PRINCIPIUM

The Newsletter of the Initiative for Interstellar Studies
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- IAC Oct 2019 - First Report
- On a possible future direction for optical SETI
- How to reach Interstellar Visitors - Optimum Interplanetary Trajectory Software
- How low can you go? - The Benkowski equation
- i4is Members Page & Become an i4is member
- Interstellar News

Scientia ad sidera
Knowledge to the stars

Editorial

Welcome to issue 27 of Principium, the quarterly newsletter about all things interstellar from i4is, the Initiative and Institute for Interstellar Studies.

The front cover image is *Urbium* - a new piece produced for Initiative for Interstellar Studies by our good friend Alex Storer of The Light Dreams. More about the inspiration for this inside our back cover. The back cover is a NASA visualisation of a Voyager probe, celebrating the exit of Voyager 2 from the Solar System.

The Lead Feature for this issue is *On a possible future direction for optical SETI.* Dmitry Novoseltsev again brings us imaginative thinking - and in this case a possible future for the space debris cluttering our local space.

We have the first of two reports from the 70th International Astronautical Congress, Washington DC in October 2019.

We have more on the i4is membership scheme, plus our regular member's page with more about members-only website content.

As usual, we report recent Interstellar News, including i4is activities both outreach and educational, the second interstellar object, on 2I/Borisov and recent interstellar papers in JBIS.

The piece on *Nomadic Planets and Interstellar Exploration* by T Marshall Eubanks is postponed until Marshal has more time. He’s a busy man - as glimpses of his work elsewhere in this issue will testify.

In our next issue, P28 February 2020, will include our IAC 2019 Report - part 2, a report on the Tennessee Valley Interstellar Workshop 2019, *What do we really know about the Outer Solar System?* by Phil Sutton, Lincoln University, and an introduction to the i4is Education Team.

We mourn the passing of Chris Corner, a good friend and collaborator with i4is. We will have a memoriam piece about Chris in P28.

For Members of i4is

Members have access to -

Networking - i4is.org/members/networking-opportunities

Principium preprints- i4is.org/members/preprints

Videos - i4is.org/videos

More in The i4is Members Page - page 13

CONTENTS

Membership of i4is

Please support us through membership of i4is. Join the interstellar community and help to reach the stars! Privileges for members and discounts for students, seniors and BIS members - details page 16 and our members page 13.

More at i4is.org/membership.

Please print and display posters - page 7 (white background) and 14 (black background), the student poster following this editorial page and all our poster variants at -

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

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

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

Patrick J Mahon, Editor, patrick.mahon@i4is.org

Keep in touch!

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

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

Follow us on Twitter at @I4Interstellar

And seek out our followers too!

Contact us on email via info@i4is.org.

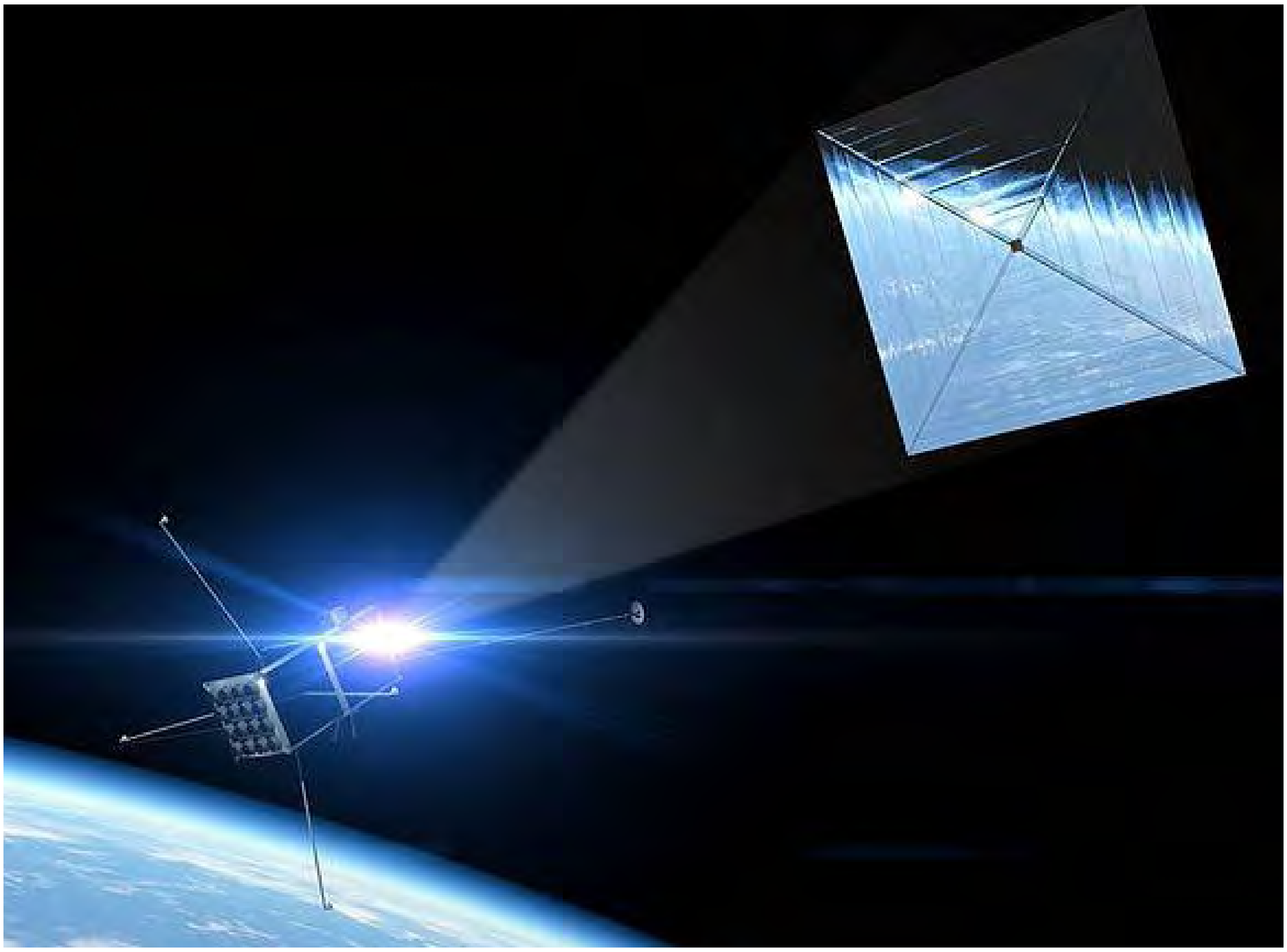
Back issues of Principium, from number one, can be found at www.i4is.org/Principium

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

JOIN I4IS ON A JOURNEY TO THE STARS!

Do you think humanity should aim for the stars?

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



The 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:

- member exclusive posts, videos and advice;
- free or discounted publications, merchandise and events;
- advanced booking for special HQ events; and
- opportunities to contribute directly to our work.

To find out more, see www.i4is.org/membership
80 % discount for full time students!

LEAD FEATURE

On a possible future direction for optical SETI

Dmitry Novoseltsev

Another striking contribution from Dmitry Novoseltsev. Here he suggests that the idea of a kinetic jet engine provides a way of using orbital debris for propulsion and that the spectral signature produced by this process may be a visible technosignature indicating the presence of a technologically advanced civilisation.

Recently, the focus of SETI (the Search for Extra-Terrestrial Intelligence) has changed considerably. Not having succeeded in the search for radio signals which would with high probability be interpreted as an artificial message, researchers have switched to searching for so-called "technosignatures" – the theorized by-products of various technological processes [1]. A similar approach is called "Dysonian SETI" because one of the characteristic technosignatures previously considered was infrared radiation from a hypothetical Dyson sphere.

A significant proportion of the new studies is focused on optical signals, due to significant recent progress in the registration and processing of such data. At the same time, many rocky earth-like exoplanets have been discovered in recent years. Currently, there is interest in trying to detect the weakest optical signals from them, such as the hypothetical night lighting of cities.

As another possible future direction for optical SETI, I would like to propose the following idea:

I will assume that a hypothetical space civilization on an earth-like exoplanet, which began activities for the exploration of nearby space, might have technical capabilities similar to our modern approach to rocketry and space technology, based on chemical fuels. In this case, as they approach the level of development corresponding to Type I on the Kardashev scale, the problem of accumulation of space debris (SD), and in particular small space debris, in the near-planet space, significantly complicating further space activities, will become as urgent for them as it is for us. This problem was considered, in the Earth context, in the framework of the all-Russian scientific conference with international participation, "Space debris: fundamental and practical aspects of the threat", which took place on 17-19 April 2019 at the Institute of Space Research at the Russian Academy of Sciences in Moscow.

At this conference, I presented the concept of rational utilization of small fragments of SD as fuel for interorbital maneuvers of spacecraft (SC) using a kinetic jet engine (KJE) [2].

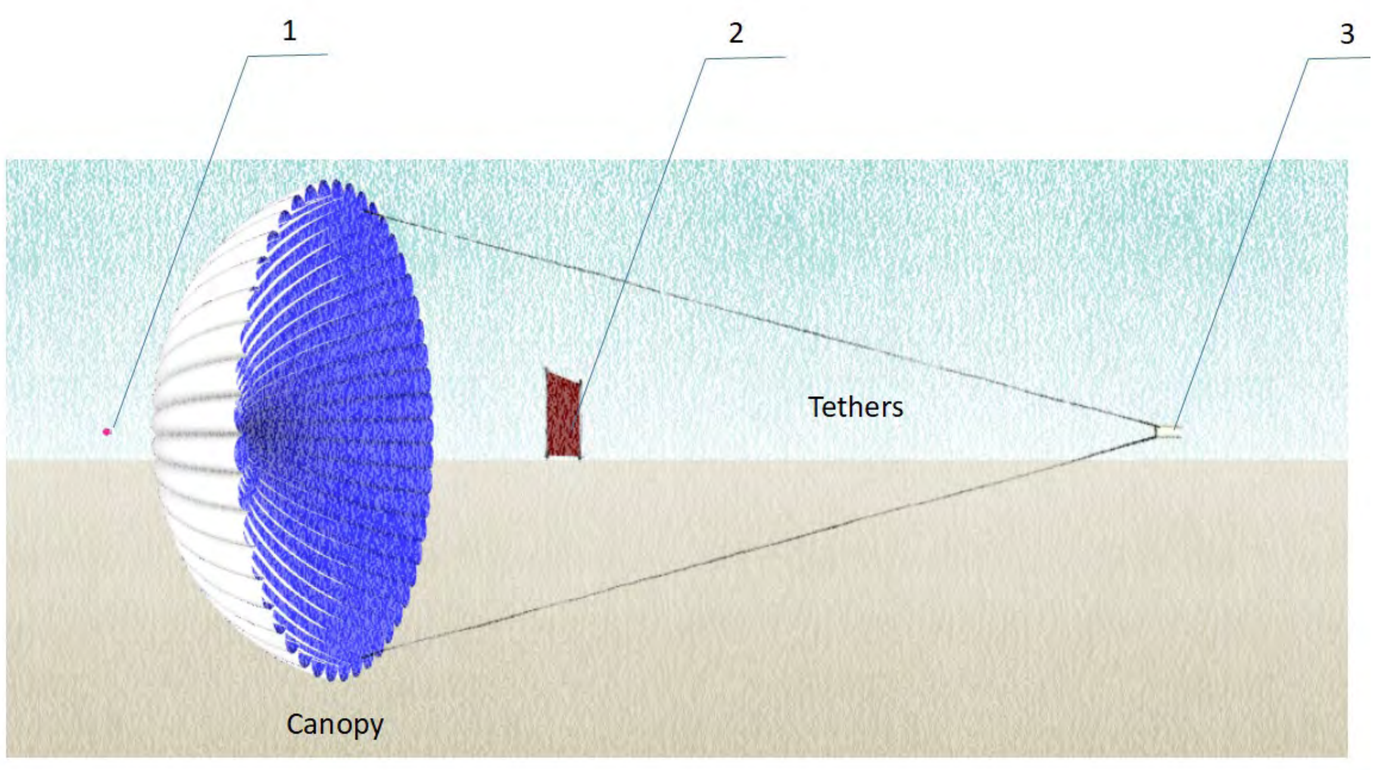
The concept of a KJE has been previously discussed in a number of works, and was finally formulated in the form of a "kinetic sail" by Podvysotsky & Panov [3]. The proposed design is fundamentally similar to the concept of a pulsed nuclear rocket engine with a sail, which was developed in the United States within the framework of the Medusa project [4], based on the implementation of an explosion at the focus of the sail, followed by the transmission of an impulse from the expanding gasified products of the explosion to the inner working surface of the sail. With a sufficiently large sail area, the dynamic and thermal loads on its structure should not exceed the permissible values for the structural materials used.

A kinetic sail involves the use of energy which is not due to nuclear, but kinetic, explosions. In the classical model of V V Podvysotsky, this involves a controlled collision of specialized spacecraft: "probes" colliding with "targets" at the focus of the sail [3]. In the case of the use of SD in a KJE, the function of the "probes" is performed by the fragments of SD, and the "target" is located onboard the SC at the sail's focus. The most probable use of a KJE would be single-pulse interorbital flights, although with additional propulsion a SC with KJE, also using gravitational slingshot maneuvers could travel further within our Solar System and beyond.

In a frontal collision of a fragment of SD with a target, both travelling at orbital velocities, the specific kinetic energy of the collision will be about 1.3 x 10^8 Joules. Since the specific heat of combustion of traditional chemical rocket fuels is of the order of 10^7 J/kg, the use of 1 kg of SD will be energetically equivalent to the use of 10-15 kg of fuel onboard the SC for a similar maneuver. Taking into account the efficiency of the launch vehicle, this is equivalent to more than 500 kg of the starting mass of the rocket. Given this, the utilization of SD in a KJE, unlike most other known methods, would be economically feasible, and could potentially be commercialized in the implementation of space activities, including by relatively small private companies.

The use of unmanaged SD fragments in a KJE, instead of guided “probes”, would require extremely accurate data on their mass and co-ordinates. However, the solution to this problem, for the entire array of SD in near-earth space, is in any case highly relevant to the near future, not least to enable early evasive maneuvers by particularly valuable spacecraft.

