligman agrees that a hydrogen ice body would not survive the journey time from the nearest GMCs, but points out that there are nearby star-forming regions (like the hydrogen left from the Carin and Columba moving groups of stars formed 30-40 million years ago) that are believable creation sites near enough for ‘Oumuamua to have survived the journey to the solar system. Loeb is adamant that the actual formation of hydrogen ice bodies itself is out of the question wherever one may choose - though he hedges his bets by saying if they were made it could only be in GMCs. It is Avi Loeb from the Hoang and Loeb paper who has been particularly promoting these arguments especially because he wants to promote his own ideas about ‘Oumuamua.

Principium 23- November 2018

What is Oumuamua?

The Loeb/Bialy Conjecture and i4is Project Lyra

Front cover of Principium 23 - visualisation of a possible explanation of 'Oumuamua "Wrecked Solar Sail" by Alex Storer - introducing *NEWS FEATURE -*

What is Oumuamua? The Loeb/Bialy Conjecture and i4is Project Lyra,

John I Davies

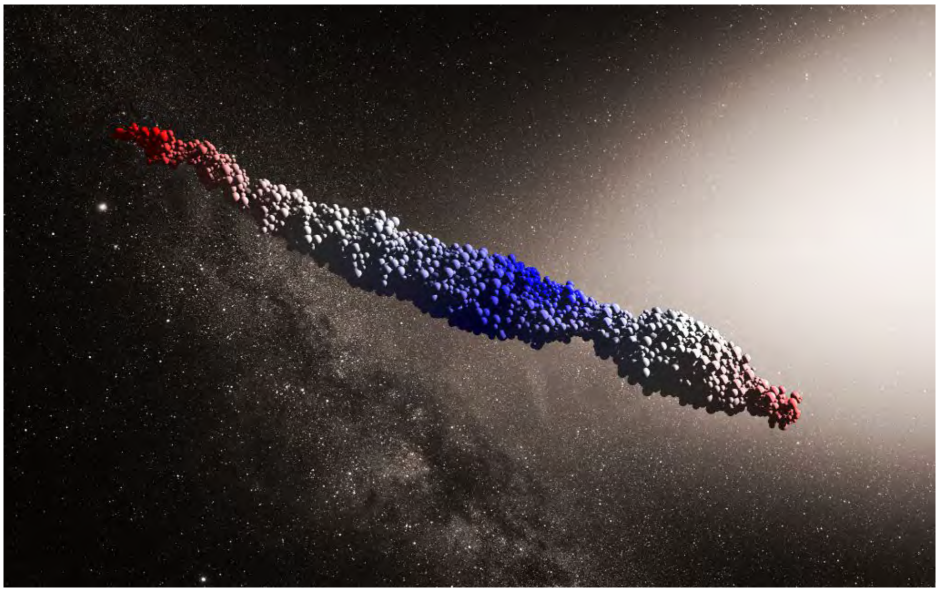
This gets us back to where we started and the promulgation of fanciful ideas about the origin of ‘Oumuamua - an article in Scientific American in January 2021 that describes the arguments between Seligman and Loeb points out that Loeb has a vested interest in getting the classical explanation of ‘Oumuamua’s origins questioned - he has a book coming out called *Extraterrestrial: the First Sign of Intelligent Life Beyond Earth*. Loeb is in full promotional mode. The Observer of Sunday 31 January has an article about Loeb and his theories. Because he is a Harvard astrophysicist it takes his ideas seriously and gives him rein amongst other things to criticise Seligman’s ideas again, claiming that he, Loeb, is a misunderstood unconventional thinker that the scientific community cannot understand because they are too blinkered. He is careful not to leave himself too open to possible future ridicule if his ideas are debunked by saying: “I’m not arguing for sure that it was an artificial object. I’m saying it’s a reasonable plausibility based on the evidence”.

A more destructive criticism of Loeb and his intercession here is by Etan Siegel in Science, Jan 28 2021 [1]. He sees Loeb on a personal publicity campaign. “For the better part of the past four years, Harvard astronomer Avi Loeb has appeared all over the media to gather public support for an idea that absolutely defies the scientific evidence.” Siegel points out that Loeb is connected to the Breakthrough Starshot project, and complains that Loeb has been bombarding journalists for the last 4 years with attempts to get his ideas circulated, while claiming he has no personal wish for fame or recognition. Siegel sums his view up with:

> “Loeb…has written papers with his postdocs and students insisting that ‘Oumuamua is just as likely to be an alien spacecraft (that looks suspiciously like a light-sail) as it is to be one of the expected ~10^{25} naturally occurring objects in our own galaxy. Despite the fact that the spectral signatures of the object — its color, reflectivity, size, etc. — are consistent with a natural origin, Loeb offers only loud, immodest speculation about aliens and diatribes about community groupthink.”

[1] The Uncensored Guide To ‘Oumuamua, Aliens, And That Harvard Astronomer, Ethan Siegel. open version www.forbes.com/sites/startswithabang/2021/01/28/the-uncensored-guide-to-oumuamua-aliens-and-that-harvard-astronomer/?sh=3cac5adf6abe

One recent addition to the canon of work on ‘Oumuamua has perhaps finally laid to rest the more fanciful queries about its characteristics. Zhang and Linn in Nature Astronomy Sept 2020 [1] have modelled a mechanism which can easily explain all the “peculiarities” of the body. They infer that the progenitors of ‘Oumuamua-like ISOs may be kilometre-sized long-period comets from Oort clouds, kilometre-sized residual planetesimals from debris disks or planet-sized bodies at a few astronomical units, orbiting around low-mass main-sequence stars or white dwarfs. The precursor bodies can be “standard” rock-pile bodies. The disturbing body drags these apart gravitationally – similar to what happened to Shoemaker-Levy 9 as it passed too close to Jupiter. Unlike Shoemaker-Levy 9 the elongated body can escape the disruptor, though heated to the extent that most of the volatiles except some deep-buried water and carbon dioxide are evaporated. As it leaves the disruptor, kicked into an interstellar trajectory, the body cools and forms a hard shell strong enough to hold it together despite any wild dynamical motion the ejection from the disruptor has brought about. So we have a long thin body, rigid though possibly rotating chaotically, depleted in most volatiles like CN. As it enters the solar system it heats up and residual water buried deep in the body reaches the surface by the time it passes perihelion and starts to outgas – accelerating it slightly. The arguments about how unlikely it is to have such bodies are answered by the fact the authors provide three mechanisms by which they can come about. They predict we will eventually find many more of them.



Model of rotating 'Oumuamua, colour coded to represent bulk rotation

Credit: Zhang and Linn

Is that it then, proven/disproven? Maybe, maybe not, but the mere fact one can find a realistic mechanism to explain what we have seen should show that one needs to look at viable physical explanations before we get overly fantastical.

Of course there may be no bad thing about a bit of speculation in science and society but the question is how much are we promulgating bad science by producing unfounded speculation where there is a fairly prosaic explanation for something. If we see a corn circle in a field do we still consider it might be made by aliens even after the people who made it tell us they did it? If we can explain the ticks on a roll of chart paper by the signals from a pulsar should we still be saying "of course you never know - it may be Little Green Men"?

[1] Zhang, Y., Lin, D.N.C. *Tidal fragmentation as the origin of 1I/2017 U1 (‘Oumuamua)*. Nat Astron 4, 852–860 (2020).
Open publication: arxiv.org/abs/2004.07218

About The Author

Alan Aylward is Emeritus Professor of Atmospheric Physics in the Department of Physics & Astronomy at University College London. His main work was in ionospheric research, thermospheric research and modelling of the earth's thermosphere and ionosphere moving on to modelling of planetary thermosphere/ionospheres (Mars,Titan, Jupiter and Saturn) and later modelling of exoplanet atmospheres. He also has substantial experience in spacecraft technology and software development.

71st International Astronautical Congress 2020

The Interstellar Report - Part 2 of 2

This year's Congress was a ***Cyberspace Edition*** offered without registration fee, free of charge for a global community. Principium readers were therefore able to 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 part two of this report we aim to complete our reports of 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 -

- Patrick Mahon (PJM)
- John I Davies (JID)
- Angelo Genovese (AG)
- Max Daniels (MD)

Our thanks to all of them.

Our reporters views are, of course, their own and don't necessarily reflect the views of the editors of Principium or of the Initiative and Institute for Interstellar Studies.

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 -

iac2020.vfairs.com/en/registration

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

CONTENTS

B5,1,7,x59095	Edge computing and its applications in satellites	Mr. Archit Latkar	Ramaiah Institute of Technology	India

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/B5/1/manuscripts/B5,1,7,x59095.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/B5/1/presentations/B5,1,7,x59095.show.mp4

Open paper: None found

Reported by: John Davies

Mr Latkar observed that satellites are currently unable to perform computationally challenging tasks on board. He suggests that "Edge computing seeks to setup a distributed platform for integrating cloud technology in IOT networks" [1]. His team aim to extend technologies such as image processing, blockchain and deep learning into space - and even to small spacecraft such as cubesats - by providing a network of specialized satellites, esats, to provide services to other satellites in the vicinity - based initially on the example of Iridium satellite constellation and using ideas from the SpaceX Starlink network. They have built mathematical models and examined costs, timescales and some specific challenges. The modelling includes -

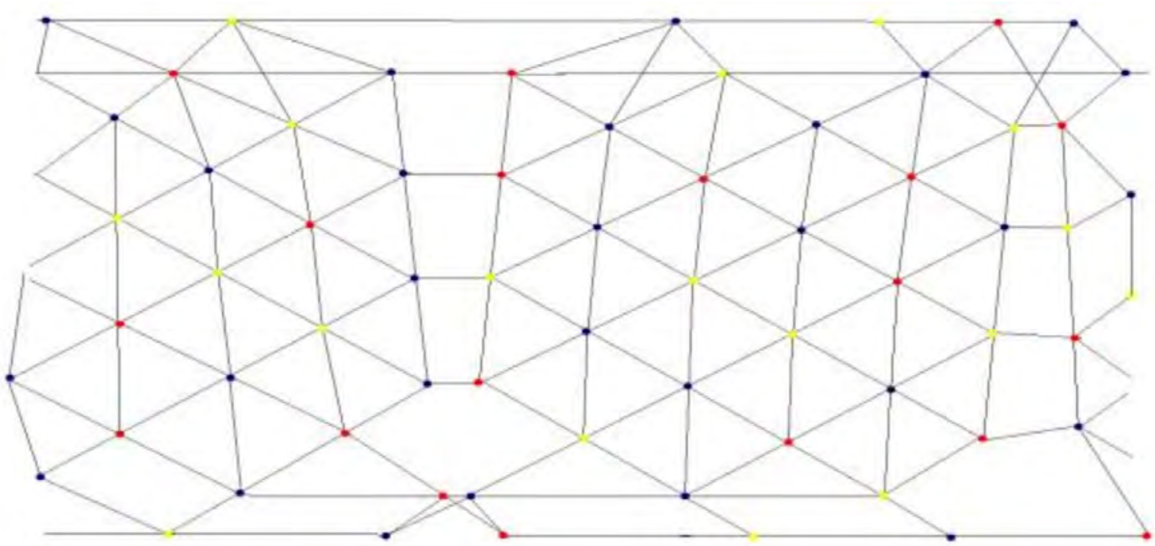
- Optimised placement and cost of esats in the Satellite Edge Network
- Optimising Resource Allocation - notably between three distinct types of esat in the network
- Estimating Time Delay - between esats in the network using queueing theory

They use a lossless model, handling congestion by handing requests between satellites of the same type.

The challenges they see are -

- Data Reduction - identifying the inadequacy of current protocols for this application
- Usability - mainly ease of integration with the user satellites
- Data Abstraction - to provide consistent user interfaces
- Service Management - to handle user requests and to integrate new services
- Privacy and Security - suggesting that existing non-defence satellite networks are weak in this respect

Mr Latkar and the team envisage a satellite edge network architecture which can potentially revolutionise the space industry. If we are to base our initial exploration of the stars on large numbers of very small probes then networking between them is likely to be a key technology and maturing this closer to home can contribute to development.



Network of 18 esats used to model behaviour showing three types (red, green and blue).
Credit: Latkar et al

Authors: Archit Latkar and 10 others, all Ramaiah Institute of Technology

[1] en.wikipedia.org/wiki/Internet_of_things

A5,4-D2.8,6,x60658	Knowledge and Technology Building Blocks for Space Access Architectures	Mr. Arun Subramanian Venkataraman	Invenk Solutions	India

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/manuscripts/A5,4-D2.8,6,x60658.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/presentations/A5,4-D2.8,6,x60658.show.mp4

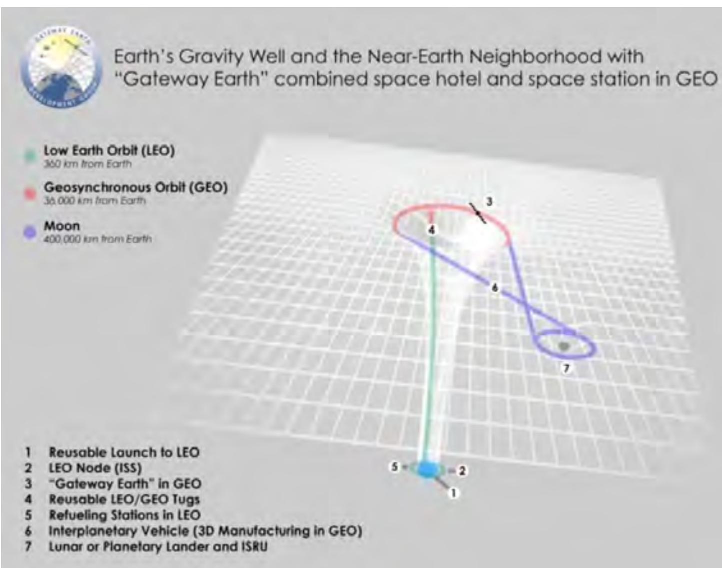
Open paper: None found

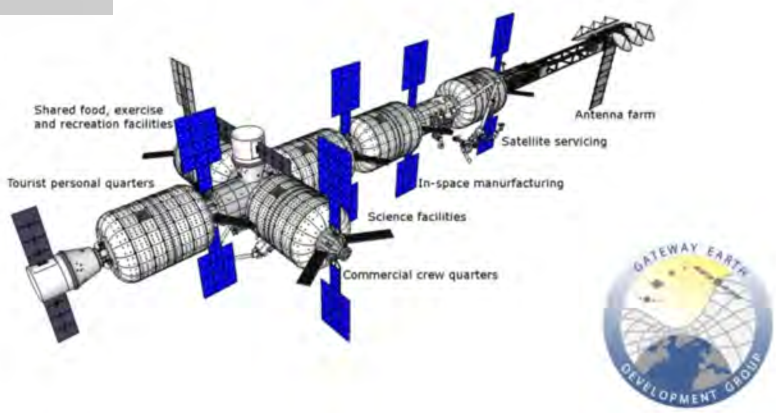
Reported by: John Davies

Gateway Earth Development Group (GEDG) aims to develop a near-geostationary gateway for human exploration of the solar system. The baseline design uses Bigelow B330 inflatable modules (bigelowaerospace.com/pages/b330/). Located just above geostationary orbital radius, the gateway would provide a repair and recycling station a Satellite Repair and Manufacture Facility (SRMF), for geostationary (GEO) satellites as well as vehicles to the Moon and beyond. The NASA OSAM concept (On-orbit Servicing, Assembly, and Manufacturing - nexis.gsfc.nasa.gov/OSAM-1.html) for in orbit servicing and construction is an existing idea with similar functions. The gateway would build upon the reduced cost of GEO resulting from low-thrust orbit raising from low earth orbit (LEO) as opposed to the current use of a geostationary transfer orbit (GTO) [1]. The paper identifies relevant patents in these areas of technology and, in a substantial appendix wider technological distribution of capabilities in -

- Manufacturing in Space
- Satellite Payload Health Monitoring
- Satellite Payload Performance Monitoring
- Satellite Freighters
- In-Space Recycling & Reuse Technology

We need this vision of "routine" access, manufacturing and servicing if we are to achieve the large scale capability required by many of our interstellar visions - for example see the Bigelow modules envisaged by Michel Lamontagne for the construction of the Icarus Firefly probe on the cover of Principium 22.