In addition to the absence of formal legal prohibitions on their practical implementation, there are two further advantages of using a KJE in comparison with a pulsed nuclear jet engine of the Medusa type: the exclusion of the radiation impact of the explosion on the structure and payload, and the absence of



Concept of rational utilization of small fragments of SD as fuel for inter-orbital manoeuvres of spacecraft using a kinetic jet engine (KJE). #1 fragment of space debris approached by the spacecraft, #2 "target" from the spacecraft to create the required collision, #3 spacecraft payload propelled by impulse on sail transmitted from the sail through tethers.

Derived from Novoseltsev paper [2]

restrictions on the minimum power of a kinetic explosion (as opposed to a nuclear explosion). The latter not only greatly simplifies the experimental flight testing regime for a KJE, but would also allow the use of small fragments of SD for interorbital flights of ultralight SCs, including perhaps a new type of StarChip (AttoSat), with a unit weight of about 5-10 g [5]. This class, in particular, includes such modern prototypes as the KickSat Sprite and AmbaSat. In addition to using techogenic SD (created by space operations), it would also be possible to use fragments of natural SD – that is, small meteoroid bodies – in this way.

The main technical problem in this case would be the choice of a target material with a sufficiently high detonation combustion rate and completeness of gasification, providing complete shatter-free gasification of the target in contact with the fragment of SD within the working volume of the reflector of the KJE, as well as a high degree of transmission of the kinetic energy of the SD fragment to the target gasification products.

A modern prototype of the target materials for a KJE are such explosives as trinitrotoluene, which has a speed of detonation combustion of more than 7 km/s. The spectral characteristics of the combustion products are also well known.

Reference [2] showed that exponential growth in the number of StarChip SCs, as public devices owned by both public and commercial organizations and a wide range of individuals, is entirely possible in the coming years, similar to the growth of the market for personal computers or mobile phones over recent decades. To enable such SC to implement inter-orbital maneuvers using a KJE may require us not only to target the use of larger and smaller fragments of SD, but potentially the use of additional material – for example, small fragments of lunar soil, delivered with the help of directional explosions.

If such a scenario was implemented by a hypothetical space civilization, the use of a set of KJEs in the near-planetary space could potentially be observed as a weak irregular flicker of an earth-like exoplanet in the optical range, with typical spectral characteristics corresponding to the combustion products of a number of chemical fuels. This phenomenon should be significantly different from the typical collisions of natural cosmic bodies, and thus possible to detect.

I would propose that we consider this phenomenon as one possible technosignature for an intelligent alien civilisation.

References:

1. NASA and the search for technosignatures. A Report from the NASA Technosignatures Workshop. November 28, 2018.

https://arxiv.org/ftp/arxiv/papers/1812/1812.08681.pdf.

2. Д.А. Новосельцев О возможности рациональной утилизации фрагментов околоземного космического мусора с использованием кинетических ракетных двигателей. Всероссийская научная конференция с международным участием «Космический мусор: фундаментальные и практические аспекты угрозы». 17-19 апреля 2019. Сб. тез. С. 82.

http://www.inasan.ru/wp-content/uploads/2019/04/Abstract-book.pdf .

Editors note: paper by Novoseltsev on possibility of rational utilization of fragments of near-Earth space debris using kinetic rocket engines

3. В.В. Подвысоцкий. Некоторые способы использования космического паруса. http://lnfm1.sai.msu.ru/SETI/koi/articles/86.pdf.

4. Johndale C. Solem. “Some New Ideas for Nuclear Explosive Spacecraft Propulsion,” LA-12189-MS, October 1991.

https://fas.org/sgp/othergov/doe/lanl/docs1/00189777.pdf.

5. In Quest to Reach Alpha Centauri, Breakthrough Starshot Launches World’s Smallest Spacecraft. First Prototype ‘Sprites’ – Precursors to Eventual ‘StarChip’ Probes – Achieve Low Earth Orbit

http://breakthroughinitiatives.org/news/12.

About the Author

Dmitry Novoseltsev (Дмитрий Новосельцев) is Deputy CEO of the Siberian Mechanical Engineering, Non-Profit Partnership (www.npsibmach.ru). He has a PhD in Technical Sciences, awarded by Omsk State Technical University, for his thesis “Vacuum, compressor technics and pneumatic systems”. He is a regular contributor to the Space Colonization Journal (jour.space).

Interstellar News

John I Davies reports on recent developments in interstellar studies

i4is at the BIS West Midlands Space Day

The West Midlands branch of the British Interplanetary Society is one of the most active in the UK and we were again invited to their annual Space Day. This was on 5 October at The Hive, a community building in Worcester. Our deputy chair of Education, Tishtrya Mehta and a new member of the i4is team, Anna Vestentoft, introduced young and old to space and interstellar concepts.

Here is Tishtrya at the i4is table. Note the copy of the August 2018 issue of Principium (distributed at IAC 2018 in Bremen).

Credit: Anna Vestentoft

More on our blog *i4is at BIS Space Day* i4is.org/spaceday2019/

Starship Congress 2019 San Diego 13-15 September 2019

This year's theme was Bend Metal! The programme was nevertheless wide ranging - starshipcongress.org/static/images/ssc2019.pdf - from the near term such as the Planetary Society's solar sail demonstrator - *LightSail 2: Sailing on the Light of a Star* - via venture capital, solar system access and ambitions to The Minimum Viable Starship and a final Bend Metal Hackathon. Speakers included Icarus Interstellar pioneers Andreas Tziolas and Richard Obousy, famous faces including David Brin and institutions including the University of San Diego, UCSD and the L5 Society.

We hope to feature some of the SSC2019 content and people in the next issue of Principium.

First Steps to Interstellar Probes- i4is Project Glowworm

John Davies presented this talk to the Astronomical Society of Edinburgh (ASOE) on 4 October 2019. This

The Society meets at the Augustine United Church Centre, George IV Bridge, Edinburgh.
Here John addresses members in a beautiful building in the heart of a beautiful city. Credit:ASOE

was one of the most interested and interesting audiences John has experienced.

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

John summarised interstellar studies to date including the early predications of Tsiolkovsky and the lightsail equation of Robert Forward -

“The acceleration of a vehicle of mass M and reflectance η driven by an incident laser power P is -

-where c is the velocity of light and the factor 2 comes from the double momentum transfer to the sail by the reflected photons. - *Roundtrip Interstellar Travel Using Laser-Pushed Lightsails* - Robert L Forward, J Spacecraft Vol 21, No 2 1984 - see below for link.

He spent most time on the Glowworm project, drawing heavily on the paper presented by i4is colleague Zachary Burkhardt at IAC 2019, Bremen, and his more detailed internal paper at the International Space University, Strasbourg,

Questions were searching and and, in several cases, challenging. The members were clearly very well informed.

John provided a handout of references by topic, **all on open access**, which readers may find useful -

Photon propulsion

Tsiolkovsky - *Tsiolkovsky - Interstellar Pioneer* - Principium 20 February 2018 - page 21

i4is.org/wp-content/uploads/2018/02/Principium20.pdf

Forward - *Roundtrip Interstellar Travel Using Laser-Pushed Lightsails* - Robert L Forward, J Spacecraft Vol 21, No 2 1984 pdfs.semanticscholar.org/25b2/b991317510116fca1e642b3f364338c7983a.pdf

Lubin - *A Roadmap to Interstellar Flight,* Philip Lubin, UCSB, Journal of the British Interplanetary Society (JBIS), 69, pp.40-72 2016 www.nasa.gov/sites/default/files/atoms/files/roadmap_to_interstellar_flight_tagged.pdf

Burkhardt - *Project Glowworm: Testing Laser Sail Propulsion in LEO*, Zachary Burkhardt, ISU at International Astronautical Congress 2018, Bremen - www.researchgate.net/publication/328202365_Project_Glowworm_Testing_Laser_Sail_Propulsion_in_LEO

Glowworm i4is.org/what-we-do/technical/project-glowworm/

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

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

Fusion Propulsion

Icarus Firefly – *Reaching the Stars in a Century using Fusion Propulsion: A Review Paper based on the ‘Firefly Icarus’ Design,* Patrick J Mahon, Principium 22 August 2018, page 3 i4is.org/wp-content/uploads/2018/08/Principium22.pdf

i4is Project Lyra - see also Interstellar News item - *2I/Borisov - the second interstellar object* - in this issue

Hein, A M et al, 2019. *Project Lyra: Sending a spacecraft to 1I/’Oumuamua (former A/2017 U1), the interstellar asteroid*. Acta Astronautica, 161, 552-561. – first published Nov 2017 arxiv.org/abs/1711.03155

Hibberd, A, Hein, A M, & Eubanks, T M *Project Lyra: Catching 1I/'Oumuamua-Mission Opportunities After 2024. 2019* arxiv.org/abs/1902.04935

Hibberd, A et al, *Feasibility of a Mission to Interstellar Comet C/2019 Q4 (Borisov)* September 2019 arxiv.org/abs/1909.06348 - see also News item - *2I/Borisov - the second interstellar object.*

Interstellar objects

Bialy & Loeb, *Could Solar Radiation Pressure Explain 'Oumuamua's Peculiar Acceleration?* The Astrophysical Journal Letters, Volume 868, Number 1, 2018 arxiv.org/abs/1810.11490

Seligman & Laughlin, *The Feasibility and Benefits of In Situ Exploration of 'Oumuamua-like Objects*, The Astronomical Journal, Volume 155, Number 5, 2018 iopscience.iop.org/article/10.3847/1538-3881/aabd37

Tennessee Valley Interstellar Workshop (TVIW) November 10-15

The TVIW was in Wichita for the 6th Interstellar Symposium and NASA Advances Interstellar Propulsion Workshop. Many names familiar to i4is and to Principium readers - Greg Matloff, Marc Millis, Geoff Landis, David Messerschmitt, Andrew Higgins, Gerald Cleaver, James Schwartz, Kenneth Roy, Philip Lubin, Les Johnson and others we ought to know better!

And a very wide range of talks and round table discussions and a major product - outlines for research in two major advanced propulsion directions -

- Directed Energy - a five-year-plan answering open questions regarding phased-array lasers and fundamental sail materials
- Highly Energetic Nuclear Processes - five-year goals with respect to fusion, fission, and antimatter propulsion missions.

2I/Borisov - the second interstellar object

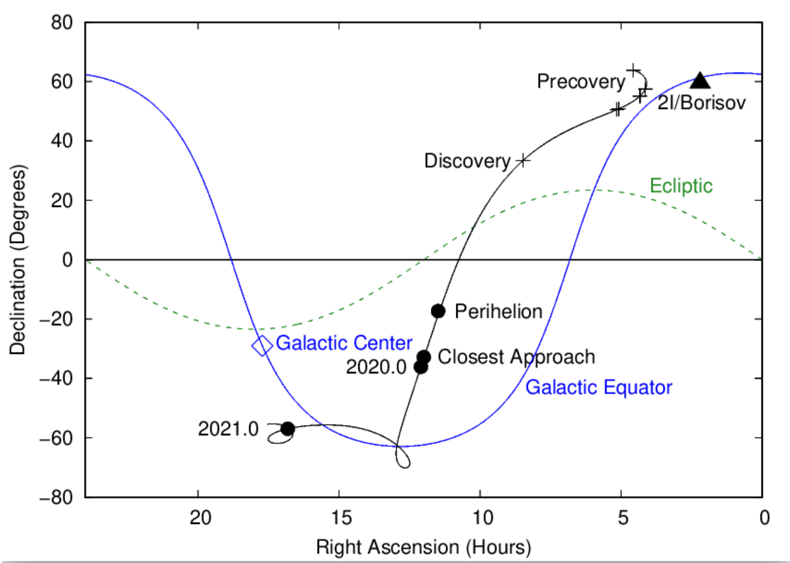
Much news of the second interstellar object since our last issue. Several mentions in this Interstellar News and in reports from IAC. The i4is Project Lyra team was, of course, very interested in this and published a paper on possible intercept trajectories *Sending a Spacecraft to Interstellar Comet C/2019 Q4 (Borisov)*, Adam Hibberd, Nikolaos Perakis, Andreas M Hein, September 2019 arxiv.org/abs/1909.06348v1

They concluded that an earlier detection of Borisov would have made a SpaceX Falcon Heavy launch possible last year and that, for the future, a combined powered Jupiter flyby with a solar Oberth manoeuvre and a launch in 2030, we could reach C/2019 Q4 (Borisov) in 2045, using the new NASA Space Launch System and an up-scaled Parker probe heatshield technology. The paper attracted attention ranging from phys.org and *Ciel et Espace* magazine to NBC News and Fox News.

More about heatshields for solar Oberth manoeuvres in our report of IAC 2019 of a paper by Benkowski (Johns Hopkins University Applied Physics Laboratory, JHU-APL).

In this issue we also feature a piece by Adam Hibberd on the calculations required for our intercept planning - *How to reach Interstellar Visitors - Optimum Interplanetary Trajectory Software* - and an explanation of Benkowski's equation for a solar Oberth manoeuvre *How low can you go? - The Benkowski equation.*

Our i4is colleague, T Marshall Eubanks, points out that Borisov has been found in images from before its discovery and gives us a plot of its position, both past and future -



Update on Interstellar objects

Interstellar objects continue to fascinate us, see Adam Hibberd's piece on calculating intercept missions and references in our report prom IAC 2019, both in this issue. Here is just a selection of recent references -

The Dynamics of Interstellar Asteroids and Comets within the Galaxy: an Assessment of Local Candidate Source Regions for 1I/'Oumuamua and 2I/Borisov -Tim Hallatt (University of Western Ontario, London, Ontario), & Paul Wiegert (McGill University, Montreal) - arxiv.org/abs/1911.02473

Initial characterization of interstellar comet 2I/Borisov - Piotr Guzik et al (Jagiellonian University, Kraków & others in Poland and Netherlands). arxiv.org/abs/1909.05851

Characterization of the Nucleus, Morphology and Activity of Interstellar Comet 2I/Borisov by Optical and Near-Infrared GROWTH, Apache Point, IRTF, ZTF and Keck Observations - Bryce T Bolin (Caltech) et al (too numerous to mention!) arxiv.org/abs/1910.14004

Pre-discovery Activity of New Interstellar Comet 2I/Borisov Beyond 5 AU - Quanzhi Ye, arxiv.org/abs/1911.05902

2I/Borisov closest approach 7-8 December

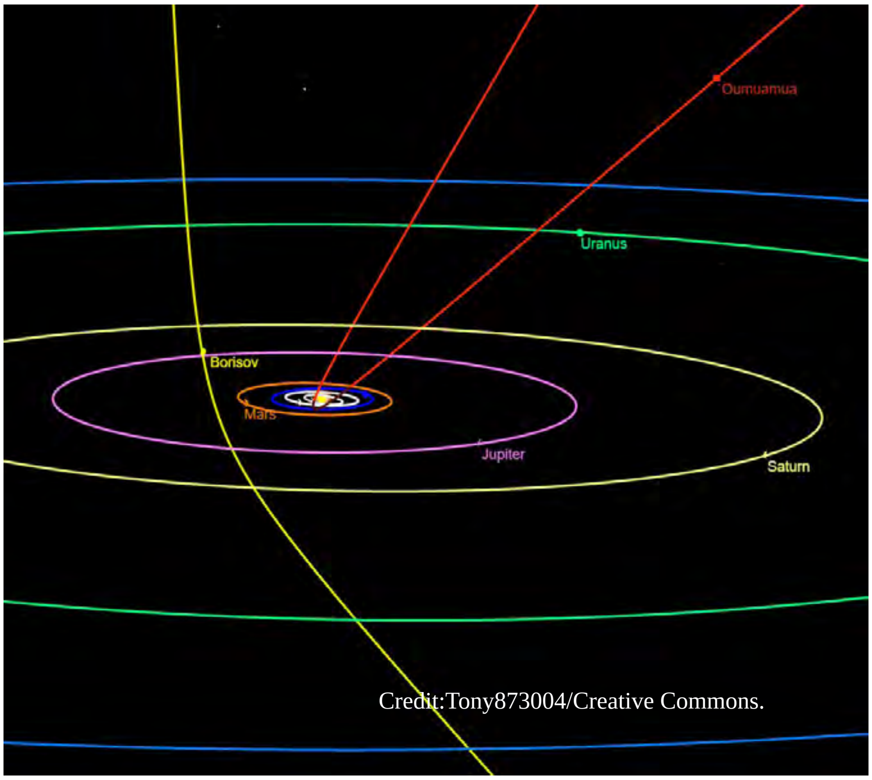
The interstellar comet 2I/Borisov will reach perihelion on 7-8 December and should be observable with a large amateur telescope. It's on a very different trajectory than 1I/Oumuamua.

Some helpful links -

https://en.wikipedia.org/wiki/2I/Borisov#2019%E2%80%932020

https://www.skyandtelescope.com/astronomy-news/will-amateurs-be-able-to-see-the-new-interstellar-comet/

Serious amateurs interested in Borisov will have other sources, of course. It would be great to have any images and comments from observers for possible publication in Principium.



Credit:Tony873004/Creative Commons.

i4is at the International Space University

i4is is again involved in Masters projects at the International Space University. Here is Initiative for Interstellar Studies Executive Director Dr Andreas Hein lecturing their course #MSS20 on Systems Modeling.

Credit: ChrisWelch/ISU

Electric sails are potentially more effective than light sails near most stars

The ever creative Professor Avi Loeb (Harvard and Breakthrough Starshot) has looked into the subject of electric sails. In the piece - *Electric sails are potentially more effective than light sails near most stars* - with Manasvi Lingam (Florida Institute of Technology), arxiv.org/abs/1911.02765, he assesses the relative merits of electric sails working by the deflection of stellar wind particles through electric force versus light sails driven by stellar radiation. They conclude that this could be the most effective use of existing forces for interstellar travel - though the timescales are rather long - of the order of one million years!

Amongst others they cite work by Nikolaos Perakis and Andreas Hein of i4is - *Combining Magnetic and Electric Sails for Interstellar Deceleration* - in Acta Astronautica (2016). See also the piece in P21 by Tishtrya Mehta (Warwick University, UK) on the related work of Professor Dr Claudius Gros, Johann Wolfgang Goethe-Universität - entitled - *"Slow down!": How to park an interstellar rocket* - also at i4is.org/slow-down/.

Recent interstellar papers in JBIS

The Journal of the British Interplanetary Society has again featured matters interstellar since we last reported.

BIS members can access JBIS both online and in old-fashioned print. And remember BIS members receive a 20 % discount on annual membership of i4is i4is.org/membership/.

VOLUME 72 NO 6 JUNE 2019 General interstellar issue

THE MOTIVATION AND FREQUENCY OF INTERSTELLAR MIGRATIONS: A Possible Answer to Fermi's Paradox Gregory L Matloff

Greg suggests that technologically advanced interstellar civilizations might defer interstellar migration until their host stars enter the post-main-sequence ~10^8 -year subgiant phase. Increased stellar luminosity will then enhance the performance of solar-photon-sail spacecraft.

TOWARDS A COMPREHENSIVE BIBLIOGRAPHY FOR SETI: Alan Reyes & Jason Wright

Announcing a living bibliography for academic papers and other works published in the Search for Extraterrestrial Intelligence (SETI) using the NASA Astrophysics Data System (ADS).

ULTRAHIGH ACCELERATION NEUTRAL PARTICLE BEAM-DRIVEN SAILS James Benford & Alan Mole

Concept for a 1 kg probe that can be sent to a nearby star in about seventy years using neutral beam propulsion and a magnetic sail.

THE IMPLICATIONS OF NON-FASTER-THAN-LIGHT TYPE-3 KARDASHEV CIVILIZATIONS Agustín Besteiro

Analysing the implications of non-faster-than-light (non-FTL) communications in galactic civilizations.

HUMANITY'S FIRST EXPLICIT STEP IN REACHING ANOTHER STAR: The Interstellar Probe Mission Pontus Brandt et al

An Interstellar Probe mission concept using today's technology. Science targets include the physics of the interstellar medium and obtaining the first external image of our own heliosphere, a flyby exploration of Kuiper Belt Objects (KBO), such as Quaoar, the circum-solar debris disk, and astrophysical observations of the Extragalactic Background Light (EBL) enabled by going beyond the Zodiacal Cloud.

See also Brandt's presentation and others from Johns Hopkins University Applied Physics Laboratory in the IAC2019 report in this issue.

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 has always been about drawing 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.

We'll keep you up to date as we add to this content in the next issue of Principium and in our members' email newsletter.

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.

Members Newsletter

We have now sent out six exclusive email newsletters to members with the latest news of i4is and the whole interstellar endeavour. These arrive in your Inbox when there is something really worth reporting.

Principium preprints

Collections of articles due to be published in upcoming issues of our quarterly, Principium. The articles you find here are made available exclusively to our members before they are made freely available when Principium is published. These are late drafts so may not be exactly what appears in Principium (i4is.org/members/preprints/) we hope they also form an easy to search archive of content. Here is a recent selection -

Title	Author	Added
On a possible future direction for optical SETI	Novoseltsev, D	2019-11-17
News Feature: IAC: The Interstellar Papers – Part 1	Davies, J I	2019-11-17
How low can you go? - The Benkowski equation	Hibberd, A & Davies, J I	2019-11-17
The State of the Art in Fusion Propulsion	Schillo, K	2019-08-01
Competition RESULT	—	2019-08-01
Timetable of Interstellar Papers (IAC)	—	2019-08-01
News Feature: All Comets Great and Small	Davies, J I	2019-04-04
News Feature: IAC 2018 Special Session - Swarm Systems	Davies, J I	2019-04-04
Précis of progress & activity by i4is-US	Kennedy III, R G	2019-04-04
Fine Tuning our Lasers: Updates on Project Dragonfly and Glowworm	Fries, D	2019-04-04
News Feature: The Membership Team	Davies, J I	2019-04-04
Project Glowworm: Testing Laser Sail Propulsion in Low Earth Orbit	Burkhardt, Z	2019-02-02
The TVIW Power of Synergy Symposium: Promoting a Grand Transformation	Rather, J D G	2019-02-02
Territory in Outer Space	Daniels, M	2019-02-02
Amerigo: Brief Overview of a 1000 AU probe study	Bockett, J	2019-02-02

Videos

Videos of events we have held and other original material including -

- *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*

We'll be adding videos from this year's *Second Foundations of Interstellar Studies* workshop soon.

Help us to grow!

Print the poster on the following page, on page 7 (white background) and a student poster on page 5. Tell your friends and colleagues and - if you have time - think about joining our team.

Become active in i4is

We need all your talents - it isn't all rocket science but requires time and the unique talents of our members and especially active volunteers are vital to all we do.

Here are just a few of the major contributors of time, brains and effort - the diversity of occupations, talents and countries should be apparent!

Tishtrya Mehta, PhD student at the University of Warwick specialising in Solar Physics, and Deputy Chair in Education and Outreach - Initiative for Interstellar Studies, United Kingdom

Robert G Kennedy III PE, president, Ultimax Group Inc, Knoxville, Tennessee Area, President of Institute for Interstellar Studies - US (I4IS-US)

Alex Storer, Graphic & Multimedia Designer, Sheffield, United Kingdom

Zachary Burkhardt, recent postgraduate student, International Space University, Strasbourg, France

Angelo Genovese, Senior Electric Propulsion Engineer at Thales Deutschland, Board member of i4is.

Nikolaos Perakis, Aerospace Engineer & Physicist, PhD student at Technical University of Munich (TUM), Germany

Samar AbdelFattah, Advanced Development Engineer at Sypron Solutions, Egypt

Robert Matheson, Economist on the Policy Analysis Team, Covering Goods and Tariffs at Department for International Trade (DIT)

Adam Hibberd, Freelance Software Engineer, UK

Tam O'Neill, Systems Administrator at M & Co, Glasgow, UK and Project Manager at i4is

Conor MacBride PhD Student in Solar Physics at Queen's University Belfast and Web Editor at Initiative for Interstellar Studies

Terry Regan, Heavy Goods Vehicle Engineer & model maker at i4is

Elena Ancona, Mission Control Engineer, EUMETSAT

Efflam Mercier, Concept Artist, Los Angeles, California

David A Hardy, Artist, AstroArt, Birmingham, UK

Become an i4is member

Patrick J Mahon

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!

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 have time you can get actively involved with our projects but we appreciate that not everyone who shares our interstellar vision has the time or resources to do this.

In addition to supporting the programme, members have access to privileged content. This included exclusive reports in our Members Newsletter from the Second Foundations of Interstellar Studies Workshop in June. You also have access to videos of i4is events including the complete Starship Engineer course we delivered at the BIS in 2016, and ‘The Interstellar Minimum’ test paper to explore your knowledge of starship engineering. We will shortly also be publishing videos of all the presentations at the Second Foundations of Interstellar Studies Workshop.

We send an email newsletter exclusively to members, containing the latest news on interstellar developments and our own activities.

Early drafts of Principium articles are also shared with members before general publication of each issue.

More details are on the i4is members’ page on page 13 in this issue of Principium. You will get access to all this content, and much more, if you choose to join.

For the real "rocket scientists" (and engineers) try our *Test Paper: The Interstellar Minimum* based on the Magellan Starship concept from the novel The Songs of Distant Earth by Arthur C Clarke - https://i4is.org/?s2member_skip_confirmation&s2member_file_inline=yes&s2member_file_download=InterstellarMinimum.pdf.

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

Join i4is and help us build our way to the Stars!

News Feature: 70th International Astronautical Congress 2019

The Interstellar Papers - Part 1

Reported by John I Davies

The 70th IAC in Washington DC 21-25 October was an even more massive and impressive event than last year's in Bremen. There were thousands of presentations and we could only schedule coverage of papers by the Initiative for Interstellar Studies (i4is) team & others of interstellar interest. And we did see some of the rest of the show! Here is a brisk trot through what we saw and heard. We distributed print issues of Principium 26 at the event including the timetable in that issue. There will be more from IAC 2019 in P28 in February.

The quoted links to papers and presentations are accessible to all IAC 2019 participants. We have looked for versions of the papers on open access and quoted links where we found them. Please get in touch via Principium@i4is.org if you find more.

We must again thank the IAF Media Office for press access to the Congress. Delegate fees would have been a significant expense in addition to the travel and accommodation overheads, which we donated personally, our normal practice since the foundation of i4is. We are and will remain a low-overhead organisation.

Monday 21 October	**SESSION: Innovative Concepts and Technologies**	iafastro.directory/iac/browse/ IAC-19/D4/1/

Hive: A New Architecture for Space

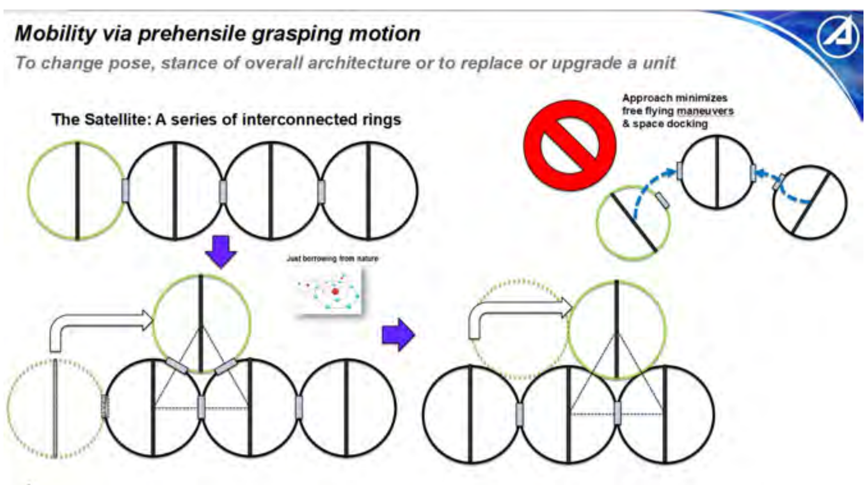
Dr Henry Helvajian The Aerospace Corporation USA

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/manuscripts/IAC-19,D4,1,1,x55085.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/presentations/IAC-19,D4,1,1,x55085.show.pptx

Open paper: not found

Dr Henry Helvajian presented a new architecture for reconfigurable spacecraft, starting from cubesat units. HIVE is bio-inspired modular architecture with units arranged in rings which act as rails. Effectively flat-packed using 20 kg units assembled in space, reconfigurable in rings linked together. This means that moving modules demands a minimal thruster requirement. Units typically stacking and unstacking in flexing rows of interconnected rings. Rings can have a solar cell centre. Movement and reorientation with reaction wheels built in so with less momentum dumping and thus less propellant mass. The advantages include manufacturability, packaging, on orbit deployment and assembly.