Contrast between the Earth's gravity well and the Moon - showing LEO-Moon deltaV advantage (above)

Visualisation of Gateway Earth, just beyond GEO (right)

Both images credit: Gateway Earth Development Group

Authors: Venkataraman + Lewis Leslie, Robbie Anderson and Matjaz Vidmar - latter 3 all University of Edinburgh. And one other, the presenter of the video - not clearly identified.

[1] GTO payload is a key performance parameter for launchers. Example GTO performance -

GSLV Mk III (India) payload 4,000 kg to GTO (www.isro.gov.in/launchers/gslv-mk-iii)

Delta IV Heavy (USA) 10,100 to GTO (www.ulalaunch.com/docs/default-source/rockets/delta-iv-user%27s-guide.pdf - Figure 2-9 . Delta IV Mission Capabilities)

A4,2,7,x58825	The InCosmiCon Research Center and its activities in the field of SETI, Big History and interculturality	Dr. Paolo Musso	University of Insubria	Italy

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/2/manuscripts/A4,2,7,x58825.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/2/presentations/A4,2,7,x58825.show.mp4

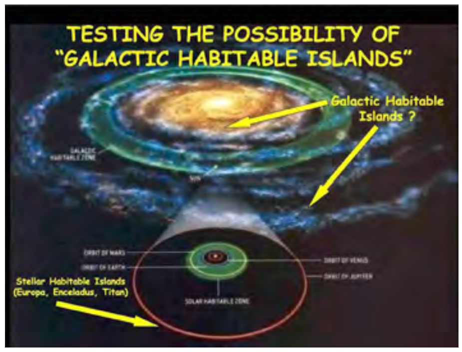
Open paper: None found

Reported by: John Davies

The University of Insubria (Italy) and the Universidad Católica Sedes Sapientiae, Lima (Peru), created a new research centre called InCosmiCon (Intelligence in the Cosmic Context), based at the Department of Human Sciences, Innovation and Territory (DISUIT) to investigate the nature of intelligence in an interdisciplinary way, as announced at IAC 19, Washington, in 2019. See the report of D Musso's talk in Principium 29, May 2020, page 37. Their work on translating Spanish texts to the languages of indigenous Amazonian peoples has been extended to Yánesha, Asháninka, Yine, Shipibo and Matsigenka. This continuing effort aims to use the unique laboratory of these mutually unintelligible languages as a testbed for the interpretation of SETI search results. The project sees some urgency here given the likely attrition of these languages.

Other InCosmiCon work includes -

- computer simulation of possible "galactic habitable islands" outside of the currently understood galactic habitable zone, as in the Solar system where habitable "islands" (eg Europa, Enceladus, Titan, and others) may exist outside of the previously limited habitable zone.
- Optical SETI in Peru - unique in South America.
- New algorithms for SETI - 5 possible "candidates" so far - spectral entropy, cognitive radio, autocorrelation, artificial intelligence, compressive cyclic analysis.
- Beauty in science - Global Research on the Aesthetic Dimensions of Science (GRADS), was conceived before InCosmiCon by Professor Brandon Vaidyanathan [1]. Investigating the relevance and the universality of beauty in science. The two projects are now cooperating. Aesthetics may well stand alongside science and mathematics as a common framework of understanding between ETIs.



Parallel between possible habitable islands the Soar System and in the Galaxy

Credit: Musso

There are 46 other authors listed on this paper, reflecting the breadth of involvement in InCosmiCon.

Broadening SETI in this way looks like an important addition to what would inevitably have implications way beyond hard science and engineering if and when SETI succeeds and thus requires a "best efforts" approach well before this happens.

IAC-20,A4,2,12,x59772	SETI Search: Plausibility of a SETI Probe and Search Parameters for an Interstellar SETI Search	Dr Ugur Guven	UN CSSTEA[2]	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/2/manuscripts/A4,2,12,x59772.pdf

IAF cited presentation video:iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/2/presentations/IAC-20,A4,2,12,x59772.show.mkv

Open paper: None found

Reported by: John Davies

Dr Guven argues that the best way to do a SETI study is in outer space away from the atmospheric and magnetic distortions of Earth. He draws lessons for the form of a probe to do this from UFO sightings, most of which exhibit "symmetry along one or more axis". He discusses two probe propulsion and power altenatives, nuclear and antimatter and suggests a long term spiral SETI search by very long-lived probes.

[1] Dr. Brandon Vaidyanathan is Associate Professor and Chair of the Department of Sociology at The Catholic University of America.

[2] Centre for Space Science and Technology Education in Asia and the Pacific (CSSTEAP), www.cssteap.org/,

C4,9,2,x59647	Integrated optimization of trajectories and layout parameters of spacecraft with air-breathing electric propulsion	Mr. Alexander Golikov	Central Aerohydrodynamic Institute (TsAGI)	Russian Federation

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/C4/9/manuscripts/C4,9,2,x59647.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/C4/9/presentations/C4,9,2,x59647.show.mp4

Open paper: None found

Reported by: John Davies

Mr Golikov makes the case for small spacecraft in ultra-low Earth orbits (150-250 km) using air-breathing electric propulsion (ABEP) to maintain altitude. There is a clear tradeoff between altitude (more propellant input at lower altitudes) and drag (also increasing at lower alttudes). The paper provides an analytic solution thus setting requirements for the ABEP system.

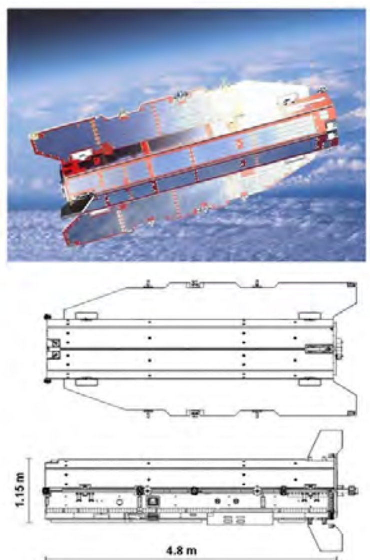
The pioneering ESA GOCE mission [1] was an early demonstrator of the possibilities but its lifetime was limited by the amount of Xenon propellant carried. The paper proposes to use only the atmosphere as the "working fluid". The ABEP system configuration would consist of -

- air intake
- thermalizer to decelerate the gas particles to thermal velocities
- ionization chamber
- acceleration region to accelerate the ionized gas in an electromagnetic field
- neutralizer for the ejected plasma particles

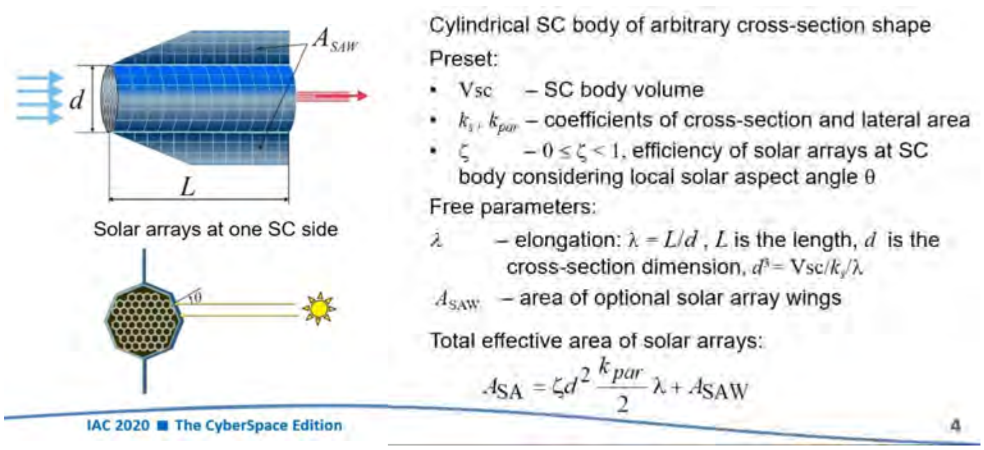
- with solar panels providing the power.

The system is, in effect, propellantless.

Based on models of the atmosphere, aerodynamic drag and of the air intake and thermalizer the paper derives conditions for long-term spacecraft existence in orbit. The paper presents curves showing dependencies of the minimal ABEP power on orbit altitude, minimum allowable gas number density in the ionization chamber and required power on the range of allowable altitudes.



The GOCE spacecraft
Credit: Steiger et al [1]



Layout of Spacecraft with ABEP

Credit: Golikov and Fitatyev

Authors: A A Golikov, A S Fitatyev

[1] ESA Gravity Field and Steady-State Ocean CirculationExplorer(GOCE) 17/03/2009 - 11/11/2013.

The Deorbiting of GOCE – A Spacecraft Operations Perspective, Steiger et al - 5th International GOCE User Workshop. Paris, 2015 - www.researchgate.net/profile/C_Steiger/publication/280114310_The_Deorbiting_of_GOCE_-_a_Spacecraft_Operations_Perspective/links/55aacf4208ae815a04279220/The-Deorbiting-of-GOCE-a-Spacecraft-Operations-Perspective.pdf

D4,5,7,x60941	Analysis of technology, economic and legislation readiness levels of asteroid mining industry: a base for the future space resource utilization missions	Ms. Smiriti Srivastava	Space Generation Advisory Council (SGAC)	Republic of Singapore

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/5/manuscripts/D4,5,7,x60941.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/5/presentations/D4,5,7,x60941.show.mp4

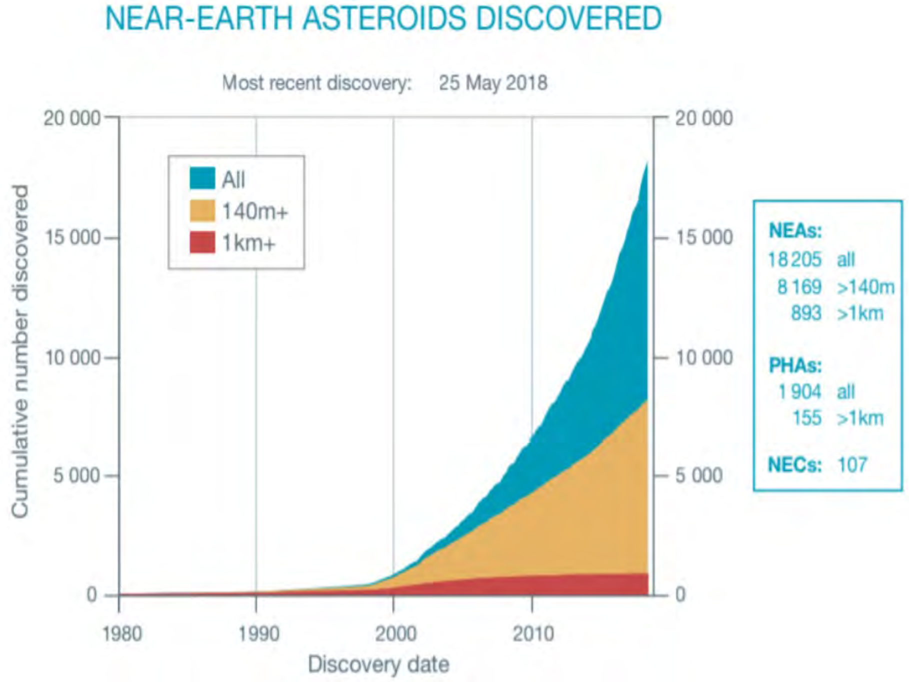
Open paper: None found

Reported by: John Davies

This paper ranges from technological readiness through business, economics, policy and legislation to sustainability and feasibility. Asteroids typically have low deltaV requirements by comparison with the Moon. They also contain usable materials in variety and accessibility superior to the Moon. An initial mission is judged to be at TRL 4 (Component Validation in Laboratory Environment) with extraction technologies Collection Mining/ Surface Mining, Shaft-Based Mining, Laser-Based Heating, Microwave Heating and Capture at the lower TRLs of 2 and 3. The team also developed Readiness Levels for policy (PRL), Business (BRL) and Investment (IRL). Economic analysis remains difficult since markets are not expected to arise for several decades. They also believe that previous Net Present Value (NPV)[1] analysis had omitted factors such as the cost of transport to the Earth.

The paper looks like an excellent starting point for the study of this subject, with 32 references for further study. The authors could usefully publish their work more widely.

Authors (all SGAC): Smiriti Srivastava, Swaraj Sagar, Bijaya Luitel, Pavithra Manghaipathy, Marco Romero



Number of known NEAs, NEOs discovered till June 2018 - sources - United Nations Office of Outer Space Affairs, Near Earth Objects And Planetary Defense A B Chamberlain.Near-Earth Object Program Office at the Jet Propulsion Laboratory, 2001.neo.jpl.nasa.gov.

Credit: Srivastava et al

[1] Net Present Value (NPV) is a measure of the current value of something which will be available at a future time, based on the principles of Discounted Cash Flow (DCF) - see www.open.edu/openlearn/nature-environment/financial-methods-environmental-decisions/content-section-1.3.4 - for a simple introduction.

D4,4,3,x56295	A Pragmatic Interstellar Probe Mission: Progress and Status	Dr. Ralph L. McNutt, Jr.	The Johns Hopkins University - Applied Physics Lab (APL)	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/IAC-20,D4,4,3,x56295.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/presentations/D4,4,3,x56295.show.mp4

Open paper: None found

Reported by: Angelo Genovese (all images credit: McNutt)

This paper is about a robotic "Interstellar Probe" through the outer heliosphere and into the nearby "Very Local" interstellar medium (VLISM) using near-term technology. This challenging mission has been studied for more than 60 years, the central technical question being an enabling propulsion system.

To provide input to the upcoming Solar and Space Physics Decadal Survey, NASA's Heliophysics Division has funded the Johns Hopkins APL to consider a near-term, "pragmatic" Interstellar Probe mission with the following fundamental requirements:

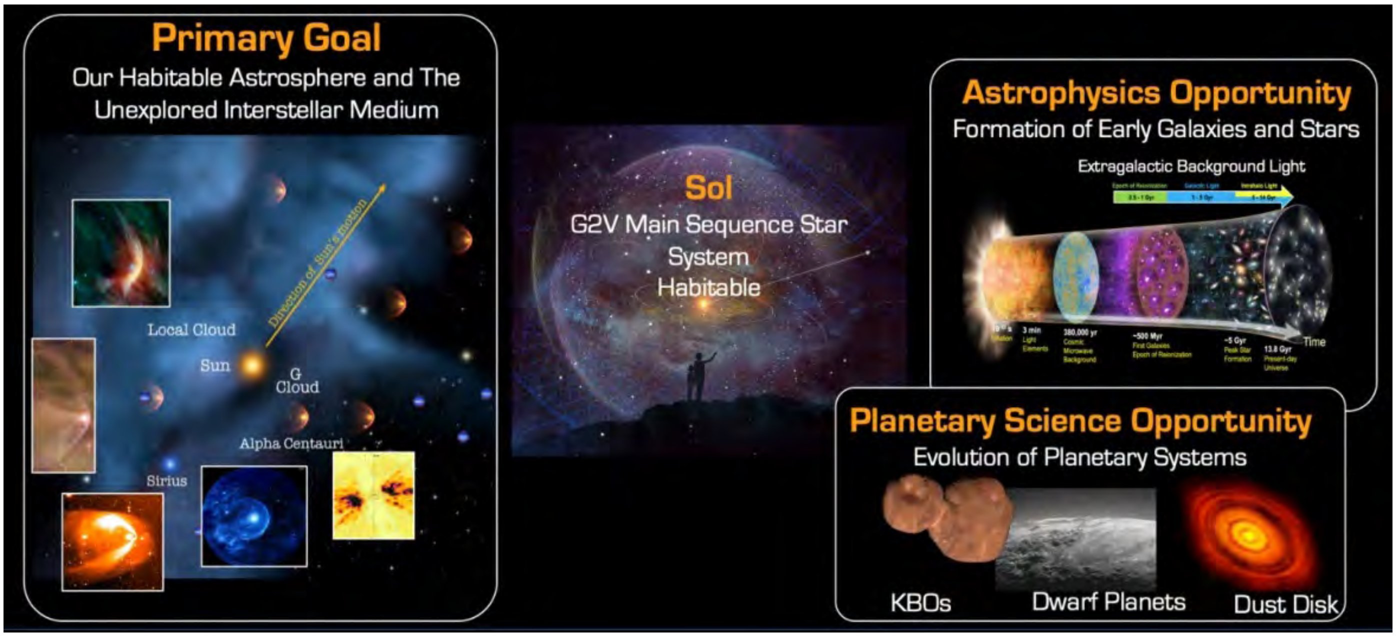
(1) READINESS, ready to launch no later than 1 January 2030;

(2) DOWNLINK, return science data from up to 1,000 astronomical units away;

(3) POWER, no more than 600 watts required at the beginning of mission and no more than 300 watts available at mission's end;

(4) LONGEVITY, spacecraft lifetime of not less than 50 years.

This paper provides a progress report on continuing refinements and trades being addressed in the study.



Propulsion

Near-term trades support the use of the Space Launch System (SLS) Block 2 configuration with existing or near-term kick stages and an unpowered Jupiter gravity assist (Option 1) or a Jupiter gravity assist powered by the uppermost stage (Option 2). An "advanced" concept using a near-Sun ("Oberth") manoeuvre is also being investigated by building from Parker Solar Probe thermal shield technology (Option 3).

Payload

A nominal core payload of 10 heliospheric instruments is included with a mass of ~90 kg. The baseline scenario tends to be driven to a spin-stabilized configuration to accomplish all heliospheric science observations with a minimum-sensor/aperture (and hence minimum mass) implementation. To accommodate desired plasma wave sensitivity, a plasma wave system (PWS) with four, 50 m long wire antennas.

Trajectory/ Launch Vehicle

Based upon the analyses to date, the use of an SLS Block 2 with an Atlas V Centaur and a Star 48 BV has been baselined for the launch configuration. This has been examined for use on both Option 1 and Option 2.

The overall separated wet mass of the spacecraft sets the performance of the final escape trajectory from the Sun's gravity field. The baseline design uses a launch capability of 860 kg including 101 kg of hydrazine propellant, yielding a 28% mass reserve for Option 1. With the same mass reserve for Option 2, 170 kg of propellant is needed for a launch capability of 930 kg. Maximum asymptotic escape speeds from the Sun tend to range from ~7.0 to 7.5 AU/yr for this initial baseline (present Voyager 1 speed is 3.6 AU/yr).

Spot checks for a particular trajectory show that asymptotic escape speed is not a strong function of spacecraft mass: each additional 50 kg of wet mass decrease the flyout speed by ~0.17 AU/yr.

As regards Option 3 (Oberth manoeuvre as close as possible to the Sun), refractory metal shields would be required for the thermal protection system (TPS), as done for the Parker Solar Probe. However, their added mass would negate any advantage to be gained from firing a kick stage near the Sun.

To support further investigations of the viability and possible advantages of Option 3 on the asymptotic escape speed, APL is currently examining the state of ultra-high temperature (UHT) materials; lightweight, high-strength metal carbide layers on carbon cores to provide the required UHT shield materials. Such materials have the potential of use up to 4,200K, with the mechanical strength of carbon fibre maintained. A TPS based upon this material could significantly lower the mass for Option 3. This will, in turn, allow a bestcase analysis of the utility of Option 3 using near-term existing materials.

Downlink

This challenging requirement (capability to operate and successfully downlink scientific data to Earth from at least 1,000 AU) is mostly driven by pointing as the downlink beam from the spacecraft must intersect the receiver on the Earth. The Voyager telecommunications system, with sufficient attitude control fuel, power, and no hardware failures, was estimated to be operable to ~300 AU. The Voyager usage of X-band was possible with no reaction wheels and could deal with pointing with the attitude control jets as the lower frequency opens up the required pointing accuracy.

The near-term technology, mass, and lifetime requirements have pushed the baseline selection toward a body-fixed high-gain antenna (HGA).

Power Considerations

Current estimated power requirements are shown below for one RTG (two RTGs are baselined); the downlink and payload requirements tend to be the power drivers.

Subsystem	**Power (W)**
Payload	94
Telecom	101
Power	25
Avionics	13
Total	233

Baseline power budget for one RTG showing margins -

RTG Capability	300
Margin	22%

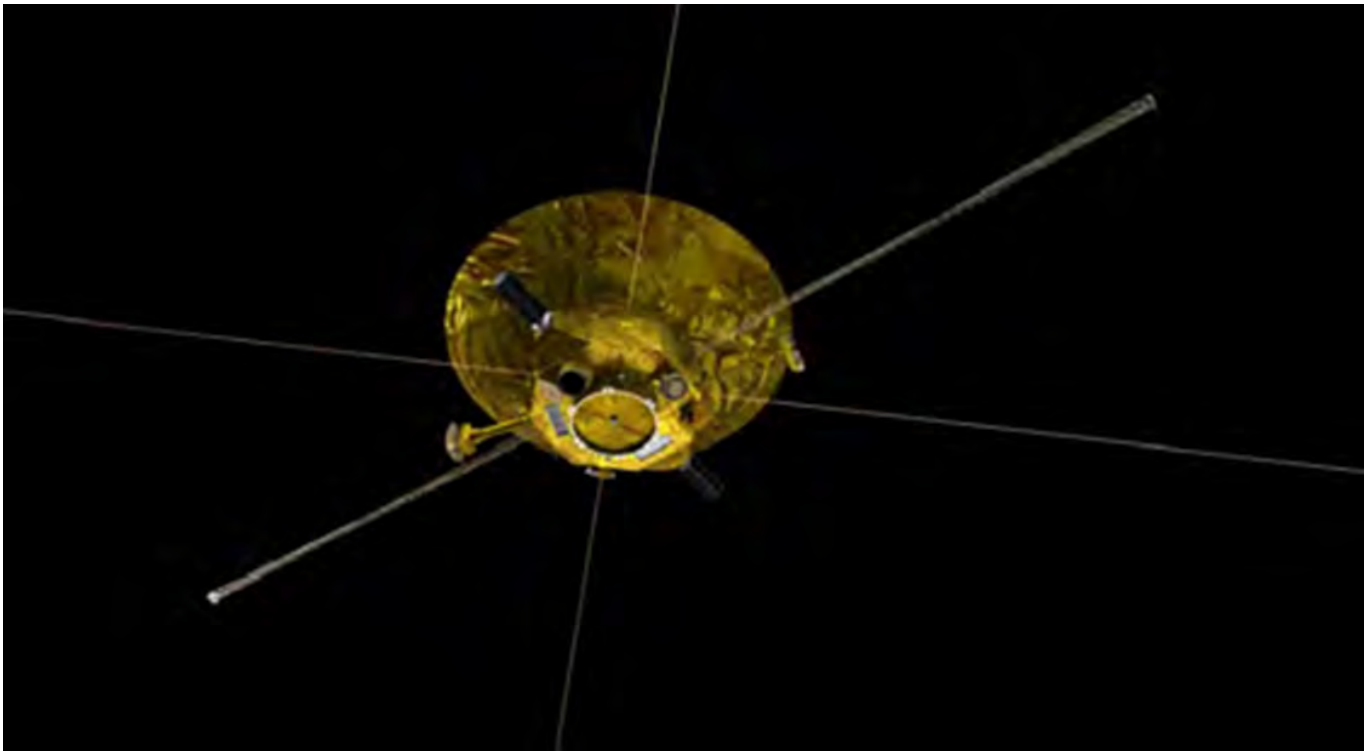
Credit: McNutt

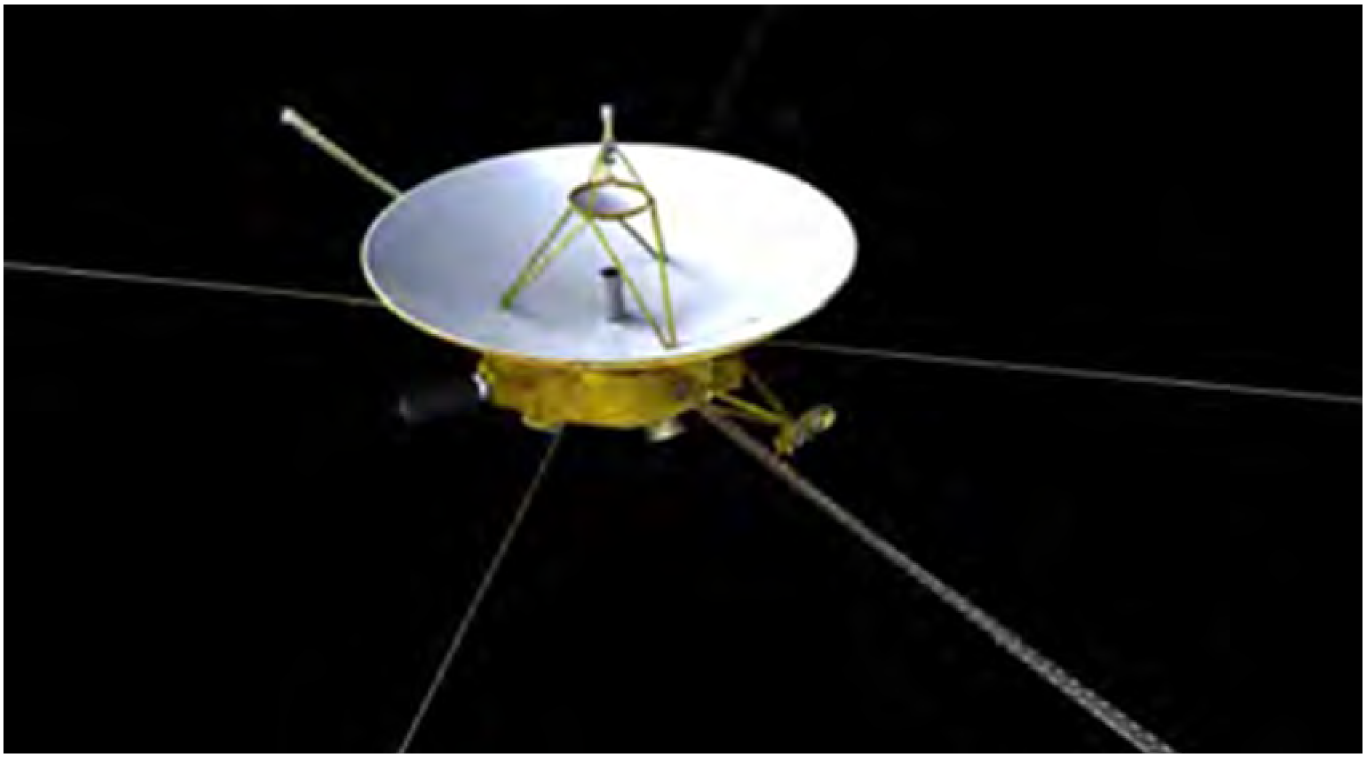
Mechanical Design

A corresponding baseline mechanical design has been established based upon the preceding considerations. The approach has been to establish a basic spacecraft design for an Option 1 trajectory for the heliospheric core mission and then examine changes to that design as needed for implementing the same mission using Option 2. Implementation with an Option 3 trajectory will require fundamental changes in approach and will be dealt with separately in the upcoming year of the study.

The spacecraft is (not surprisingly) dominated by the HGA (5 m diameter) as depicted below (credit: McNutt).

Views from below (top) and from above (bottom) of the current baseline concept. Prominent features are the HGA, four PWS antennas, two magnetometer booms, and two RTGs, The symmetry is needed to help spin balance the system, both for observations and the downlink requirements.





C4,9,3,x60528	Sitael's activities on the development of air breathing technology	Dr. Tommaso Andreussi	Sitael Spa	Italy

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/C4/9/manuscripts/C4,9,3,x60528.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/C4/9/presentations/C4,9,3,x60528.show.mp4

Open paper: None found

Reported by: John Davies

Air-breathing electric propulsion is being explored by several organisations worldwide. For a Russian example see the paper by Golikov (C4,9,2,x59647) earlier in this report. This paper emphasises the importance of an inexhaustible supply of propellant and an inexhaustible supply of energy, solar radiation. This Air-Breathing Electric Propulsion (RAM-EP) system has been under development since 2014.

The authors see this as a form of In Situ Resource Utilisation, as studied for asteroids and the Moon. Under this definition we could also include all other forms of air-breathing propulsion and even the Bussard ramjet!

Very Low Earth Orbit (VLEO) is defined as altitudes between 150 and 250 km.The advantages of VLEO are - better resolution by any optical payload, improved radiometric performance, lower communication latency especially important for bi-directional and real time telecommunication services, geospatial position accuracy, reduction in dimensions and mass of the payload, simple de-orbiting strategy (they also claim that risk of debris creation is "fully eliminated"), significant protection from space radiation allowing use commercial of the shelf (COTS) electronic components instead of space qualified components (thus reducing costs) and better space accessibility from VLEO.