Flexing prehensile rings Credit: Helvajian/The Aerospace Corporation

Master Planning and Space Architecture for a Moon Village

Mr Daniel Inocente Skidmore, Owings and Merrill LLP, USA

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/manuscripts/IAC-19,D4,1,2,x52434.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/presentations/IAC-19,D4,1,2,x52434.show.pdf

Open paper: not found

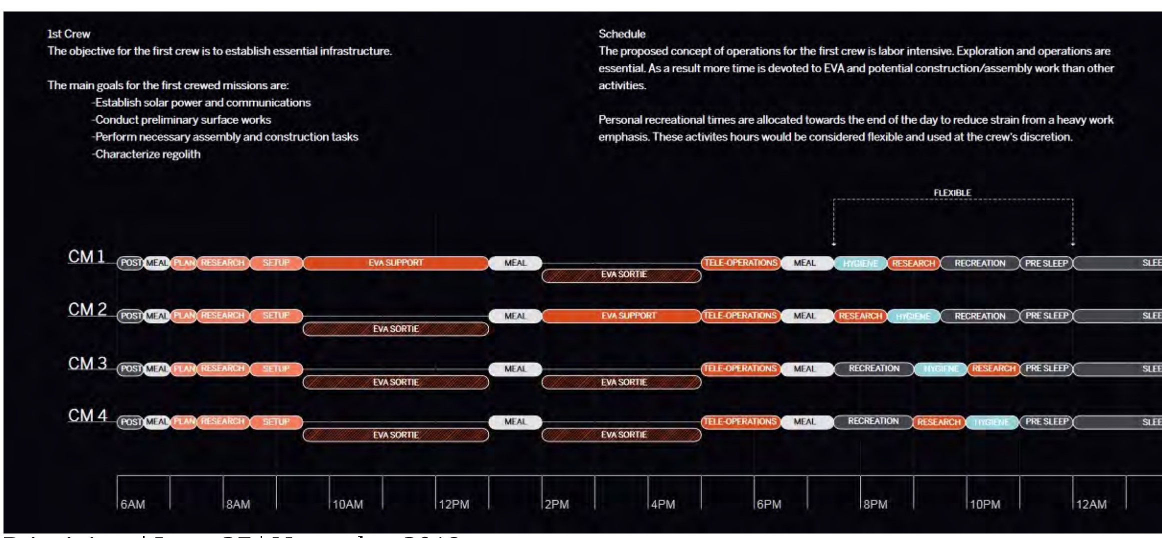
Mr Inocente told that this was based upon an earlier ESA study and ideas based upon the modularity of the International Space Station (ISS). ESA's innovation here was to use "real architects" in the team.

Credit: Inocente / Skidmore, Owings and Merrill LLP

Reconfigurable structure ideas came from ETH Zurich *The Cubli: a cube that can jump up, balance, and 'walk'* (https://www.youtube.com/watch?v=n_6p-1J551Y), MIT Rus Lab and Lund University, Denmark.

The current favoured site is the south pole of Moon for its potential sources of water. The team envisage a typical unit 300 m³ volume and tall structures - clearly much less of an engineering challenge in 1/3 gravity.

To this reporter the architectural ideas looked a little like the "Radiant City" of Le Corbusier, not entirely successful on Earth (see https://en.wikipedia.org/wiki/Ville_Radieuse#Criticism and *Defensible Space; Crime Prevention Through Urban Design*, Oscar Newman, 1973) - but the Moon may be different!



Excerpt from "Crew Systems - Concept of Operations" Credit: Inocente / Skidmore, Owings and Merrill LLP

Steps toward self-assembly of lunar structures from modules of 3D-printed in-situ resources

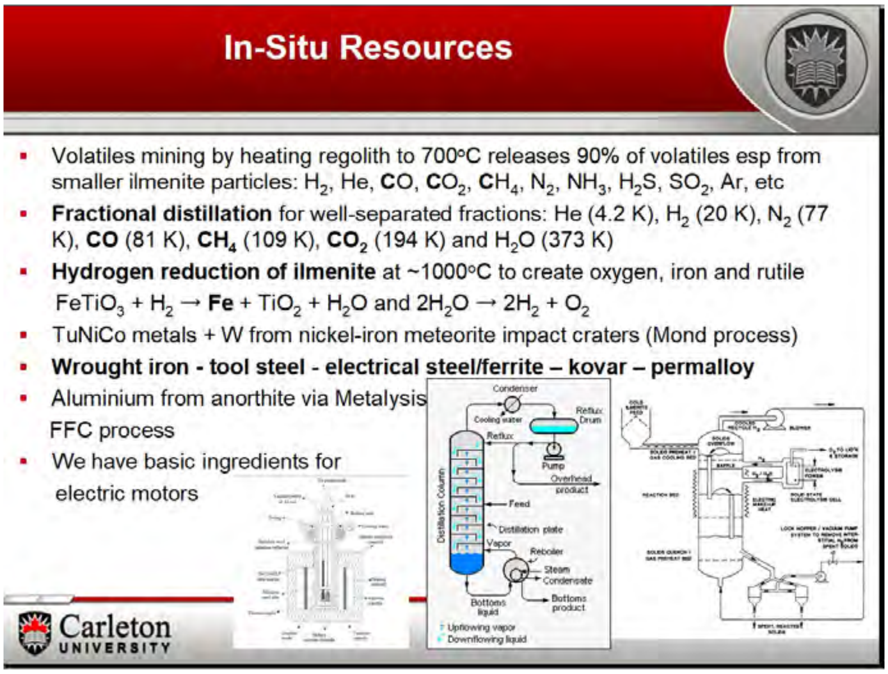
Prof Alex Ellery Space Exploration and Engineering Group, Carleton University, Canada

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/manuscripts/IAC-19,D4,1,4,x49787.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/presentations/IAC-19,D4,1,4,x49787.show.ppt

Open paper: not found

Prof Ellery opened by telling us that the materials required for lunar structures were mostly easily extracted - carbon, water (for electrolysis to hydrogen and oxygen), tungsten, nickel, cobalt. He mentioned the Mond process as just one of the chemical refining processes appropriate to extraction of usable material. He explored the idea of 3D printing entire self-assembling robots - structure, actuators, sensors and electronics –from lunar-derivable material. For example the "Reprap" 3d printer can already self reproduce (see *RepRap – the replicating rapid prototyper*, Rhys Jones et al, http://fab.cba.mit.edu/classes/865.18/replication/Jones.pdf).

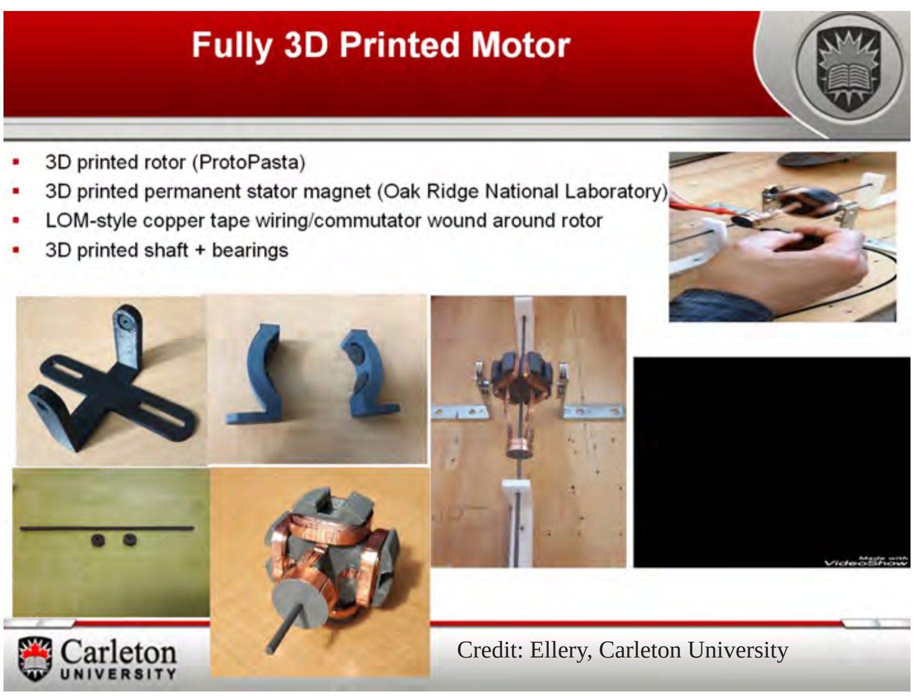


Credit: Ellery, Carleton University

The specific task of creating electric motors is perhaps the greatest challenge and this looks possible - with evidence from lab trials. The wiring coils remain the trickiest challenge - and remain to be achieved in these lab conditions. The first exercise was comparing functions required versus available materials, the "Lunar Industrial Ecology". Lunar equivalents were required for the lab construction and Oak Ridge Laboratory, for example, was helpful with rare earths.

A target is 3D printing the TRIGON (transformable robotic infrastructure-generating object network) panel system, a modular robotic construction system (https://www.academia.edu/5530534/Self-assembling_modular_robotic_structures).

Motor construction was proved - with the exception of wiring coils - which represent a remaining challenge. The motor shaft was not 3D printed but there is a prototype under development for this.



Credit: Ellery, Carleton University

Automated Multidisciplinary Design and Control of Hopping Robot Swarms for Exploration of Extreme Environments on the Moon and Mars

Mr Himangshu Kalita University of Arizona, USA

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/manuscripts/IAC-19,D4,1,5,x54105.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/presentations/IAC-19,D4,1,5,x54105.show.pptx

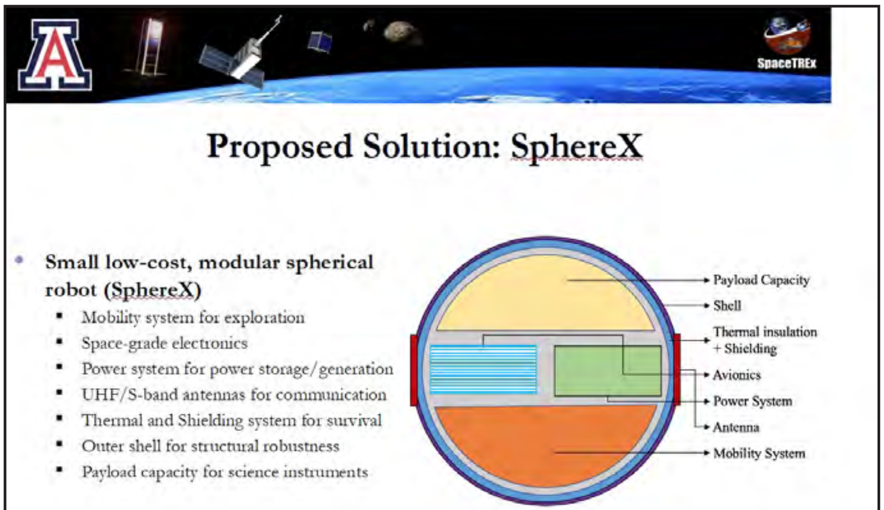
Open paper: https://www.researchgate.net/profile/Jekan_Thangavelautham/publication/336316572_Automated_Multidisciplinary_Design_and_Control_of_Hopping_Robots_for_Exploration_of_Extreme_Environments_on_the_Moon_and_Mars/links/5d9bfb71299bf1c363ff099a/Automated-Multidisciplinary-Design-and-Control-of-Hopping-Robots-for-Exploration-of-Extreme-Environments-on-the-Moon-and-Mars.pdf

Mr Himangshu Kalita told us that existing "normal" rovers can't reach many extreme and rugged environments such as caves, canyons, cliffs and crater rims of the Moon, Mars and icy moons. These include science goals identified by the Outer Planets Assessment Group (OPAG) with Planetary Decadal Study back in 2006 (https://www.lpi.usra.edu/opag/opag_pathways.pdf).

He cited -

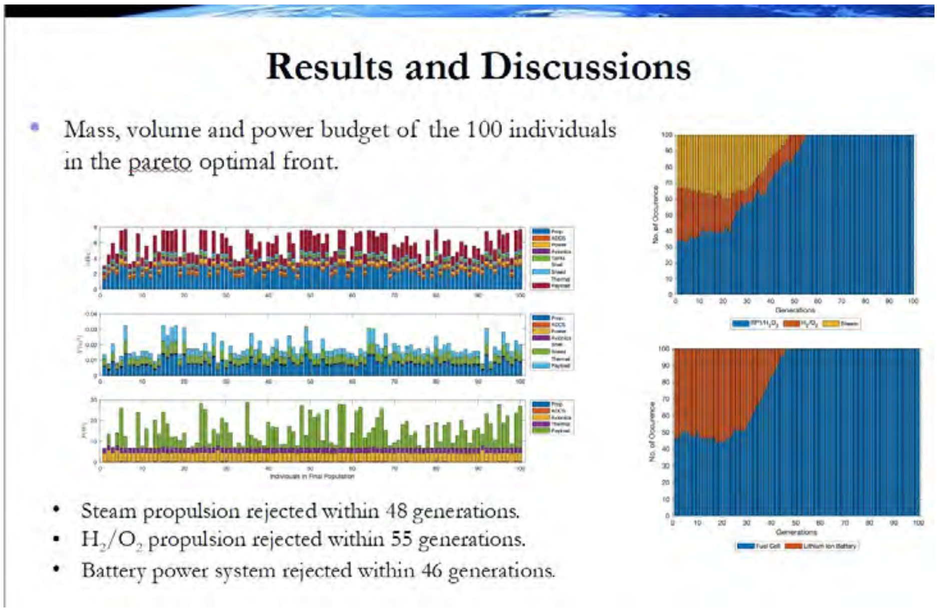
- Limitations in precision landing
- Inability to traverse rugged environments
- Operations culture where risks are minimized at all costs

There is a need for low-cost platforms to perform high-risk, high-reward science on surfaces with extreme environments and pointed to the JPL Mars Cube One (MarCO) as a step in this direction (https://www.jpl.nasa.gov/cubesat/missions/marco.php).