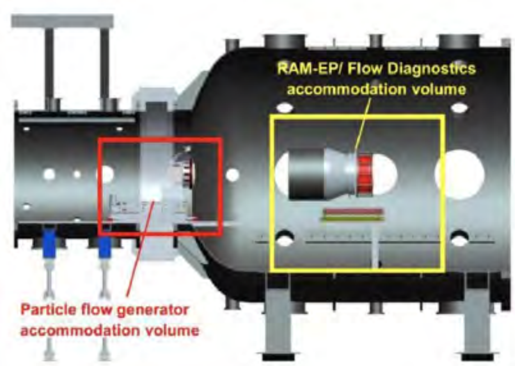
By testing their RAM-EP concept on-ground SITAEL claim an important milestone in air-breathing electric propulsion history with the first ignition and stable operation of a full air-breathing system operated in a representative environment. A 5 kW class Hall thruster was placed in front of the system intake and operated with atmospheric propellant to generate a VLEO representative flow. The test showed thrust of 6 mN but at this stage the test setup showed a drag force of 26±1 mN so there is clearly work still to be done.

This work is part of two programmes -

• AETHER (EU H2020 project, GA 870436)

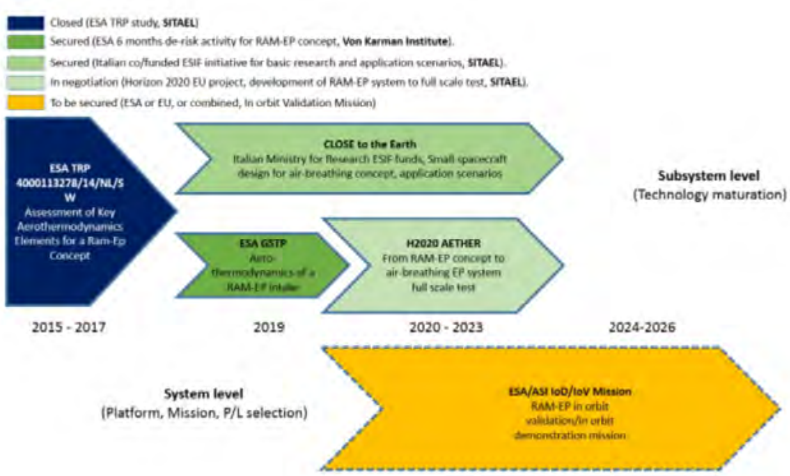
• Close to the Earth (Italian MIUR project, ARS0l_00141)

- from the European Union and Italian government respectively. In orbit demonstration is expected by the mid 2020s.



RAM-EP concept validation test setup in SITAEL's IV4 vacuum facility.

Credit: Andreussi / Sitael Spa



RAM-EP Development Roadmap

Credit: Andreussi / Sitael Spa

A3,4A,8,x59688	Trajectory analysis and design for an European Fast Kinetic Deflection Mission	Mr. Marcello Sciarra	Deimos Space SLU	Spain

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/4A/manuscripts/A3,4A,8,x59688.pdf

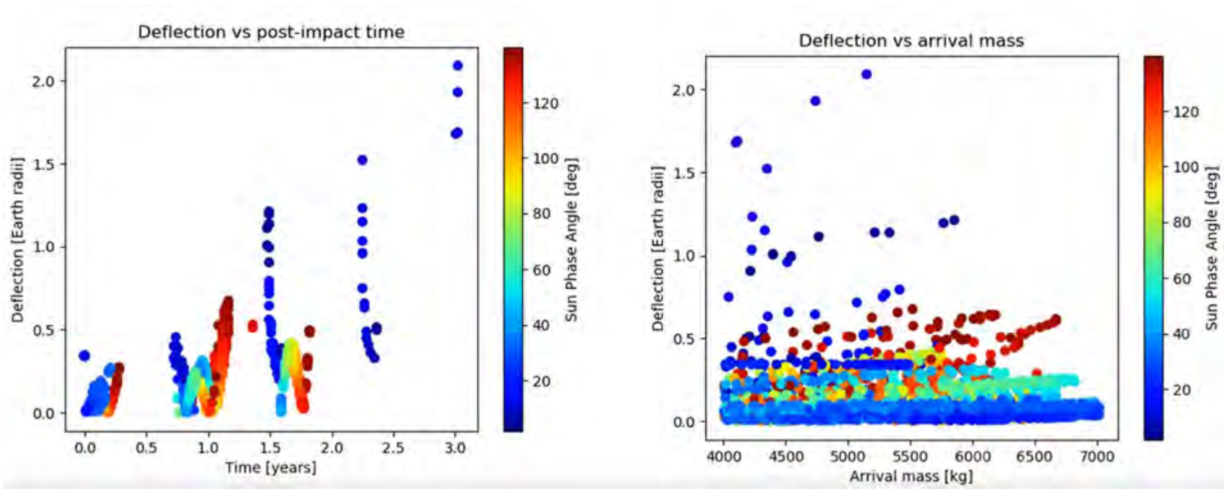
IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/4A/presentations/A3,4A,8,x59688.show.mp4

Open paper: None found

Reported by: Adam Hibberd

This research here was conducted by the Deimos/Elecnor Group and involves determining the degree of deflection of an asteroid as induced by an impactor launched from Earth. The collision is assumed to be inelastic (with β=2). The deflection is quantified by the change in closest approach distance of the Asteroid in the Modified Target Plane (MTP), this being measured in units of Earth radii.



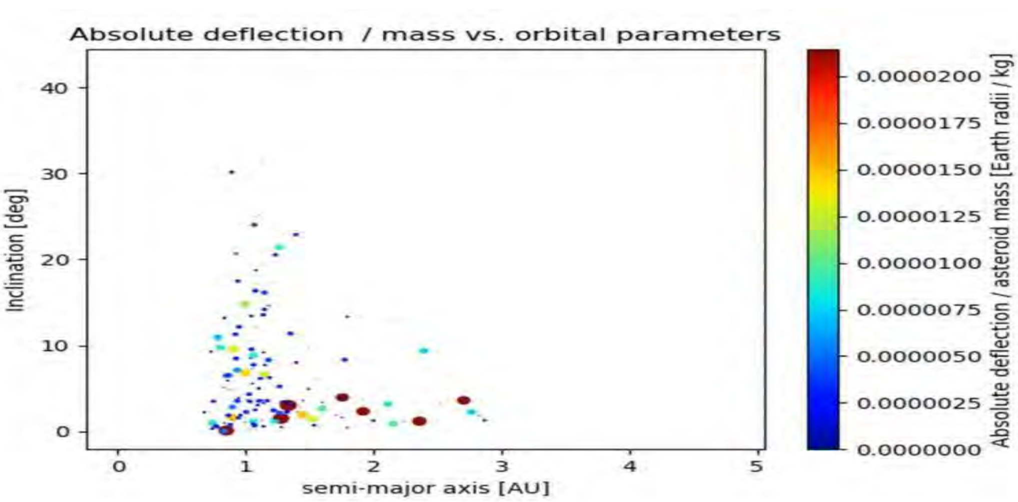
The targets are selected from a catalogue of PHA (Potenitally Hazardous Asteroids) and NEA (Near Earth Asteroids).

The process is to take an Asteroid, construct a grid of launch dates and flight times, solving the Lambert problem at each point on this grid (which gives a trajectory connecting Earth and the Asteroid up). These trajectories are then filtered according to three criteria:

1) They must have impact speeds of 5-15 km/s

2) They must have a solar phase angle of < 140 degs

3) The impact must occur before the closest approach of the Asteroid to Earth



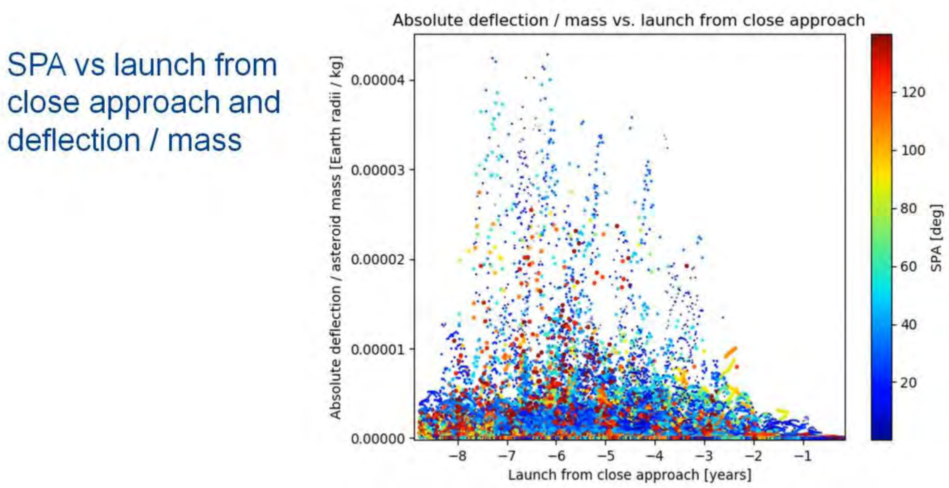
Deflection / mass
vs
sma and inclination

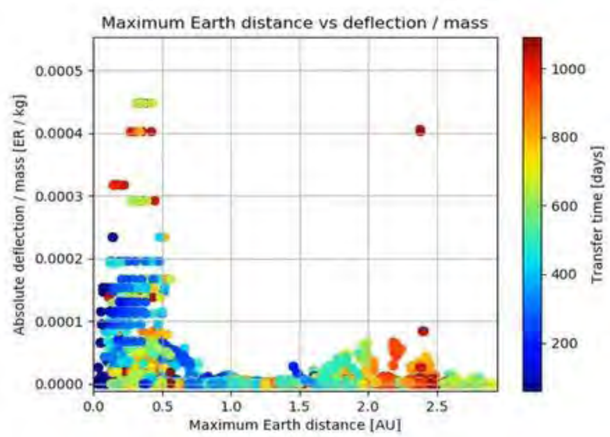
For the trajectories which satisfy the above, the deltaV applied by the impactor to the Asteroid is determined and the perturbed Asteroid trajectory is then propagated to determine the aforementioned degree of deflection.

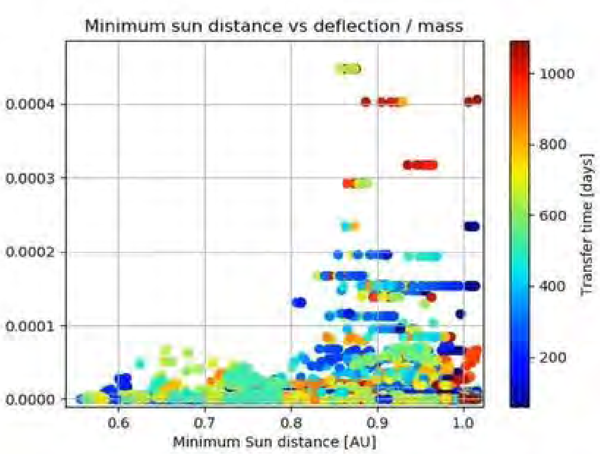
Further assumptions are made which are not detailed here, except that an Ariane 6.4 is used to launch the spacecraft.

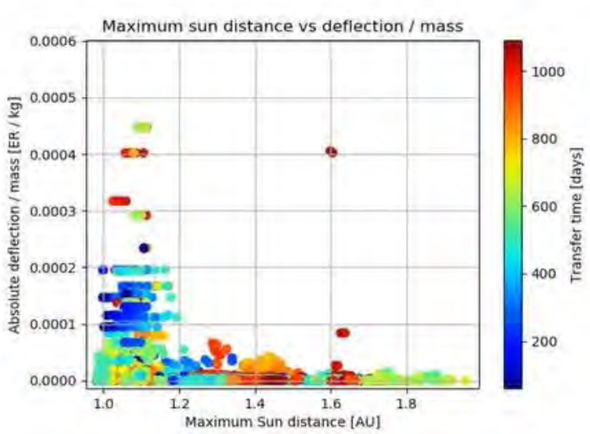
Results are that the lower the inclination of the Asteroid is to the ecliptic, the higher the degree of deflection. In addition, the longer the post-spacecraft-impact time, the higher the degree of deflection. There is also very little correlation between impactor mass and degree of deflection, because spacecraft (s/c) mass is coupled with launcher performance. Thus with greater s/c mass, the impact velocity is reduced because the hyperbolic escape speed of the launcher from Earth is reduced.

Also, generally speaking, the earlier the launch date compared to s/c impact time, the greater the degree of deflection. Please refer to attached plots.









A4,2,6,x60955	A Comprehensive View of SETI: Technical, Legal, and Outreach Considerations	Ms. Mirandah Ackley	International Space University	France

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/2/manuscripts/A4,2,6,x60955.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/2/presentations/A4,2,6,x60955.show.mp4

Open paper: None found

Reported by: Max Daniels

Ms. Ackley and colleagues observed that there are gaps in the field of the search for extra-terrestrial intelligence (SETI) that hinder its progression. These are in three areas: science and technology, legal and policy implications, and outreach endeavours. To remedy these gaps, the authors first asked three questions:

1) How can we detect signals from other intelligent lifeforms?

2) What should humanity do after a positive detection?

3) How can we raise awareness of SETI within our societies to normalise detection initiatives?

Question 1) was answered by adopting general principles, followed by two phases:

1) Analysing data from space telescopes that use light curves to detect exoplanets (the Galactic Technosignature Observatory (GTO));

2) The launch of an interplanetary CubeSat (NoisyCube) that aims to characterise the distortion of the Earth's signature from its orbital satellite infrastructure.

For both phases, the methods are extended to the detection of artificial objects. The authors stressed the importance of GTO and NoisyCube data being made available to the public.

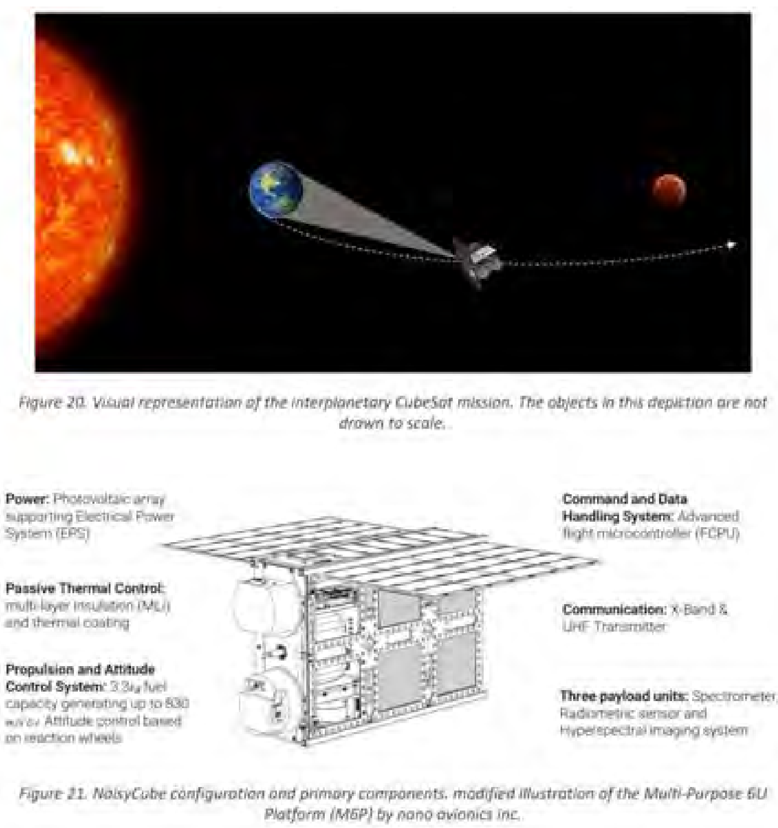


Figure 1: Visual representation of the interplanetary CubeSat mission (not to scale)

Credit: Ackley and colleagues (paper)

[1] A.E. Goodman, Diplomacy and the Search for Extraterrestrial Intelligence (SETI), Acta Astronautica 21/2 (1990) 137–141.
www.sciencedirect.com/science/article/abs/pii/0094576590901417 (paywalled)

Question 2) was answered by considering the four proposals of Goodman [1] and first identifying their weaknesses, which comprise:

1) There are no examples of SETI being treated as part of space exploration

2) Its communication to the general public

3) The uncertainty of findings.

To address shortcomings in the existing legal framework, the authors proposed updates to the 2010 International Academy of Astronautics post-detection principles. They suggested legitimising these principles by framing NoisyCube as space exploration, and so tying SETI legally to the Outer Space Treaty. Modelling humans' relations with animals, they concluded that it is necessary to move away from an anthropocentric view of the world towards an appreciation of each individual component of the cosmos.

Question 3) was answered by making three objectives:

1) To normalise SETI as a topic

2) To disseminate related science to alter the narrative that extra-terrestrial intelligence is only science fiction

3) To share findings and proposals developed by researchers.

For these objectives, they identified three target audiences (and forms of outreach):

1) The general public (through publicity-generating merchandise and a website)

2) The SETI and space community (also through merchandise and a website)

3) Young children (through a children's book).

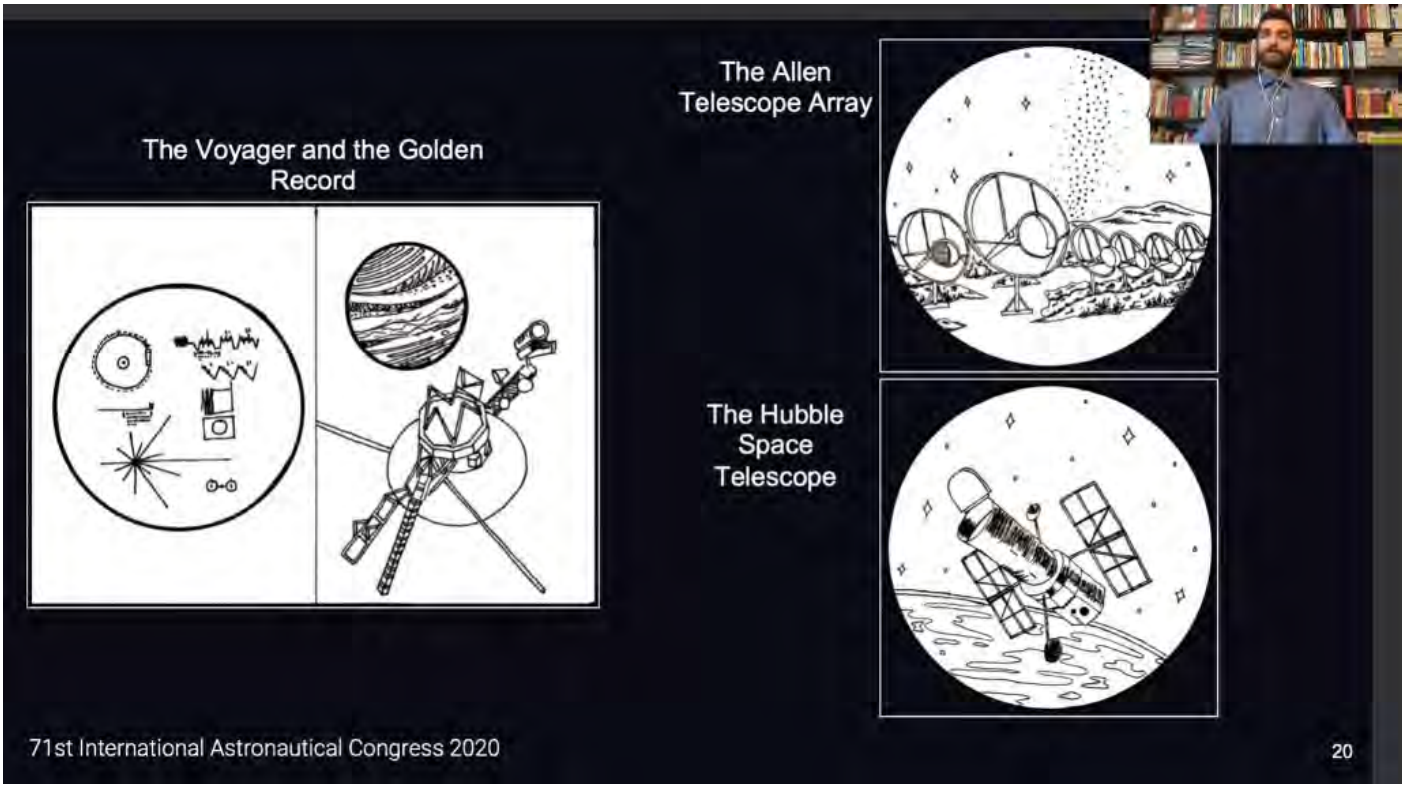


Figure 2: Merchandise branding, part of the outreach for the normalisation of SETI
Credit: Ackley and colleagues (presentation)

Authors: Mirandah Ackley and 10 others (primary authors), and 10 others (contributing authors), all International Space University

E1,6,8,x56502	How online influencers help tell the world the story of space	Mr. Remco Timmermans	International Space University (ISU)	United Kingdom

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/E1/6/manuscripts/E1,6,8,x56502.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/E1/6/presentations/E1,6,8,x56502.show.mp4

Open paper: None found

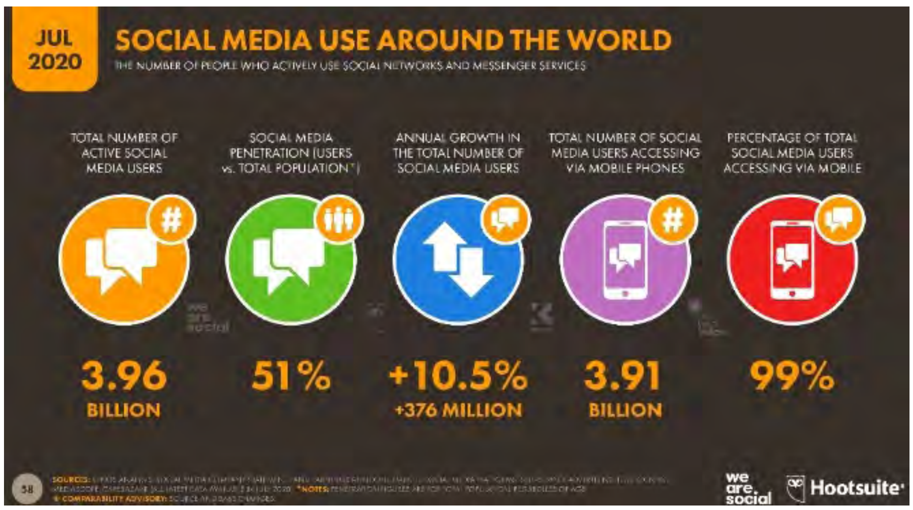
Reported by: John Davies

Mr Timmermans is Media and Content Coordinator for Groundstation Space at the Noordwijk Space Campus, Netherlands and has managed a number of programmes for the ISU. Here he gives a generic marketing overview of how different industry sectors have used online influencers in social media. Influencers fall into three categories fan-based (broad category, potentially numerous but sometimes not easy to identify), brand ambassadors (your own, niche but influential) and paid influencers (not numerous in the space sector apart from volunteers encouraged by expenses paid conference attendance). Perceived authenticity is vital - as is continuous monitoring and testing influencers and tags to see how well they are working. NASA, ESA and ESO (European Southern Observatory) are particularly successful - responding to social media posts promptly especially for live events. Return of investment (ROI) has not been well enough monitored and the sector remains immature in many respects. The paper cites a number of campaigns as examples of social media use in the space sector.

Authors:

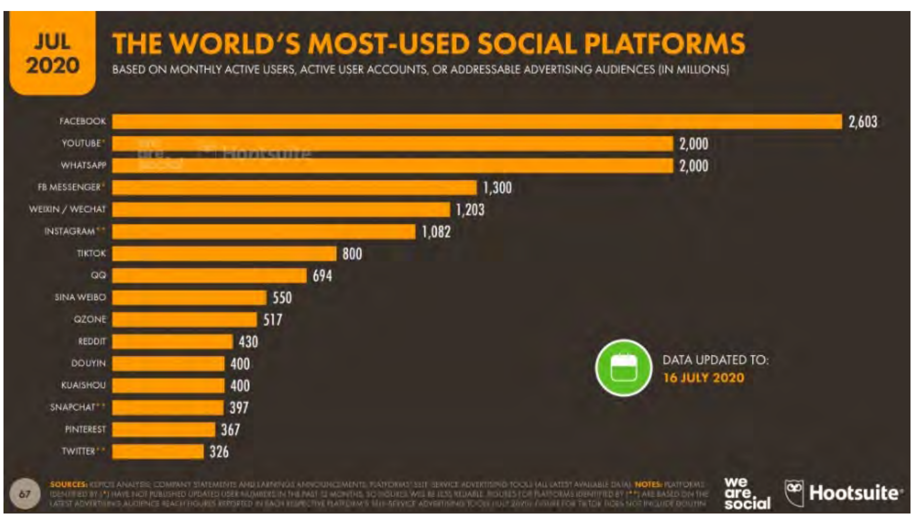
Remco Timmermans (@timmermansr)

Tara Foster (@taraustralis).



Social Media use around the world (source:WeAreSocial)

Credit: Timmermans/Foster



Reporters note: Ownership of the six most used of these (more than one billion monthly active users) is shared. The (owners) are Facebook, YouTube (Google), Whatsapp (Facebook), FB Messenger (Facebook), Weixin aka Wechat (Tencent), Instagram (Facebook). Tencent and the next most used, Tiktok, are widely thought to have close relations with the government of China.

This is a relatively small "pond".

Social Media use by platform (source:WeAreSocial)

Credit: Timmermans/Foster

D4,1,3,x59908	ChipSats - New Opportunities	Frederic Schoutetens	International Space University (ISU)	France

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/1/manuscripts/D4,1,3,x59908.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/1/presentations/D4,1,3,x59908.show.mov

Open paper: None found

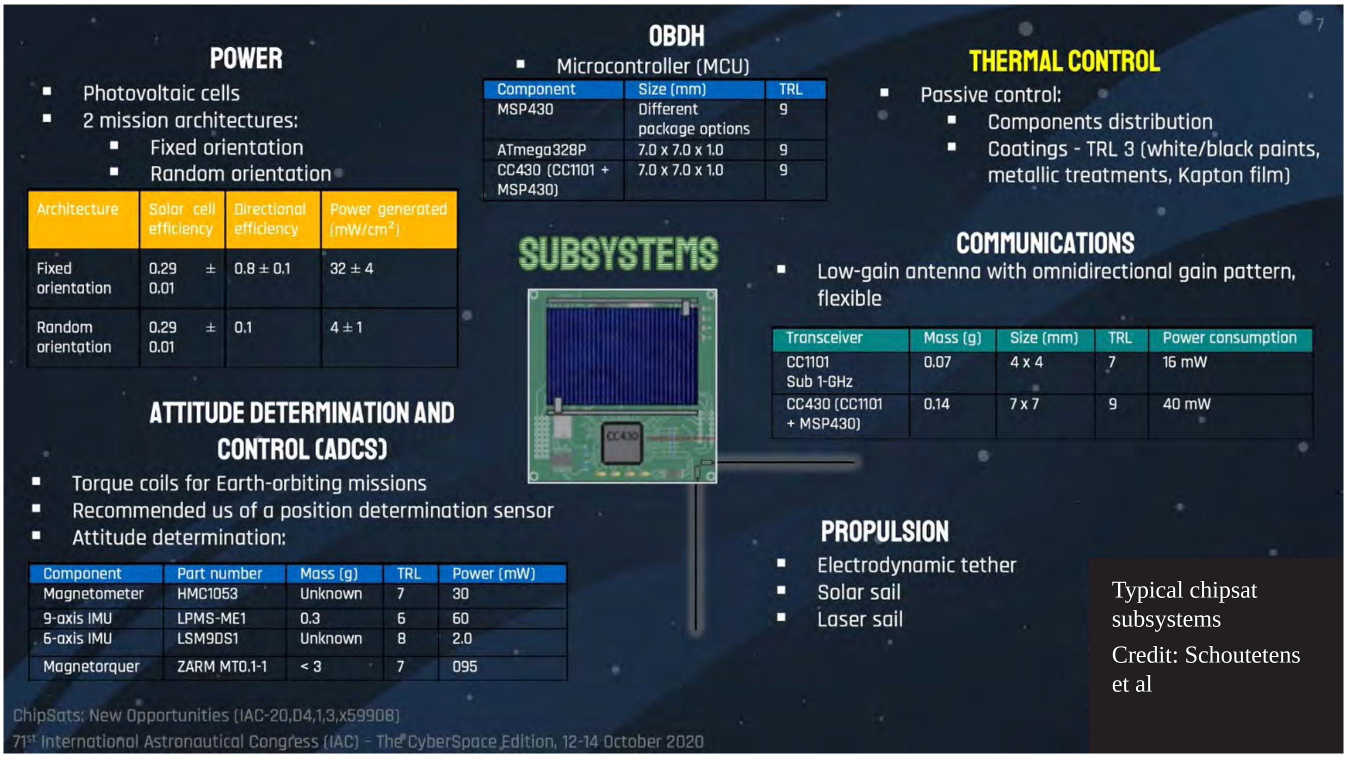
Reported by: Patrick Mahon

Andrea Carrillo (one of the co-authors of this ISU paper) highlighted how the huge cost per kilogramme of launching a spacecraft into orbit had driven continual miniaturisation of satellites, with it now being possible to create a simple but viable spacecraft the size of a credit card: a ChipSat. The concept dates back to 1994, but came of age in 2011, when Zachary Manchester designed the KickSat 1 mission (a CubeSat containing 104 'Sprite' ChipSats) as part of his PhD at Cornell. Although KickSat 1 was ultimately unsuccessful, KickSat 2 successfully deployed its Sprites in orbit in 2019.