Credit: Kalita / University of Arizona

His proposed solution for this role is a spherical robot, SphereX, hopping or rolling across a variety of surfaces. Hopping is optimum in low gravity environments but his sphere can also move by rolling and this operates wherever a conventional wheeled rover would be used. The team worked with the software tool, Automated Multidisciplinary Design and Control Optimization (AMDCO) framework referred to in the title of his paper. This merges optimal geometric and control design to solve the Nonlinear Optimization Problem (NLP) - iterating through many solutions with multiple input parameters to arrive at design solutions optimising results such as cost.



Credit: Kalita / University of Arizona

The Selection of an Electric Propulsion Subsystem Architecture for High-Power Space Missions

Mr Christopher Andrea Paissoni Politecnico di Torino Italy

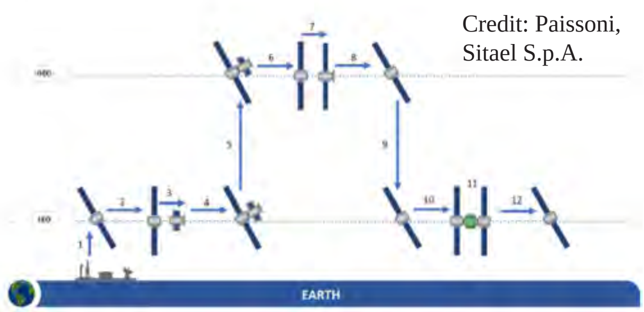
IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/manuscripts/IAC-19,D4,1,8,x53904.pdf

IAC presentation: not yet available

Open paper: not found

High-power electric propulsion is a long sought objective in propulsion technology and Hall thrusters are one of the longer established ideas. Mr Paissoni told us that high-power electric propulsion (E-PROP) requires -

- a trade-off between a high-power monolithic thruster and a cluster of thrusters of lower power.
- the amount of propellant necessary to perform high delta-v missions. Here the price of xenon prompted an investigation on alternative propellants, such as krypton.



Credit: Paissoni, Sitael S.p.A.

Figure 1: Design reference Mission (DRM) of the LEO-GEO transfer reference mission.

The high-power levels that the E-PROP suggests a direct-drive approach, ie a direct and non-isolated connection between the solar array and the thruster saving power conditioning mass.

Potentially allowing a significant reduction in system mass and cost. Mr Paissoni and his colleagues investigated possible mission scenarios and derived corresponding mission requirements and constraints - and three technological trade-offs:

- monolithic 20 kW vs 5 kW cluster configuration
- Xe vs Kr propellant
- direct-drive vs standard PPU

- evaluating each mission scenario an Analytical Hierarchy Process for the trade-off analyses and a Monte Carlo method to perform the preliminary evaluation of the trade-off weights.

An example from Hall technology Company SITAEL is 2.5-7.5 kW yielding thrust 150-330 mN with Isp 1700-3800 sec. Research activities of E-PROP are currently ongoing at SITAEL and PoliTo.

Example missions include LEO to GEO transfer in 100-200 days.

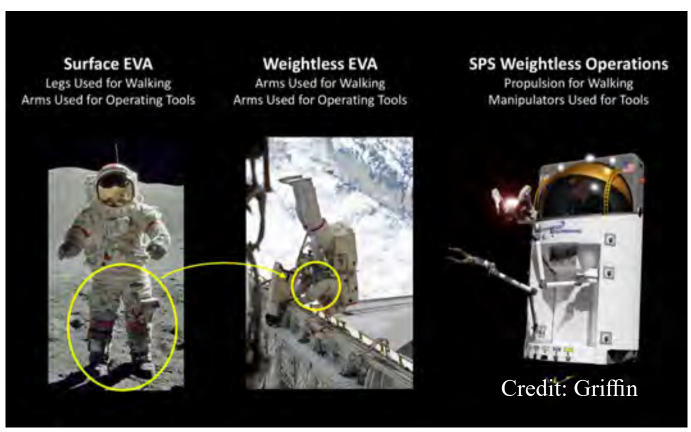
Single-Person Spacecraft Transforms Weightless Operations

Mr Brand Griffin USA

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/manuscripts/IAC-19,D4,1,12,x49199.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/presentations/IAC-19,D4,1,12,x49199.show.pdf

Open paper: not found



Credit: Griffin

Mr Griffin argues that spacesuits are sub-optimal in zero G. Using a Single-Person Spacecraft means that EVA is a docking manoeuvre requiring no airlock. It gives better micrometeor and radiation protection for the astronaut and requires much less training. Lengthy preparation for EVA is avoided. Spacesuits "made to measure" or at least in multiple sizes, are not required. Operators are no longer restricted to minimal information displays and information. And a Single-Person Spacecraft can be optionally teleoperated.

Space suits are best left to gravitational environments like the Moon and Mars. The planned Lunar Gateway could progress much more quickly if EVA did not require an airlock.

AttoSats: ChipSats, other gram-scale spacecraft, and beyond

Dr Andreas Makoto Hein Ecole Centrale de Paris - presented T Marshall Eubanks, Asteroid Initiatives / i4is

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/1/manuscripts/IAC-19,D4,1,11,x55029.pdf

IAC presentation: not yet available

Open paper: https://arxiv.org/abs/1910.12559

Abstract - https://iafastro.directory/iac/paper/id/55029/abstract-pdf/IAC-19,D4,1,11,x55029.brief.pdf

Marshall first asked - How small can we down-scale spacecraft? We are not yet at the level the Feynman "room at the bottom" paper - but how far can we yet go? (for the original Feynman transcript see *There's Plenty of Room at the Bottom - An Invitation to Enter a New Field of Physics* http://www.zyvex.com/nanotech/feynman.html).

Marshall pointed out that miniaturisation has already resulted in dramatic reductions of possible spacecraft dimensions and mass. Spacecraft of mass between 1 to 10 grams, AttoSats, are already operational.

AttoSats confer advantages including agile development, rapid design iteration and the possibility of massive redundancy. AttoSats are developable in months. Their low ballistic coefficient means decay from LEO is quick - thus this can be "clean" orbit technology. At this height power when in eclipse is a major challenge and scaling batteries is not easy. These tiny craft also yield the possibility of fast launch synthetic aperture radar or location in GPS-denied environment. At the other end of the mission scale, deep space and interstellar, we need scale link gain upwards via techniques like phase coherent distributed antennas.

Femto / Attosatellite	Size [cm]	Mass [g]	Deployer	Launcher	Result	Organisation	Launch Year
Sprite	3.5x3.5	5	3U-CubeSat	Falcon-9	In orbit	Cornell University	2014, 2017, 2019
SpinorSat	3.5x3.5 x4	< 10	3U-CubeSat	Falcon-9	In orbit	UC Berkeley	2019
Drexel PinPoint	25x25x 7		Mounted		developm ent	I4is / Drexel University	2020
ThumbSat	48x48x (15-32)	4, 15, 25			developm ent	ThumbSat	
Wafer Scale Spacecraft	25x25				developm ent	UCSB	
Monarch	50x50	2.5			developm ent	Cornell University	

ChipSats launched and under development (Image credit: Cornell University, UC Berkeley, Drexel University, ThumbSat, UC Santa Barbara)

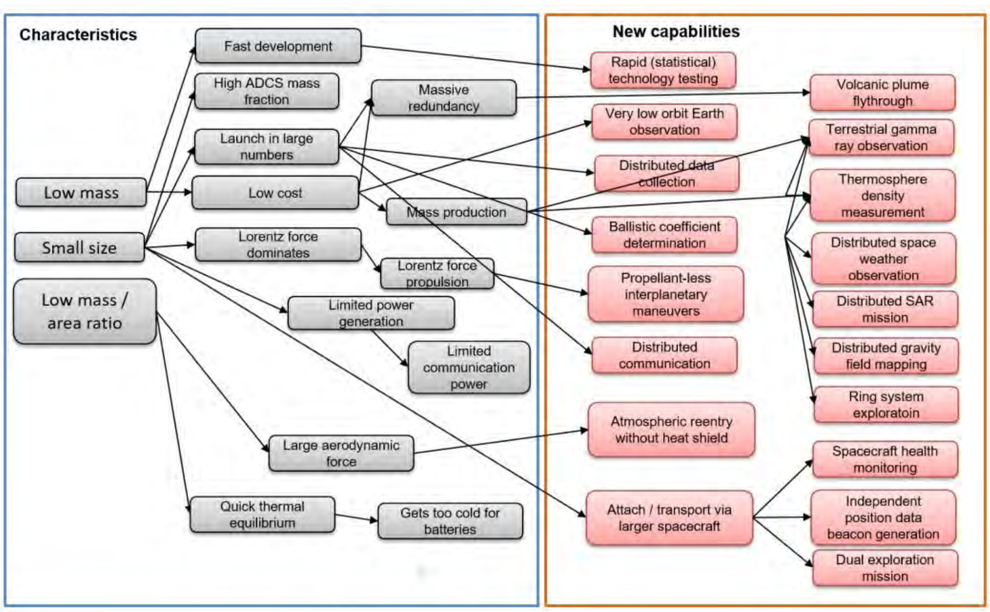


Fig. 8. AttoSat characteristics and capabilities

This paper presents the first systematic survey of the potential advantages and unique mission concepts of AttoSats. What is the state of the art of AttoSats? What are their unique characteristics? How does this map to future mission capabilities? Can we go beyond AttoSats to smart dust and nano-scale spacecraft in the milligram range: zepto- and yocto spacecraft?

Thursday 24 October	**SESSION: Strategies for Rapid Implementation of Interstellar Missions: Precursors and Beyond**	iafastro.directory/iac/browse/ IAC-19/D4/4/

Dr Mae Jemison of 100yss.org opened the session. She mentioned that the first of these had been in 2014. Public engagement is clearly a main 100yss focus and she spent some time on this, mentioning her own origins on the Chicago's South Side. She referenced the work of Tau Zero Foundation, TVIW and the Institute for Interstellar Studies, our US organisation.

An Interstellar Probe for the next Heliophysics Decadal Survey

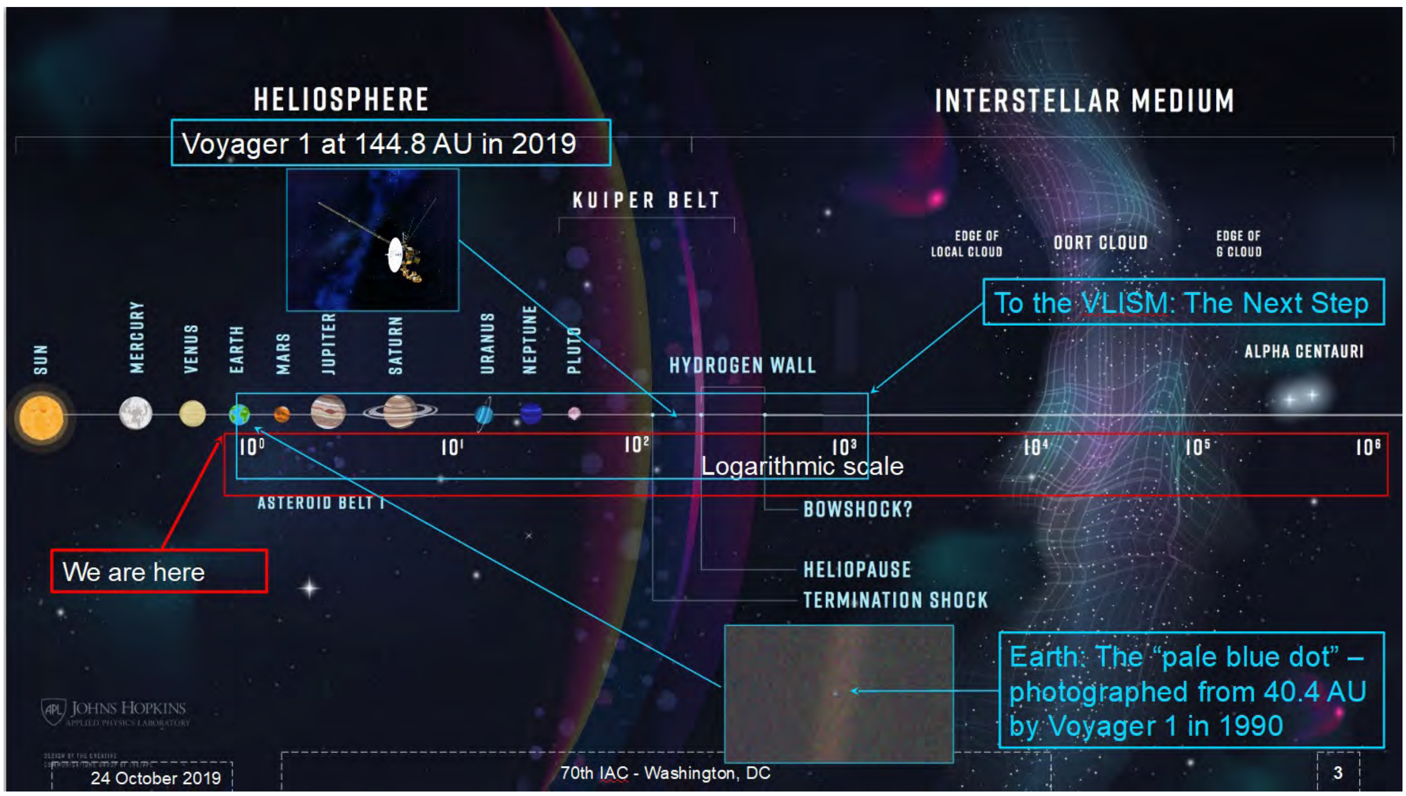
Dr Ralph L McNutt, Jr Johns Hopkins University USA

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/manuscripts/IAC-19,D4,4,1,x51106.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/presentations/IAC-19,D4,4,1,x51106.show.pptx

Open paper: not found

The Johns Hopkins University Applied Physics Laboratory (JHU-APL) proposes a mission, called *Interstellar Probe*, through the outer heliosphere and into the local interstellar medium (ISM), characterised as the VLISM the Very Local ISM. This would be using the NASA SLS (en.wikipedia.org/wiki/Space_Launch_System) or a commercial launcher. Dr McNutt told us that this would be using current known technology to take the first explicit step on the path to interstellar exploration. McNutt gave us some history



The VLISM mission, Credit: McNutt / Johns Hopkins

- the first proposed mission away from the Sun came from the Simpson Committee (Chair Professor John A Simpson, University of Chicago, 1960).