Carrillo reviewed the major elements of a typical ChipSat, including structure, thermal control, power, data, communications, attitude control, propulsion, and reviewed the Technology Readiness Levels of each, identifying thermal control, power storage, communications and attitude control as key limitations at present.

Reporter's Note: *Table 8 in the paper gives a handy list of the elements of a typical chipsat, with prices*

Table 8. Components, price, and learning outcomes of a basic ChipSat training kit		
Components	Unit Price (USD) (March, 2020)	Learning Outcomes
Base plate		
PCB design component	2.50	Soldering with 1 trail PCB
ATmega328	3.0	Working with Arduino libraries
Basic components		
Transceiver	2.66	Programming, satellite communication
Solar cells	4.0	Operating principles of solar cells
Gyroscope and accelerometer	4.99	Satellite stabilization methods
Resistors	1.0	Laws of electronics and physics
Capacitors	1.0	Laws of electronics and electrical component functionality
Total	19.15	
Sensor Selection (1 sensor included/ kit)		
Temperature, Humidity, Pressure and Volatile Organic Compounds (VOC) sensor	10.53	To measure VOC in environment
UV sensor	4.41	Optimal UV intensity for humans and in a classroom
GPS sensor	9.33	Operating principles of Global Navigation Satellite System (GNSS)
Total with min. sensor price	23.56 USD (only including GPS sensor)	
Total with max. sensor price	29.68 USD (only including VOC sensor)	
Note: the corresponding price for resistors and capacitors are approximated and are subjected to change depending on their nominal value and tolerance.		



Typical chipsat subsystems
Credit: Schoutetens et al

The team had developed an 'ISU ChipSat Roadmap', intended to enable ISU to launch its own ChipSat. The three elements were: (a) a ChipSat Programme, to strengthen ISU's capability to design, build and launch a simple 'Sputnik-style' ChipSat to Low Earth Orbit (LEO) within five years; (b) a Regulatory Framework, to work through the main legal challenges, such as licensing and debris mitigation; and (c) an Outreach Programme, to use the ChipSat programme to promote STEM education to students in underrepresented groups and countries.

Carrillo concluded the talk with a SWOT analysis of ChipSats and eleven recommendations for priority issues that will need to be addressed if the promise of ChipSats is to be realised.

Reporter's Note: *Table 10 in the paper is the SWOT analysis.*

Table 10. Analysis of strengths, weaknesses, opportunities and threats of and for ChipSats

Strengths	***Weaknesses***
Massive cost reduction	Lack of regulation
Lower entry barriers for space technology	Launch opportunity restrictions
Accessibility and rapid development	Low functionality
Redundancy due to quantity	Space debris
Design modularity	Short orbit lifetime
Opportunities	***Threats***
Distributed system	Policy restrictions
Innovation	Misuse
Lowering ground segment dependency	Debris damages
Ability for new scientific missions and new applications for social economy	Loss of satellite
	Unproven business cases

Authors: (All ISU) Frederic Schoutetens, Andrea Carrillo, Marco Marsh, Taavishe Gupta, Shreya Sarkar, Christine Tiballi, Iliass Tanouti

D4,4,1,x57895	Interstellar Probe: Science Discoveries at the Boundary to Interstellar Space and Beyond	Dr. Pontus Brandt	Johns Hopkins University Applied Physics Laboratory	United States

IAF cited paper:
iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/D4,4,1,x57895.pdf

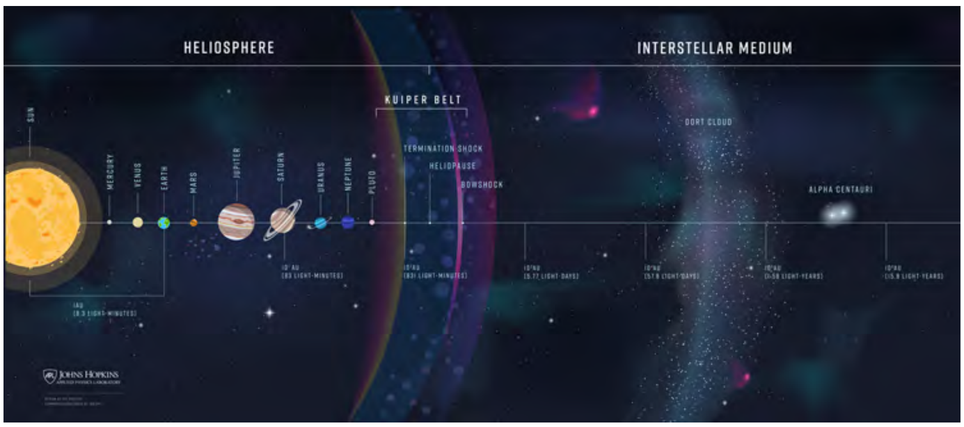
IAF cited presentation video:
iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/presentations/D4,4,1,x57895.show.mp4

Open paper: None found

Reported by: Patrick Mahon

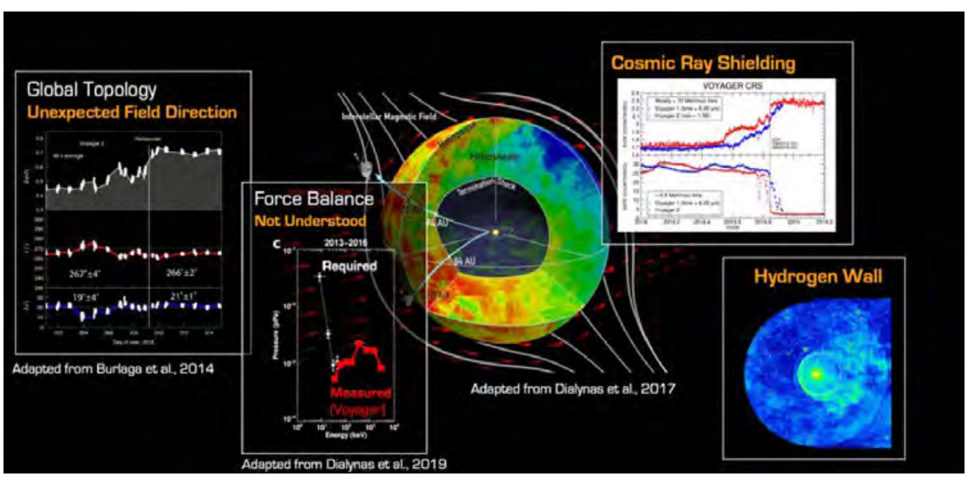
This is one of three papers delivered at the 2020 IAC, all covering different aspects of the JHUAPL Interstellar Probe project. See P31 (page 46) for a summary of sister paper D4.4.2 by Leon Alkali et al and the report of D4,4,3 by Dr. Ralph L. McNutt, Jr. earlier in these reports.

Here Brandt focuses attention on the space physics goals for such a mission, and in particular exploration of the interactions between the heliosphere and the local interstellar medium (LISM) at the heliopause, the boundary of our solar system.

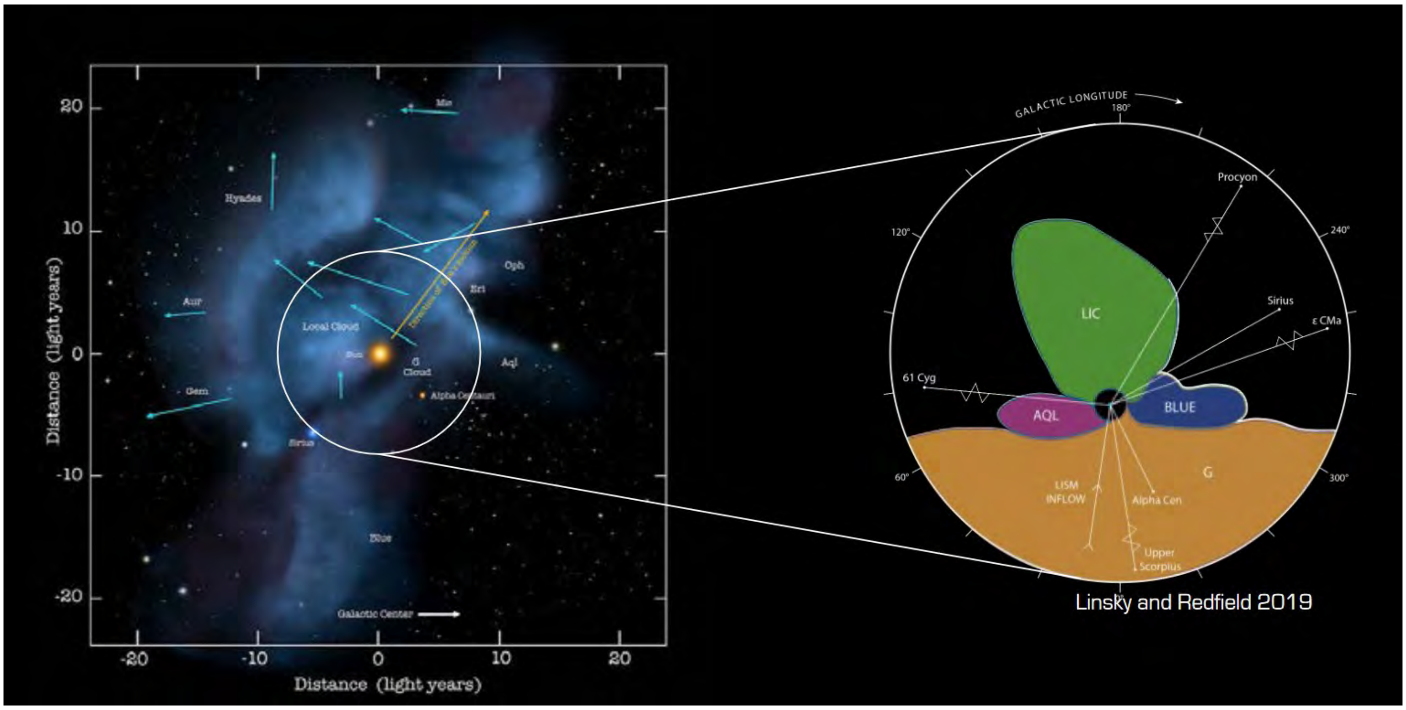


An Interstellar Probe would explore the boundary region of the heliosphere and represent the first explicit step in to the unknown LISM well beyond the heliopause. interstellarprobe.jhuapl.edu/Resources/News-and-Gallery/ Credit: JHU APL

To date, the only two spacecraft to have left the heliosphere are Voyagers 1 and 2, which did so in 2012 and 2018 respectively, both at a distance of around 120 AU from the Sun. However, their limited capabilities, so far beyond their intended design lives, mean that they have posed many more questions than they have answered. Other missions, including the Interstellar Boundary Explorer (IBEX, 2008-present) and the Cassini mission to Saturn (1997-2017), as well as the forthcoming Interstellar Mapping and Acceleration Probe (IMAP, launch due 2025) have or will probe this region remotely, but a full capability in-situ probe would transform our understanding.



" a new regime of space physics" Credit: Brandt/JHU-APL



The Local Interstellar Medium (LISM)

"...evidence is mounting that the heliosphere is in contact with four interstellar clouds with different properties and is leaving the Local Interstellar Cloud within relatively short galactic time scales". Credit: Brandt JHU APL

Questions that have been raised by the limited observations to date include the existence of a strange ribbon or belt, identified by energetic neutral atom (ENA) imaging by IBEX and Cassini, and contradictory conclusions about the global shape of the heliosphere. In addition, recent evidence suggests that the solar system is leaving the Local Interstellar Cloud (LIC) and will, over the next 6,000 years, move into a new region of interstellar space with quite different properties from the LIC.

The science mission has been designed by reference to three goals:

• Primary goal 1 (Heliophysics): to understand our Heliosphere as a Habitable Astrosphere and its Home in the Galaxy;

• Supporting goal 2 (Planetary Sciences): to understand Planetary System Evolution; and

• Supporting goal 3 (Astrophysics): to explore the Universe Beyond our Circum-Solar Dust Cloud.

These three goals are used to define the design architecture for the Interstellar Probe and the package of scientific instruments most necessary to achieve the mission objectives. Beyond heliophysics, the mission could include flybys of dwarf planets or other Kuiper Belt Objects (KBOs).

Two alternate scientific instrument packages have been defined, each weighing 80-90 kg, with one focusing on the primary heliophysics goal, while the other enables greater investigation of the two supporting goals above. Both packages include magnetometers, and spectrometers to measure plasma, particles and cosmic rays, and interstellar dust analysers. The alternate payload includes visible/near-infrared and ultraviolet cameras for the dwarf planet or other KBO flyby, swapped out for some of the heliophysics instruments.

All mission requirements have been constrained by the need for existing or very near-term technology, so that the probe could be ready to launch in January 2030. Work continues to refine the definition of the mission and the scientific payload.

D4,4,5,x58922	Mitigation of interplanetary dust for laser-driven interstellar travel	John Kokkalis	McGill University	Canada

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

IAF cited presentation video: iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/presentations/D4,4,5,x58922.show.mp4

Open paper: None found

Reported by: Patrick Mahon

John Kokkalis and co-author Monika Azmanska summarised the reasons why laser sails are a promising propulsion option for an interstellar spacecraft mission, potentially enabling a cruise velocity up to one-fifth the speed of light. However, one of the significant technical concerns is that a collision with interplanetary dust grains during the acceleration phase of the mission could create damage which propagates across the sail with catastrophic consequences.

Given that a laser sail cannot absorb more than a tiny fraction of the incoming laser energy if it is not to melt, making them from dielectric materials becomes an attractive option. For such materials, there is a trade-off between sail reflectance and thickness: more reflective sails will be thicker and weigh more. They suggest the best compromise comes with a sail that is 25% reflective, so that 75% of the laser light passes through. They have investigated whether that 'wasted' laser light can be used to burn off any dust grains in front of the sail before it reaches them. Their mathematical modelling concludes that the laser energy passing through a 25% reflective laser sail could vaporise dust grains up to 50,000 km ahead of the sail.

Once the spacecraft has accelerated to its target velocity, the laser energy will no longer be available to destroy dust grains. Instead, they propose that during the cruise phase, the spacecraft can best be protected from dust grain impacts through a combination of turning the sail side-on to the direction of travel, and incorporating a dust shield and crystal channelling to ablate and deflect incoming dust grains before they hit the leading edge of the sail.

A3,1,9,x57930	Advancing Space Exploration through Crowdfunding Space Projects	Dr. Bruce Betts	The Planetary Society	United States

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/1/manuscripts/A3,1,9,x57930.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/1/presentations/A3,1,9,x57930.show.mp4

Open paper: None found

Reported by: Patrick Mahon

Bruce Betts explained that although the term 'crowdfunding' was relatively new, the idea of funding projects through small donations from large numbers of people is something that the Planetary Society has been doing for 40 years, ever since its first fundraising drive in 1981, just a year after the organisation's formation.

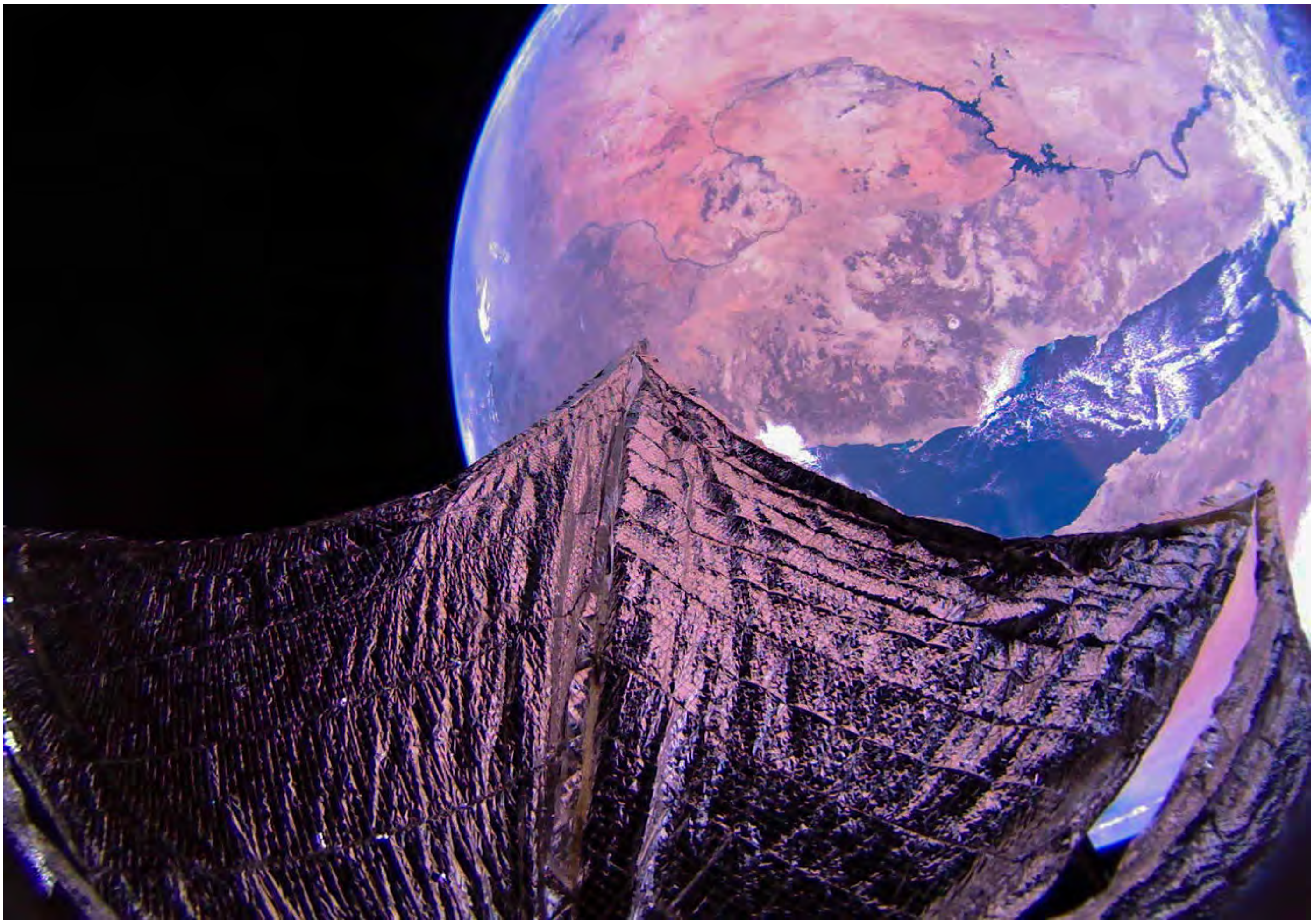
Since then, they have organised more than 100 crowdfunded projects, ranging in size from small to large. He gave several examples, including:

• their Shoemaker NEO grants to amateur and professional astronomers to help track and characterise near-Earth objects (small);

• PlanetVac, a low-cost approach to collecting soil samples during interplanetary missions, which is scheduled to fly to the Moon on a NASA-funded probe in 2023 (medium); and

• the recent LightSail 2 solar sail mission which successfully deployed in Earth orbit in mid-2019 and in mid-2020 entered an extended mission phase (large).

The Planetary Society sees crowdfunding as a highly effective way to achieve meaningful public



LightSail 2 over the Nile River and the Red Sea.
Credit: The Planetary Society

involvement in space activities. They believe there is currently untapped potential, which they want to develop and grow, by matching strong project ideas with viable crowdfunders. To this end, they intend to set up a new competitive grant programme in early 2021, which will provide seed funding to credible research and hardware development projects that might be suitable for future crowdfunding.

Authors: Bruce Betts, Jennifer Vaughn, Bill Nye (all The Planetary Society).

Some crowdfunders at the LightSail 2 launch
Credit: The Planetary Society

A4,1,1,x60743	The Breakthrough Listen Search for Extraterrestrial Intelligence: Overview	Dr. Steve Croft	University California Berkeley	United States

IAF cited paper: (abstract only)

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/1/manuscripts/A4,1,1,x60743.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/1/presentations/A4,1,1,x60743.show.mp4

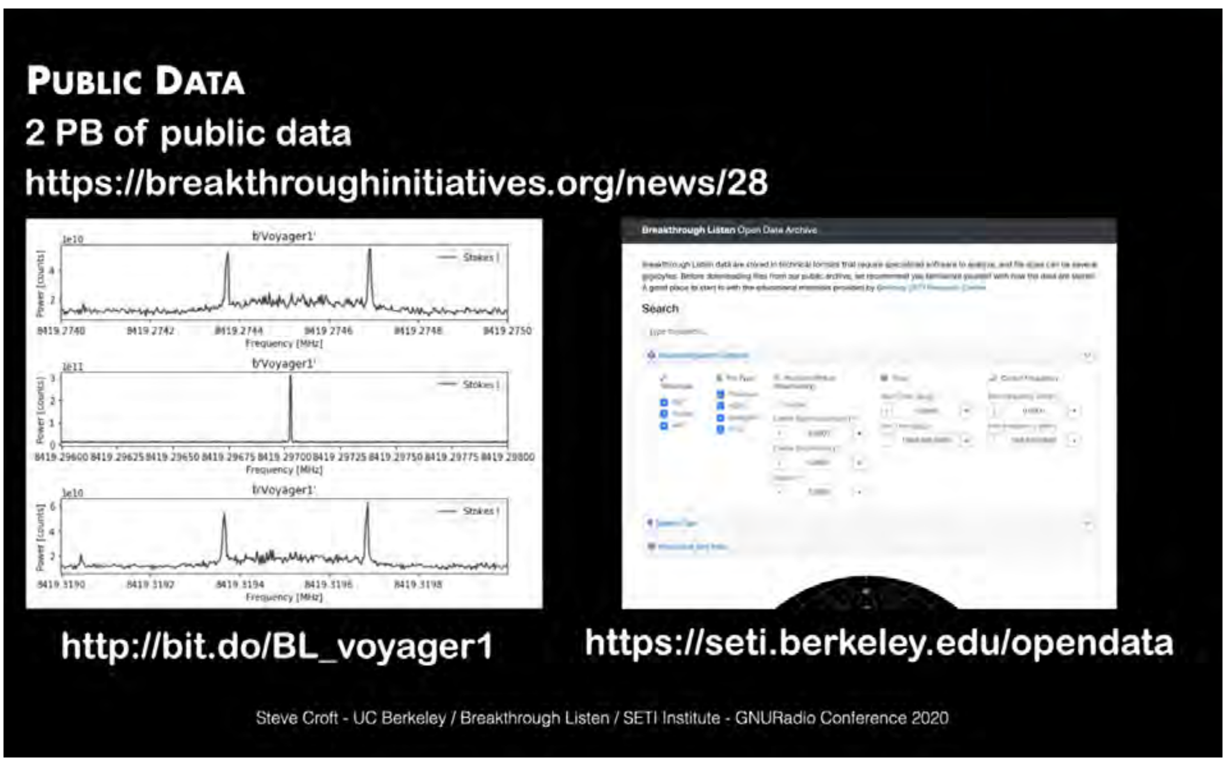
Open paper: Background on the project is available at arxiv.org/abs/1907.05519

Reported by: Patrick Mahon

Steve Croft summarised the work that the Breakthrough Listen team had undertaken to date. They were principally using three telescopes: the Green Bank radio telescope in West Virginia, USA, the Parkes radio telescope in New South Wales, Australia, and the MeerKAT radio telescope array in South Africa (see summary of talk A4.1.4 for more detail on the latter). They are using Green Bank to survey all the nearby stars in the Northern hemisphere, along with targets identified by the Transiting Exoplanet Survey Satellite (TESS) and several galaxies. Parkes is surveying the Southern hemisphere, the galactic plane, and 189 nearby stars. They are also collaborating with other telescope teams, including Jodrell Bank in the UK, and the Low-Frequency Array (LOFAR) in Ireland and Sweden. As at March 2020 they had generated over 10 PB of data.

In addition to radio SETI, they are also doing optical SETI, searching for technosignatures across 847 stars and five galaxies that have been observed to date, using the Automated Planet Finder at the Lick Observatory.

All their spectra are being made publicly available, and they are working with many interns who have done excellent work, several examples of which Croft summarised. They are also using machine learning and the Cloud to accelerate progress, and are using the open-source GNU Radio signal processing toolkit. They look forward to collaborating with many more colleagues in future to drive rapid progress in SETI.



PUBLIC DATA 2 PB of public data breakthroughinitiatives.org/news/28

bit.do/BL_voyager1 The data from Voyager is a useful test case for a technosiganture

seti.berkeley.edu/opendata All data is open. Breakthrough Listen researchers have been working with GNU Radio, a free & open-source software development toolkit providing signal processing to implement software radios (www.gnuradio.org/).

Steve Croft - UC Berkeley/ Breakthrough Listen / SETI Institute - GNU Radio Conference 2020

Credit: Croft / Breakthrough Listen

A4,1,3,x60842	On the search for artificially dispersed signals towards the Galactic center and nearby stars with the Breakthrough Listen program	Dr. Vishal Gajjar	University of California, Berkeley	United States

IAF cited paper: (Abstract only – no full paper available)
iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/1/manuscripts/A4,1,3,x60842.pdf
IAF cited presentation video:
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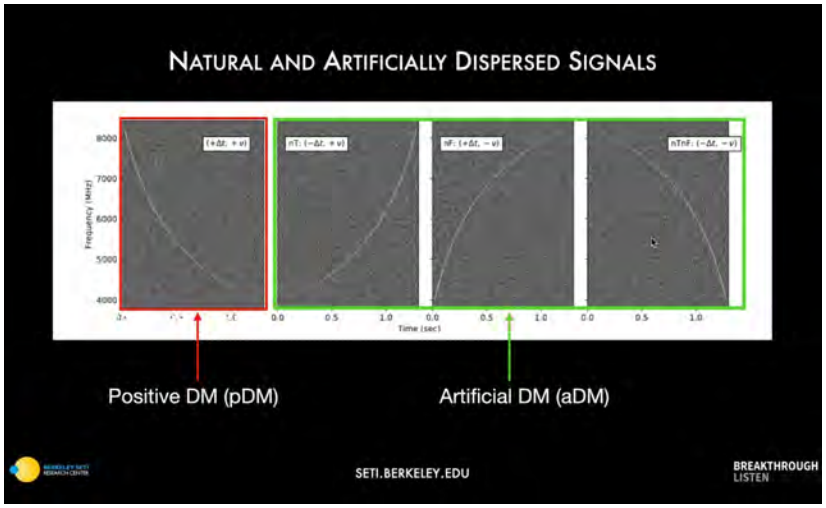
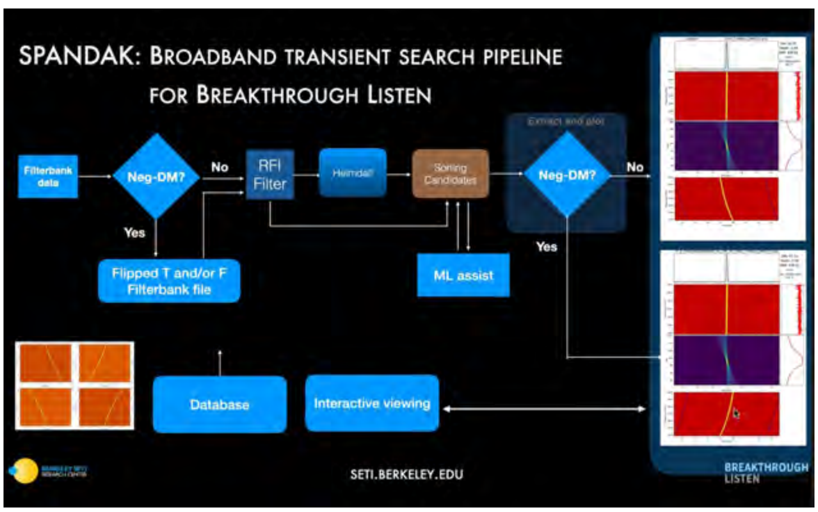
Open paper: None found
Reported by: Patrick Mahon



Vishal Gajjar asked what the best strategy might be for finding any intelligent life elsewhere in the Universe. To date, most SETI activities had been focused on looking for narrow-band signals at around 1420 MHz, the 21 centimetre line at which hydrogen, the most abundant element, naturally emits. An alternative strategy involves looking towards the Galactic Centre (GC), where the high density of stars should provide many target planetary systems. Intelligent aliens, wanting their signals to stand out from natural astrophysical sources, might create artificially dispersed signals. With radio emissions that are naturally dispersed by the interstellar medium, the high frequency component arrives first, with the lower frequencies following. They are therefore searching for signals that are dispersed in precisely the opposite way, since these seem likely to be artificially created.



The search is being conducted using a neural network-based machine learning system called SPANDAK.

To date they have identified several interesting signals, but they have all turned out to be due to natural interference from the GC. In the current (October 2020) phase of the project, they are taking the same approach but focusing the Green Bank telescope on 2,360 nearby stars instead of the GC. They have so far found 390,000 candidate signals, which were under investigation at the time of the conference.

Co-Authors: Dr. Andrew Siemion, Berkeley SETI Research Center, Dr. Steve Croft, University California (UC) Berkeley, Dr. Daniel Czech, University of California, Berkeley, Mr. Matt Lebofsky, UC Berkeley, Mr. Howard Isaacson, UC Berkeley, Mr. David MacMahon, Berkeley SETI Research Center, Ms. Claire Webb, Massachusetts Institute of Technology (MIT), Dr. Daniel Price, UC Berkeley, Dr. David DeBoer, UC Berkeley, Ms. Julia DeMarines, University of California, Berkeley, Mr. Jamie Drew, Breakthrough Initiatives, Dr. Pete Worden,, Ms. Karen Perez, Columbia University.