The present study confronts the major technical challenges before *Interstellar Probe* can become a reality. We have to convince both funders and the public. The science goals include -

1: The Heliosphere as a Habitable Astrosphere

2: Formation and Evolution of Planetary Systems

3: Uncover Early Galaxy and Star Formation

The mission requires an even greater velocity away from the Sun than existing probes like the Voyagers.

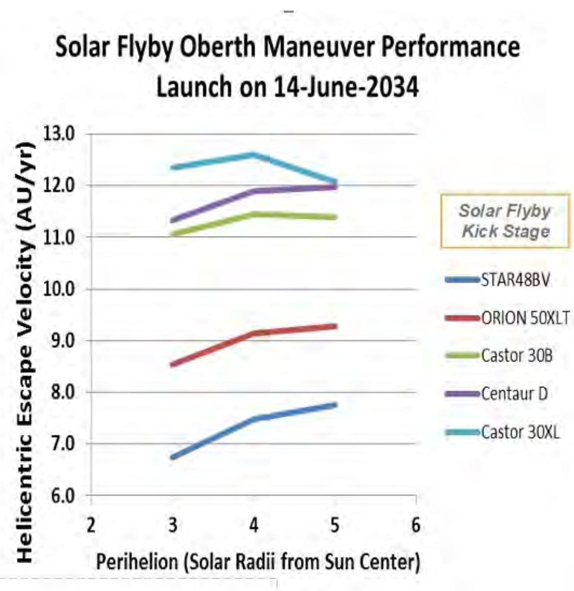
McNutt's team looked at three options -

Option 1: Unpowered Jupiter Gravity Assist (JGA) Burn all rocket stages directly after launch.

Option 2: Active Jupiter Gravity Assist - with a final rocket stage firing at Jupiter optimized perijove.

Option 3: Reverse Jupiter Gravity Assist + Oberth Manoeuvre Near the Sun - killing most angular momentum at Jupiter, falling (almost) into the Sun and getting as close as possible to the Sun to get maximum effect from a final rocket stage Oberth rocket firing.

The latter is the current option under study. This idea of an impulsive rocket burn at a very close perihelion to the Sun is described in more detail in the piece on the i4is Project Lyra calculations elsewhere in this issue of Principium (*How to reach Interstellar Visitors, Optimum Interplanetary Trajectory Software*, Adam Hibberd). The shielding requirements for these perihelion Oberth manoeuvres are clearly demanding and the existing Parker solar probe has similar demands. But McNutt told us the Parker probe is not close enough. Lessons will be learned from the Parker probe but this mission will have more demanding shielding requirements. There is a tradeoff here - a lower perihelion for higher escape velocity has to be balanced against increased shielding mass. Existing and planned final stages for that perihelion "kick" include Star 48BV, Orion 50XLT, Castor 30B, Centaur D and Castor 30XL.



Options for perihelion stages. Credit: McNutt/Johns Hopkins

In answer to a question from Marshall Eubanks, Asteroid Initiatives and i4is, McNutt thought that a probe of this sort could, in principle, reach the interstellar comet 21/Borisov.

Interstellar Probe: Cross-Divisional Science Enabled by the First Deliberate Step in to the Galaxy

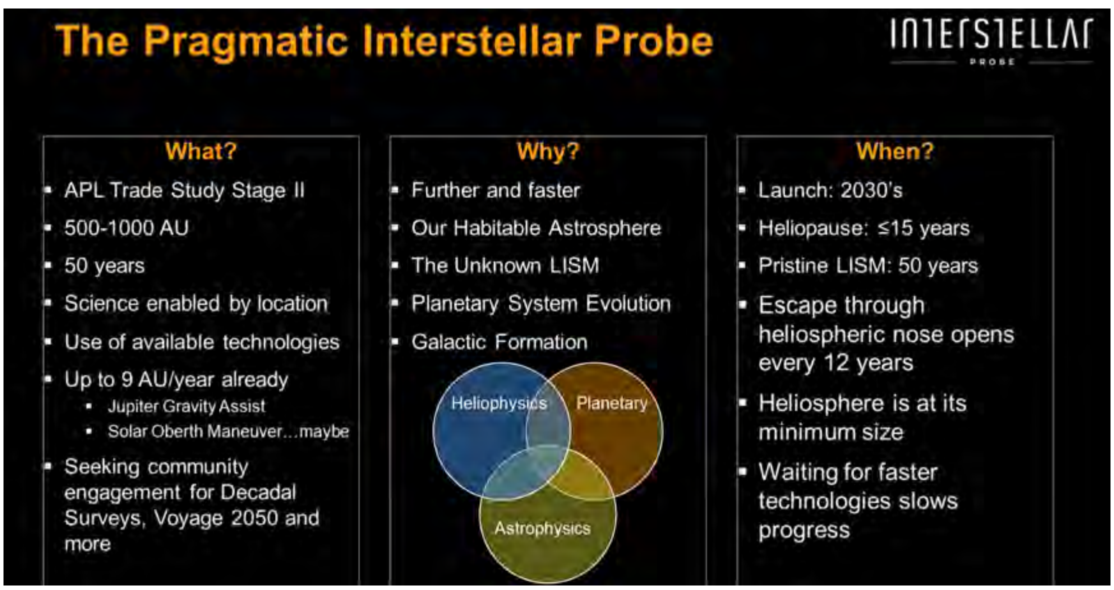
Dr Pontus Brandt Johns Hopkins University Applied Physics Laboratory USA

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/manuscripts/IAC-19,D4,4,2,x52595.pdf

IAC presentation: (titled: The Pragmatic Interstellar Probe: The First Step) https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/presentations/IAC-19,D4,4,2,x52595.show.pptx

Open paper: (similar presentation) https://indico.esa.int/event/309/attachments/3516/4660/Interstellar_Probe_-_Pontus_Brandt.pdf

Dr Brandt told us more about the Johns Hopkins University Applied Physics Laboratory (JHU-APL) *Interstellar Probe*, see the previous item in this report. He started with a summary of what, who and when.



Credit: Brandt/JHU/APL

The JHU-APL team have harvested ideas since 1970, as mentioned in the McNutt report above.

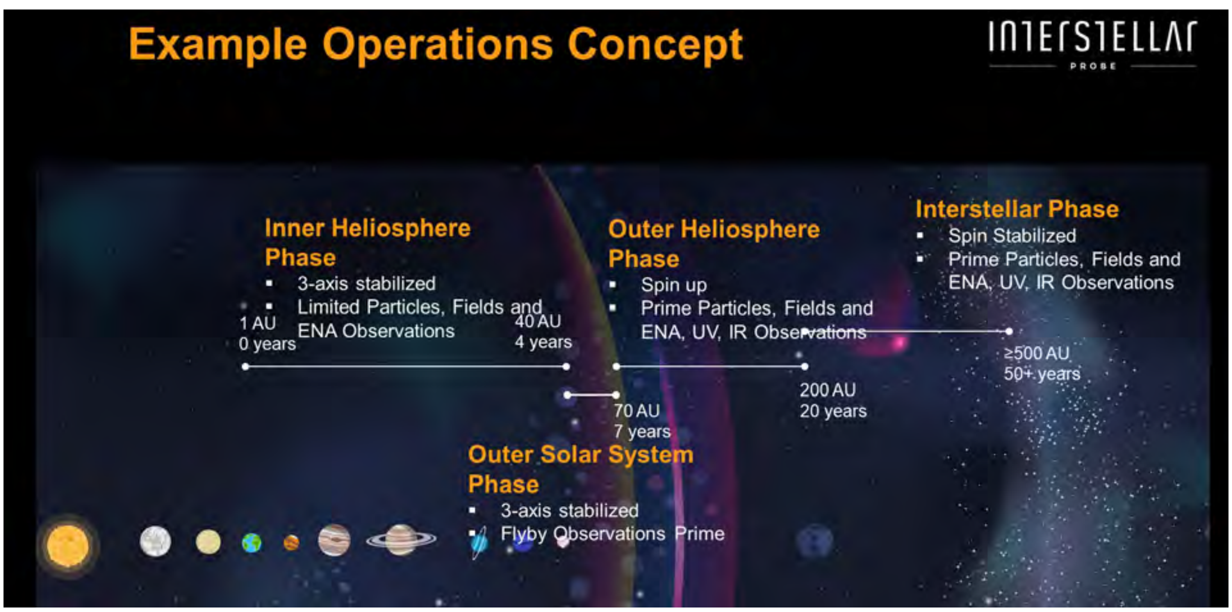
The balance of science objectives and engineering feasibility is at the core of this sort of work and Dr Brandt reported numerous occasions when cries of "Pontus it's too heavy!" could be heard from Ralph McNutt. Here is an example payload Dr Brandt showed us -

Example Payload — INTERSTELLAR PROBE

Instrument	Mass (kg)	Power (W)	Data rate (bps)	TRL	Reference
Vector Helium Magnetometer	1.9-3	3.4-10	6	6-9	Cassini
Fluxgate Magnetometer	1	2	1200	9	PSP
Plasma Wave Instrument	5-6	1.5	100	9	VAP
Solar Wind and PUI	6.1*-8	10-10.8*	1500-2500	6-9	PSP, IMAP*
Suprathermals and Energetic Ions	8*	5*	500*	9	Juno
Cosmic-ray spectrometer	3.6-14.6	6-14.7	200	9	Solar Orbiter, Ulysses
Dust Detector	1.9, 3.6, 17.2	5, 11	579	9	NH, LADEE, Cassini
Neutral Ion Mass Spectrometer	3.5-10.3	5-23.3	1-1495	5-9	Dev., JUICE, Cassini
Low-Energy ENA	11.5	3.5	100	9	IBEX-Lo
Medium-Energy ENA	7.37	0.65	99	9	IBEX-Hi
High-Energy ENA	7.2	6.5	500	7	JUICE
Ly-alpha Spectrograph	4.4-13.3	4.4-11	200	9	NH, SOHO/SWAN
VisNIR Imager	8.6	15	16	9	NH/LORRI
VISNIR/FIR Mapper	3-20	3-20	10	4	In Development
Range	65-136 kg	66-135 W	5011-7006 bps	4-9	

- where TRL is Technology readiness level (en.wikipedia.org/wiki/Technology_readiness_level), a measure of the maturity of a technology. The range quoted by Brandt goes from 4 (Component and/or breadboard validation in laboratory environment) to 9 (Actual system "flight proven" through successful mission operations). There are also performance vs mass vs power trade-offs between payload options.

There are 100s of objects in the Kuiper belt and Oort cloud which the JHU-APL *Interstellar Probe* could investigate, as well as the ISM itself. A number of mysteries already confront investigators, for example the shape of the heliosphere - is it truly spherical or is it deformed by its passage through the local ISM? The Sun is at the edge of the local cloud. It may even exit the cloud in a mere 1000 years! This is disputed but missions like this could settle the question. A typical example operations plan is -



A series of conferences and workshops worldwide (New York, Beijing, Geneva, Washington, San Francisco, Bern, Sydney) are scheduled for the coming 12 months so this work will be very visible to the interstellar community.

Dual Jupiter Swing-by Trajectory for Interstellar Probe

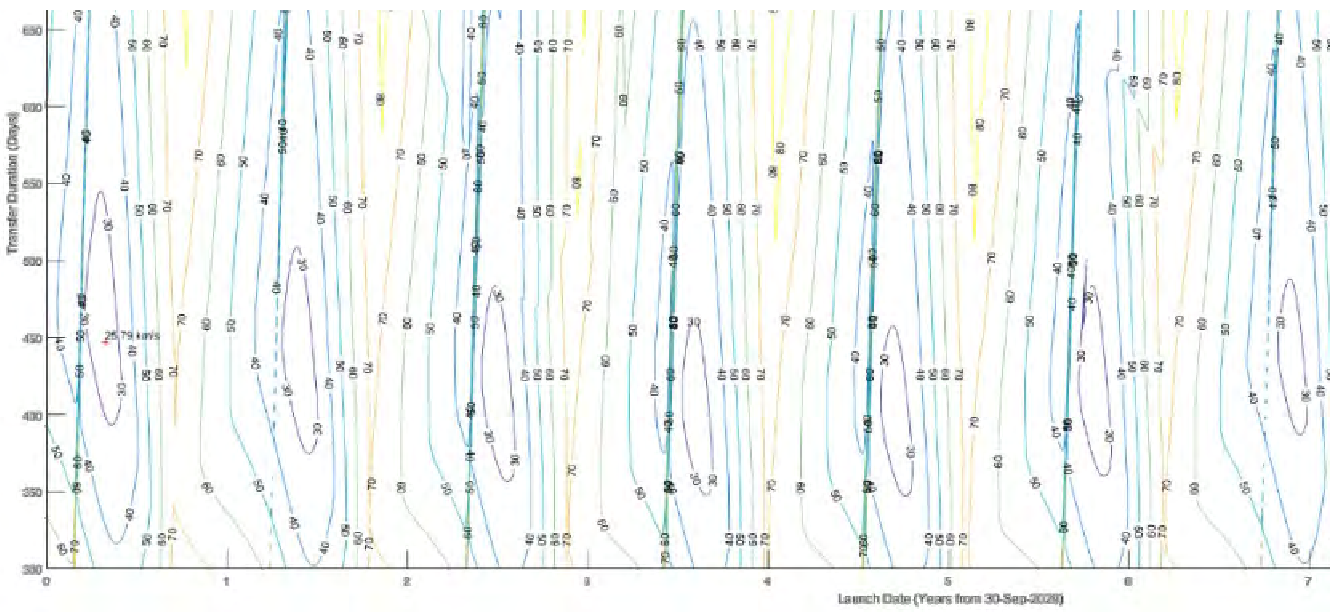
Dr. Peter Gath Airbus Defence and Space Systems   Germany

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/manuscripts/IAC-19,D4,4,3,x49584.pdf

IAC presentation: not available

Open paper: none found

Dr Gath contributed more to the *Interstellar Probe* thinking of McNutt and Brandt reported above, including a trajectory analysis of various scenarios to achieve solar system escape velocity of 95 km/s and reach 1,000 AU in about 50 years. Slingshots around planets, powered or unpowered, and Sun grazing Oberth manoeuvres will be among the potential requirements. An interesting example is double Jupiter gravity assist - one which kills orbital velocity and drops the probe towards the Sun for an Oberth manoeuvre, and a second one which adds velocity on the way out of the solar system. Dr Gath's analysis has strong parallels with the i4is Project Lyra work described by Adam Hibberd elsewhere in this issue. The Jupiter-Sun(Oberth)-Jupiter scenario depends only upon Earth and Jupiter positions so there are launch opportunities approximately once per year, see Dr Gath's pork chop plot below. The Oberth deltaV at the Sun may be reduced by electric propulsion on the way back from Jupiter to the Sun but Dr Gath is currently proposing perihelion at 2 to 5 solar radii, somewhat less than the Parker Solar Probe. Dr Gath also pointed out that closest possible perijove (for maximum deltaV) was limited by both atmosphere and radiation. The final Jupiter encounter sets the coasting trajectory of the probe and can, of course, be out of the ecliptic.



Pork chop plot of launch date (horizontal) and transfer duration from Earth to Jupiter (vertical), with years counted from 30-Sep-2029 showing yearly launch opportunity. Contours are constant energy. See en.wikipedia.org/wiki/Porkchop_plot for explanation. Credit: Gath/Airbus.

The Physics of Heat Shielding During an Oberth Manoeuvre

Dr Jason Benkoski   Johns Hopkins University Applied Physics Laboratory   USA

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/manuscripts/IAC-19,D4,4,4,x51096.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/presentations/IAC-19,D4,4,4,x51096.show.pptx

Open paper: not found

The principal constraints on the "magic" (in fact Newtonian physics) of an Oberth manoeuvre are the mass of the body being used (the Sun in this case), how close your vehicle can get to that body (constrained by its diameter and the hazards it produces, solar outbursts and heating in the Sun's case) and how much "push" you can get from your rocket at closest approach (perihelion). Of the ones we can do much about in the case of the Sun, the heating of the vehicle at perihelion is clearly a factor.

Dr Benkoski considered the physics of shielding against this, given his quoted equation -

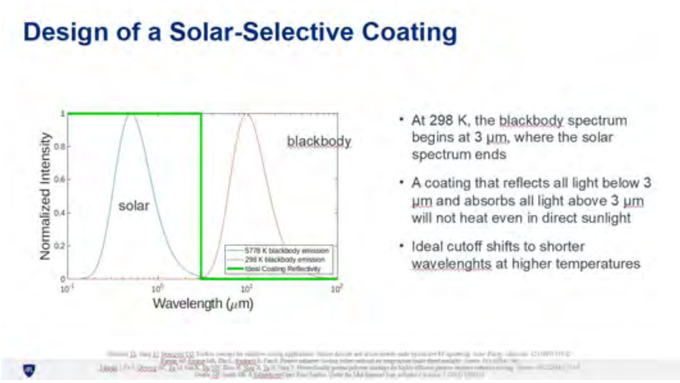
$$V_{escape} = 7.4142 \frac{\Delta V^{1/2}}{r^{1/4}}$$

Credit: Benkoski / JHU-APL

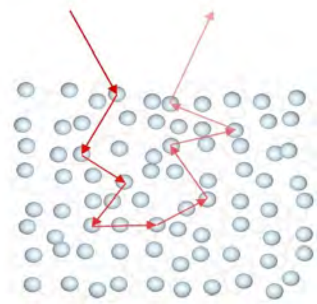
See also *How low can you go - the Benkowski equation*, Hibberd and Davies elsewhere in this issue.

Dr Benkoski told us about the shielding for the Parker Solar Probe (PSP), the current "state of the art", which will reach a perihelion of 9.9R (solar radii) in 2024. It uses an outer reflective layer backed by a carbon foam sandwich. Carbon foam is the primary insulator. He showed us a comparison of the solar spectrum and the emission spectrum of a black body at a representative temperature.

To this naive observer this looks a perfect challenge for a material designer! Absorb the solar radiation and emit it at about 100 times the wavelength - job done! Clearly it's not so easy and Dr Benkoski showed us some thinking based upon both physical models - white reflectors composed of transparent materials with internal interface-



Absorption versus emission and scattering. Both images credit Benkoski / JHU-APL



and on Mie Coefficients (single particle scattering - particle size should be same as wavelength) and Kubelka-Munk Theory for multi-scattering coatings and the extinction coefficient of imperfectly transparent materials. JHU-APL have already done lab work on solar selective coatings.

This was a brand new area to your reporter and it would be good to have a more expert survey of the topic in a later issue of Principium.

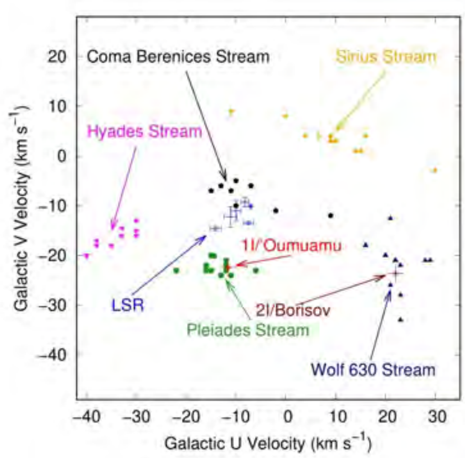
Near Term Interstellar Missions: Finding and Reaching Interstellar Objects T Marshall Eubanks, Space Initiatives Inc USA

IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/manuscripts/IAC-19,D4,4,5,x54556.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/presentations/IAC-19,D4,4,5,x54556.show.pdf

Open paper: to be announced

Marshall is a major contributor to the work of i4is, especially in the field of interstellar objects (ISOs) like 1I/Oumuamua and 2I/Borisov. He began by pointing out that we can study interstellar bodies right now, given their now known arrival in our solar system. Looking for their origins we should first look at local stars which fall into a number of streams. We typically characterise these by their velocities relative to Local Standard of Rest (LSR), the mean motion of material in our part of the Galaxy (en.wikipedia.org/wiki/Local_standard_of_rest). Oumuamua appears to be associated with the Pleiades dynamical stream. It was observed to have a non-gravitational acceleration, mostly radial and declining with distance from the Sun. This may be because it has a very low mass-area ratio, β. If so this and other factors suggest that the two objects found so far 1I/ and 2I/ are very different. The latter are simply types familiar in our own system while objects like 1I/ are unlike anything we know locally and presents a major challenge to our analysis.



Galactocentric Velocities in the Galactic Plane

Credit: Eubanks

Theoretical estimates of ISO production before the discovery of 1I/ under-predict the rate of 100-metre sized ISOs so this also suggests that there may be two types of ISOs - small bodies with normal β ejected from stellar systems, and a new, low β, population. In fact these ISOs may offer some evidence for the modelling of planetary formation. Marshall gave us much more detailed analysis of origins culminating in the proposition that this has relevance to exoplanet studies and that a fast flyby mission yielding both images and detailed compositional analysis would answer many questions. The i4is Lyra studies, showing how we can reach both ISOs discovered so far, suggest this is feasible with current technology. More about this in the piece by Adam Hibberd, elsewhere in this issue. Other missions such as the projected JHU-APL *Interstellar Probe* reported above and the ESA-committed *Comet Interceptor* (en.wikipedia.org/wiki/Comet_Interceptor) could could also reach similar objects.

The Breakthrough Starshot Initiative: Program Update and Next Steps Prof Avi Loeb Harvard University USA

Delivered by James Schalkwyk, Breakthrough Initiatives. Report postponed to P28

The Starshot Communication Downlink

Dr Kevin Parkin Breakthrough Initiatives USA

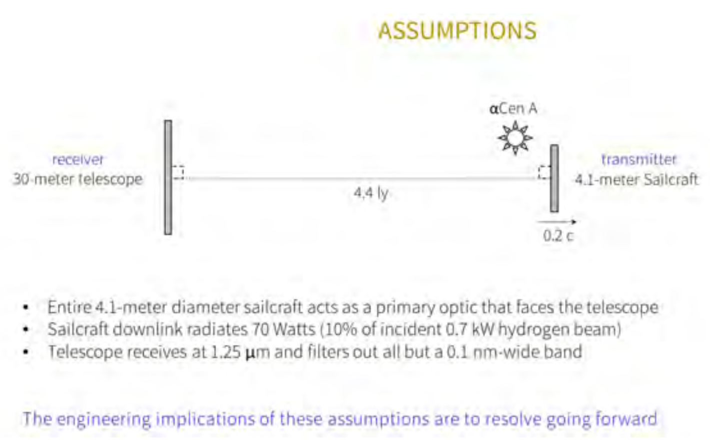
IAC paper: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/manuscripts/IAC-19,D4,4,10,x52408.pdf

IAC presentation: https://iafastro.directory/iac/proceedings/IAC-19/IAC-19/D4/4/presentations/IAC-19,D4,4,10,x52408.show.pptx

Open paper: not found

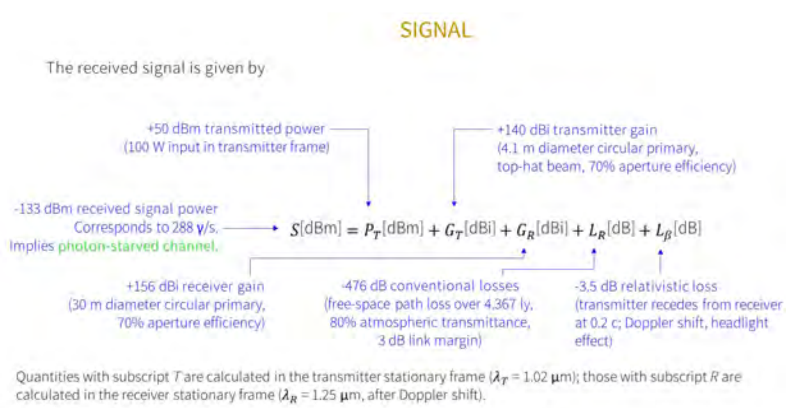
Communication from single or multiple chipsat-size spacecraft over a distance of four light years is one of the major challenges faced by the Starshot idea. Compare the New Horizons probe at Pluto - about 40 AU away - with the distance from Alpha Centauri - about 268,770 AU - and the operation of the inverse square law. $(268,770/40)^2 = 6,719^2 = 45,148,320$ or 45 million worse. Link budgets are a vital part of mission planning for virtually all spacecraft but the challenge of this one fully deserves the adjective astronomical!

Dr Parkin described a particular candidate under consideration for the Starshot mission. Parkin assumes that the spacecraft retains its sail and receives a 700-Watt hydrogen beam, derived from the interstellar medium hitting the spacecraft at its designed 0.2 c velocity. This is not yet feasible engineering but is a necessary initial assumption to discover some initial downlink capabilities. As a result the craft can transmit a 100 Watt optical beam using the whole 4.1 metre sail diameter to a 30 m diameter optical receiver and using the 1.2 micron wavelength atmospheric "window". The optical signal is pulse-position modulated. Each chipsat-size spacecraft could return 10-100 gigabits of raw data per year after the encounter with αCen A. This could be improved by mesh links between craft.



Assumptions and signal budget calculation Credit: Parkin/Starshot

See also - *The Breakthrough Starshot System Model*, Parkin (https://arxiv.org/abs/1805.01306). In the opinion of this reporter, the best explanation of the Starshot systems engineering approach yet seen.



Interstellar Probe: Humanity's First Deliberate Step into the Galaxy by 2030

Friday 25 October	Special Session - Panel Discussion	IAC reference: IAC-18 special sessions

Organiser: Ralph L McNutt, Jr, Chief Scientist for Space Science, Johns Hopkins University Applied Physics Laboratory (APL), United States

IAC paper(s): not normally provided for Special Sessions

IAC presentation(s): not normally provided for Special Sessions

Open paper(s): not found

This final interstellar session brought together six leading figures in interstellar work including -

- Stamatios M Krimigis Space Department Head Emeritus, Johns Hopkins University Applied Physics Laboratory (APL), United States
- Leon Alkalai Fellow and Manager Office of Strategic Planning, NASA Jet Propulsion Laboratory (JPL), United States
- Michel Blanc Professor, Institut de Recherche en Astrophysique et Planétologie (IRAP), France
- Robert F Wimmer-Schweingruber Director, Institute of Experimental and Applied Physics, University of Kiel, Germany
- Mike Gruntman, University of Southern California

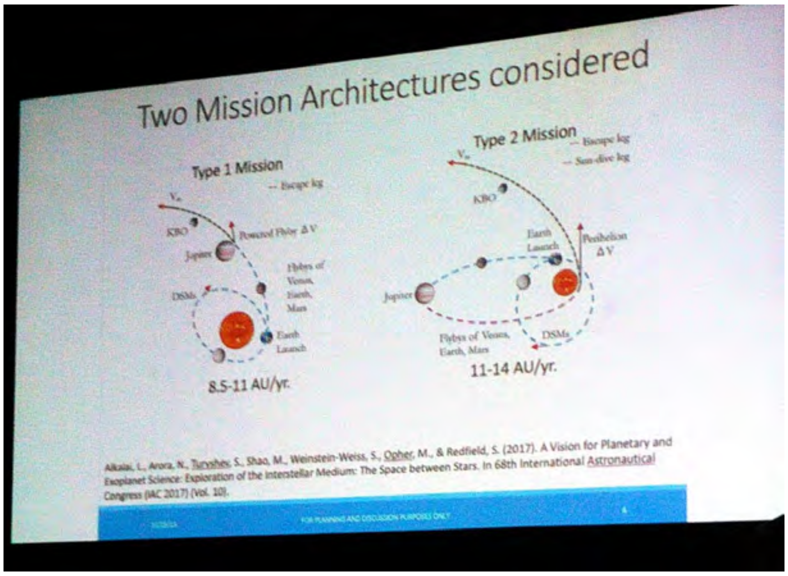
This Panel Discussion was our first report (to i4is members) from IAC 2019. Since IAF does not publish papers or presentations from Special Sessions it seemed best to report while memories are still fresh!