IAC--20,A4,1,4,x61207	Commensal SETI Survey Strategies for MeerKAT	Dr Daniel Czech	University of California, Berkeley	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/1/manuscripts/A4,1,4,x61207.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A4/1/presentations/A4,1,4,x61207.show.mp4

Open paper: None found

Reported by: Patrick Mahon

Daniel Czech summarised his short paper, which discusses a mathematical strategy for filling in as many gaps as possible in a SETI sky survey that is piggybacking on someone else's project. In brief, Breakthrough Listen has an extremely ambitious goal to observe at least one million nearby stars for technosignatures, using the MeerKAT radio telescope array in South Africa. To achieve this goal, the starting point is that the SETI observations will be performed as a secondary objective while MeerKAT is being pointed at different areas of the sky to fulfil other, non-SETI, scientific objectives. Such an approach is known as a 'commensal' survey approach, a term which originates in the biological sciences, describing a situation where 'commensal' species A benefits from co-location with species B, while species B neither benefits nor is harmed itself.

The problem with this commensal search strategy is that the primary science objectives are unlikely to lead to uniform coverage of the whole sky, leaving some regions of the sky underrepresented in the SETI dataset. If Breakthrough Listen are successful in booking any time on MeerKAT purely for their own priorities, the question arises of how to maximise the value of that limited observation time to their primary objective, given a knowledge of where their existing dataset is thinnest, and where their target stars are.

This reduces to a mathematical problem: if you have a map (the sky) with a set of points (the target stars) drawn on it, and each successive telescope observation is represented by a circle of a uniform diameter, what is the most efficient strategy for choosing where to point the telescope each time (your circles), so that by the end of your observing time you have covered the greatest number of stars/points possible?

Czech concluded with the happy news that they had developed and tested an algorithm to solve this problem – and it works.

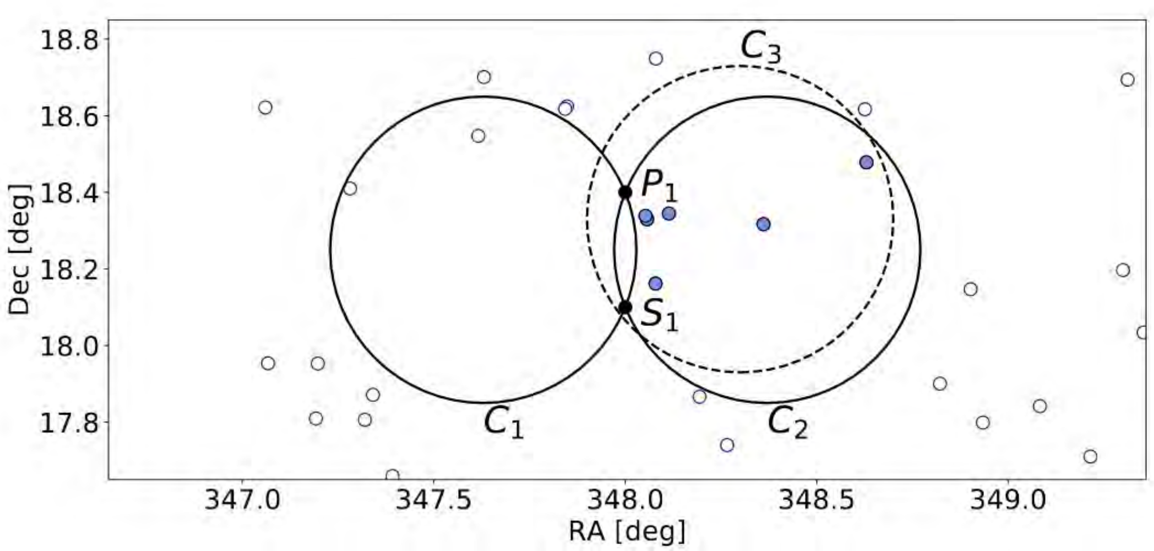


Figure 1. An illustration of the circle placement algorithm (similar to the one described by Xiao et al) applied in this work. An arbitrary portion of the sky has been selected for this example, in which each marker represents a star drawn from the selection.

Credit(image and caption): Czech

A3,4A,9,x58609	Spacecraft Trajectory Simulation for Autonomous Landing on Small Planetary Bodies	Ms. Larissa Balestrero Machado	Universität der Bundeswehr München	Germany

IAF cited paper:
iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/4A/manuscripts/A3,4A,9,x58609.pdf

IAF cited presentation video:
iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/4A/presentations/A3,4A,9,x58609.show.mp4

Open paper: None found

Reported by: Patrick Mahon

Larissa Machado introduced the paper by recounting that spacecraft had been exploring small planetary bodies (such as asteroids and comets) since 1991, when the Galileo spacecraft did a flyby of asteroid 951 Gaspra on its way to Jupiter. A decade later, NASA's Near Earth Asteroid Rendezvous (NEAR) – Shoemaker probe successfully landed on the asteroid 433 Eros. Since then, JAXA's two Hayabusa missions have successfully landed on asteroids in 2005 and 2019, while ESA's Rosetta mission to comet 67P/Churymov-Gerasimenko included a bold but only partially successful landing of the Philae lander on the comet in 2014. Landing is a pre-requisite for detailed in-situ measurement of such bodies, let alone asteroid mining, but is highly challenging, particularly if the surface is uneven. Autonomous landing capability will be necessary, given the delays in signals from Earth being received by spacecraft in the asteroid belt or even further out.

The project summarised in her paper is part of a DLR-funded programme intended to advance the Guidance, Navigation & Control (GNC) algorithms needed for autonomous landing on small planetary bodies (such as asteroids or comets) to a Technology Readiness Level (TRL) of 5. They have simulated the powered descent phase of such a mission, which is the most dangerous part of the landing phase, when the spacecraft needs to locate and avoid hazards, identify a suitable landing site, and then either land or abort back to orbit. The project models both hardware and software elements. The hardware consists of a multicopter Unmanned Aerial Vehicle (UAV), which models the spacecraft dynamics and includes sensors for navigation and hazard detection. The software includes a dynamic model of the spacecraft, a model of the microgravity forces existing in the vicinity of a small planetary body, and the GNC algorithms. The main constraint placed on the simulations is an objective to minimise propellant use during the landing phase.

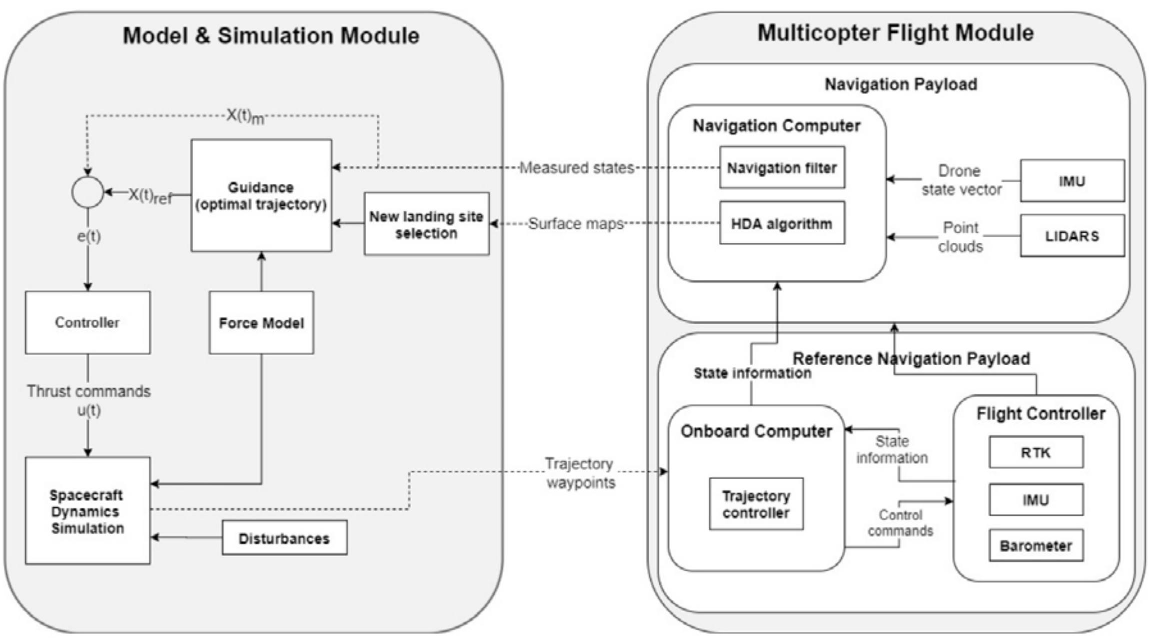
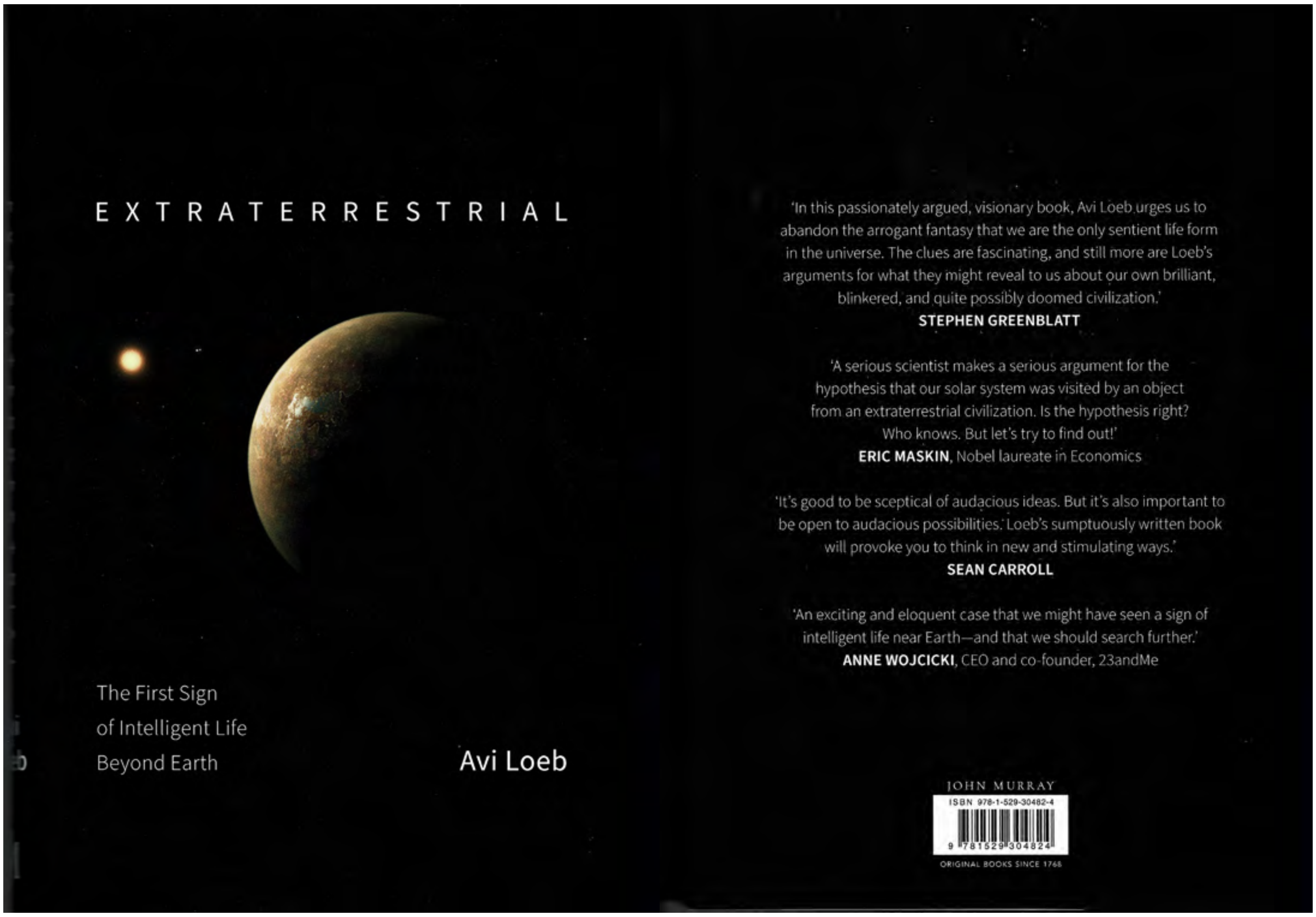


Fig. 4. Small Body Autonomous Landing Development and Validation Environment. Credit: Machado (graphic and caption)

The approach has been tested with reference to a simply ellipsoidal asteroid, and most mission parameters remained within the set constraints through to landing, although a fully vertical landing proved highly challenging. [Editor's note: this is something that SpaceX have demonstrated more recently with the Starship SN9 flight test on 2 February.] Further work will model more realistic asteroid or comet geographies, to test the model under more realistic conditions.

NEXT ISSUE



Practicalities and Difficulties of a Mission to 1I/'Oumuamua, Adam Hibberd

Book review: Extraterrestrial, Avi Loeb

Book review: The Generation Starship in SF, Simone Caroti

The self-replicating factory, Michel Lamontagne

Cover Images

Front Cover

This quarter's front cover image is a NASA visualisation of an exoplanet, *Hubble Pins Down Weird Exoplanet with Far-Flung Orbit* (www.nasa.gov/feature/goddard/2020/hubble-pins-down-weird-exoplanet-with-far-flung-orbit). They say 'A planet in an unlikely orbit around a double star 336 light-years away may offer a clue to a mystery much closer to home: a hypothesized, distant body in our solar system dubbed "Planet Nine." This is the first time that astronomers have been able to measure the motion of a massive Jupiter-like planet that is orbiting very far away from its host stars and visible debris disk. This disk is similar to our Kuiper Belt of small, icy bodies beyond Neptune. In our own solar system, the suspected Planet Nine would also lie far outside of the Kuiper Belt on a similarly strange orbit. Though the search for a Planet Nine continues, this exoplanet discovery is evidence that such oddball orbits are possible.

Back Cover

Taken during the October 2019 astrophotography workshop at Jodrell Bank Discovery Centre by Dr Anthony Holloway, Head of Computing at Jodrell Bank Centre for Astrophysics & Jodrell Bank Observatory. He says, the illumination for the rear surface replacement works created a one off extra target of interest - www.flickr.com/photos/anthonyholloway/49025699952/.

The old 250 foot Mark 1, the Lovell, must be the oldest radio telescope of any size still operating. The big pivots for the main dish came from naval gun turrets left over after the Second World War. It and the Jodrell Bank Observatory are part of the SETI search funded by Breakthrough - in addition to being a world leader in radio astronomy. Seeing this thing in his early teens in the late 1950s reinforced your editor's conviction that his career should be in electronics and space technology.

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: Hubble Pins Down Weird Exoplanet with Far-Flung Orbit
Credit: NASA
Back cover: New Surface
Credit: Anthony Holloway / Jodrell Bank

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Scientia ad sidera
Knowledge to the stars