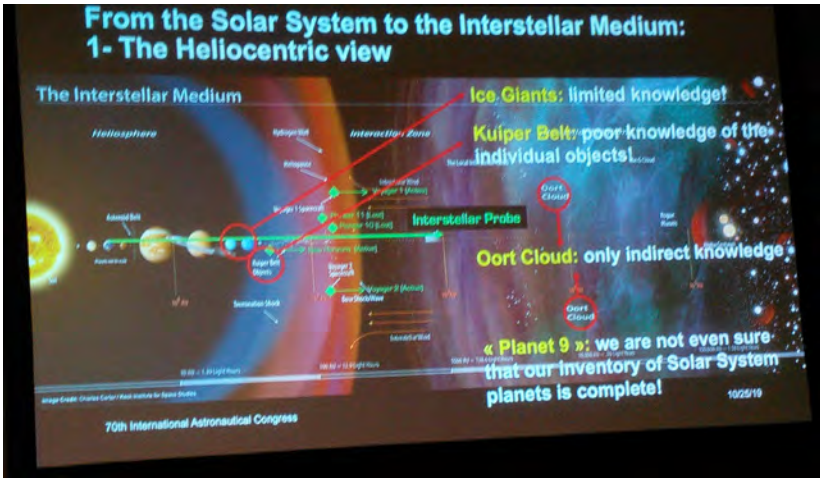
Rapid Access to the Interstellar Medium using Solar Thermal Propulsion: Results of a Feasibility Study

Leon Alkalai (JPL) told us of an element of NASA Jet Propulsion Laboratory (JPL) strategic planning, the science rationale for exploring the Interstellar Medium (ISM).
A JPL group is looking at the next decade - assuming no breakthrough technologies (Professor Alkalai was clear that this implied no disapproval of the work of Breakthrough Initiatives and Breakthrough Starshot. This JPL exercise was deliberately conservative within a 10 year timeframe).

Alkalai presenting, McNutt to the right

He cited - *A Vision for Planetary and Exoplanets Science: Exploration of the Interstellar Medium: The Space Between Stars - IAC-17-D4.4.1x41640* presented at 68th International Astronautical Congress (IAC 2017), Adelaide, Australia, September 29th, 2017 (pdfs.semanticscholar.org/ e3/59cbab9df387eb2d4e09bf7d7cf683018176.pdf) in particular the Interstellar Program Elements - Small Satellite Probes to the Local ISM: 100 – 200 AU, Deep ISM Probes to the Pristine ISM: 200 – 400 AU and Probes carrying telescope to the SGL (Solar Gravity Lens): 500 – 800 AU. He suggested that Jupiter was appropriate as a gravitational slingshot out to 50 AU but that Oberth manoeuvres (slingshot around the Sun with deltaV at perihelion - en.wikipedia.org/wiki/Oberth_effect) would be required to reach distances of 100-200 AU. One possible technology for achieve high deltaV at perihelion is Solar Thermal Propulsion (STP) using heat from proximity to the Sun to heat hydrogen via a heat exchanger (en.wikipedia.org/wiki/Solar_thermal_rocket). Alkalai stressed the importance of whole system design and told us that options would be published for public comment.





Stamatios M Krimigis, Johns Hopkins University APL, reviewed the achievements of Voyager 1 - well into the Interstellar Medium (ISM) and 20 light-hours away and of Voyager 2 just into the ISM. He contrasted the projections of ISM characteristics with those actually observed by Voyagers. The Interstellar Magnetic Field (ISMF) turns out to be about twice the anticipated value so the resultant force is about 10 times the expected value. Other surprises included the source of the (very low!) pressure in the heliosphere, the medium between the Sun and the ISM (en.wikipedia.org/wiki/Heliosphere), the shape of the heliosphere and the direction of galactic cosmic rays, not isotropic but variable under the influence of episodes of change in the ISMF. All this shows how in situ observation is vital to science - theoretical models can only be tested by direct observation,

Robert F Wimmer-Schweingruber, University of Kiel, Germany, mentioned next week's ESA long-term planning event - *the Voyage 2050 workshop, Shaping the European Space Agency's space science plan for 2035-2050,* 29 – 31 October 2019, Madrid, Spain (www.cosmos.esa.int/web/voyage-2050-workshop). He was especially inclined to see our own solar system from the outside to give us a benchmark for observation of other solar systems. Imagine an image of the solar system from the heliocentric North Pole!

Mike Gruntman, University of Southern California, remains uncertain what should be measured in the near ISM or in what direction we should first explore. My own thought was towards the Alpha Centauri system unless there is good reason otherwise - after all that's the direction we will probably go once we have interstellar capability.

Ralph L McNutt wrapped up by asking those born after 1990 to stand up. This was about one third of the audience. His message to them was - *Don't screw up!* He asked for questions.

Our colleague Gurbir Singh asked McNutt about the future of the Voyagers. He told us that only 3-5 years could be expected. The limitation curiously enough is the ability to keep the hydrazine lines to the attitude control thrusters unfrozen. If the antenna can't point at Earth then signal will be lost. The RTG (en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator) has already used 150% of the Pu238 half life.

Another questioner asked about using relay craft to extend the range of the downlink from distant probes. It looks as if the costs are not justified with current technology.

McNutt parted with the message that his APL team aimed to complete their ISM probe report to NASA in about two years.

Gurbir Singh asks a question

The JHU-APL *Interstellar Probe* proposal has also attracted the attention of *Scientific American* - https://www.scientificamerican.com/article/proposed-interstellar-mission-reaches-for-the-stars-one-generation-at-a-time1/ *Proposed Interstellar Mission Reaches for the Stars, One Generation at a Time*, Lee Billings - with an interesting thought on the sociology of such long duration projects.

How to reach Interstellar Visitors

Optimum Interplanetary Trajectory Software

Adam Hibberd

When the first interstellar object to be discovered in our solar system, 1I/'Oumuamua, was spotted by the team at the Pan-STARRS telescope in Hawaii, a team of experts from the Initiative and Institute for Interstellar Studies came together to assess the feasibility of intercepting this messenger from the galaxy. Some time before this, Freelance Software Engineer Adam Hibberd was looking into general solutions for interplanetary trajectories and had developed his Optimum Interplanetary Trajectory Software (OITS) when he became aware of the i4is work and contacted Andreas Hein. The rest, as they say, is history. Here Adam gives his account of what happened and how he and the i4is Project Lyra team pioneered the work of mission planning to reach both 1I/'Oumuamua and have now extended it to the later 2I/Borisov comet.

Adam begins with a brief autobiographical background and how he contacted Andreas Hein, going on to detail the mathematical methods he used to deliver the Project Lyra team results.

I am educated to degree level in physics and maths and in 1990, after leaving university, I was hired as a software engineer by a company in Camberley, Surrey called EASAMS Ltd. I was employed in the Ariane 4 Project which had responsibility for development, production, real-time testing and post-flight analysis of the on-board flight software for the European Ariane 4 satellite launch vehicle.

Ultimately I became a specialist in Ariane 4 Guidance which required an understanding of Optimum Launcher Ascent Trajectory to Orbit Software. This is where I picked up an interest and enthusiasm in optimum trajectory theory and orbital mechanics.

Since then I have worked for various companies as a software engineer, however in 2004 I changed my career path entirely and became a composer/musician. (This has always interested me – in fact as a child I played and composed on the piano.) As a part of the musical group Superheroes Dream, we produced a vinyl under the Coventry Tin Angel record label.

In 2017 I decided to pick up a computer keyboard again and try to get to grips with MATLAB which is a programming language which has always intrigued me. In order to do this I set myself the challenge of developing a tool for calculating optimum interplanetary trajectories. I decided to approach it with very little reference to the scientific literature, so I could view the problem with an open and objective point of reference. Having derived the theory, I then subsequently implemented the equations using MATLAB into a software application which I called 'OITS' – that's 'Optimum Interplanetary Trajectory Software'.

Naturally OITS would need accurate position and velocity calculation for the celestial bodies. My logic here was that NASA would have developed their own software to do precisely this and indeed they had – it's called SPICE (https://naif.jpl.nasa.gov/naif/toolkit.html) and fortuitously, there is a MATLAB version of this toolkit. Thus rather than re-inventing the wheel, I decided to exploit this software and link it in with my OITS tool, as third party software.

As will be explained later, the theory behind OITS also requires a global 'Non-Linear Programming', NLP solver. Having tried various options, I discovered 'NOMAD' (https://www.gerad.ca/nomad/) to be extremely good for the problem in hand.

I knew I was onto something when OITS started solving and reproducing historic missions such as Voyager 2, Cassini and Mars Insight Lander to excellent accuracy.

When the first interstellar object, 'Oumuamua was discovered in 2017, I had largely developed my software so I decided to investigate interplanetary missions to this object. With a bit of further research online I found that Project Lyra of i4is had been working on precisely the same problem as I had – missions to 'Oumuamua. I contacted Andreas Hein with my results and so started a fruitful relationship with i4is.

In the end, we produced two papers on the subject of missions to 'Oumuamua, the first of which was published by the peer-reviewed journal, 'Acta Astronautica' (https://www.sciencedirect.com/science/article/abs/pii/S0094576518317004), the second of which I was largely responsible for the research and has been published online (https://arxiv.org/abs/1902.04935).

The reason for the success of OITS in the context of the Project Lyra research, is partly because of the incorporation of the notion of 'Intermediate Points' (IP). Essentially an IP is a massless and static point in space whose distance from the centre of the Solar System is user-specified but whose polar angles (so heliocentric longitude and latitude) are allowed to be optimised by the NLP software. Such a point can be used to model something known as a 'DSM' or 'Deep Space Manoeuvre'. For a spacecraft to get to 'Oumuamua, for example, it needs to do a 'Solar Oberth', where it approaches very close to the Sun (within a few solar radii) and then a burn is applied at this perihelion point. Such a manoeuvre can easily be modelled by OITS using an IP and so viable trajectories using this technique can be investigated. An example of such a trajectory is provided below. This 3D plot was generated by OITS and manipulated by me using the MATLAB Integrated Development Environment to get it into a presentable form.

I developed an animation option for OITS and an animation for the above trajectory can be found here:

https://drive.google.com/open?id=1Pgcdl4kuz7rxSJ30PDkafvohbg2G63P8

With the discovery of the second interstellar object, Borisov, we managed to also produce a paper very quickly and take advantage of all the media attention it was receiving (https://arxiv.org/abs/1909.06348).

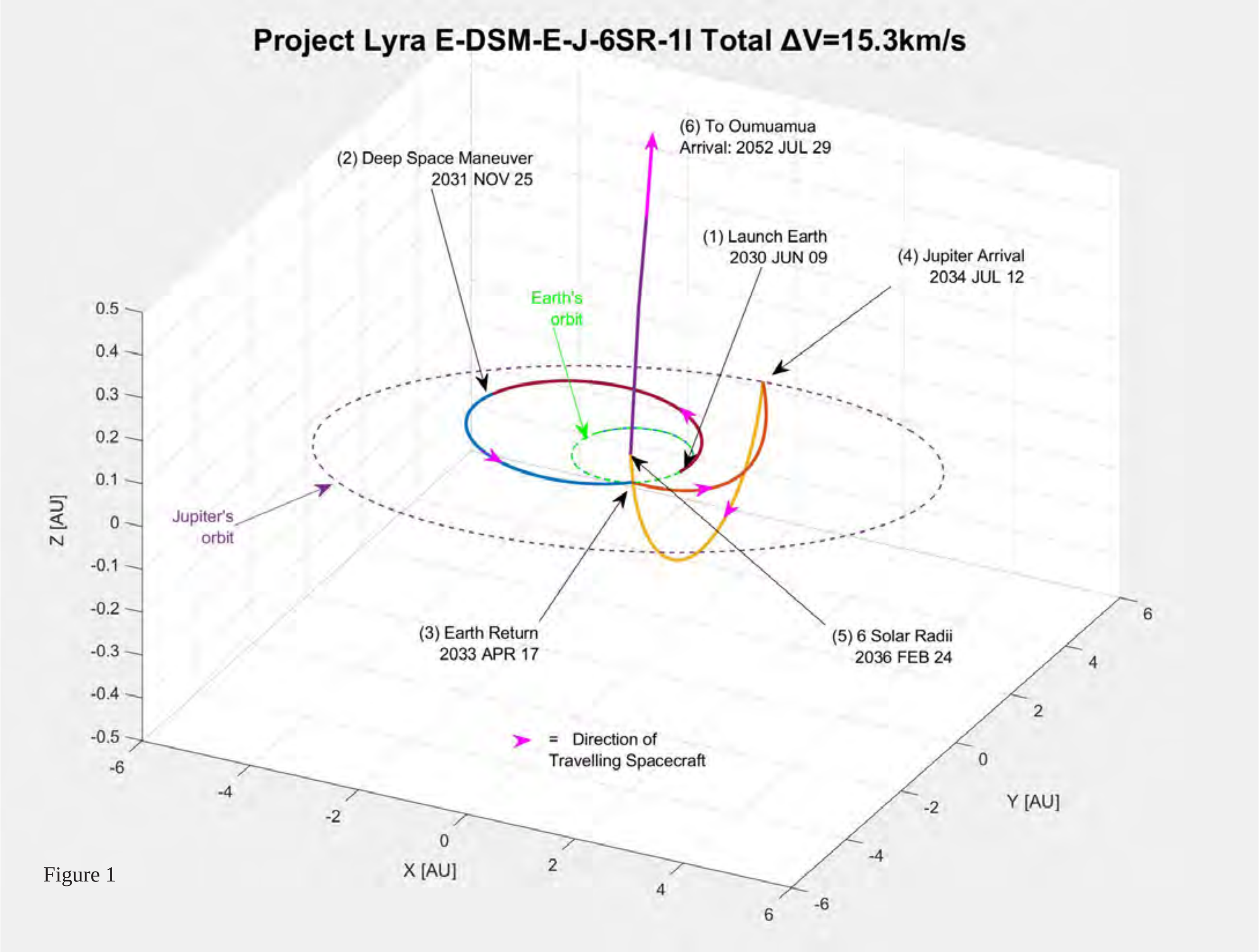


Figure 1

General Principles of Optimum Interplanetary Trajectory Software (OITS)

The following is not intended to be an accurate definition of the theory behind OITS and the precise algorithm employed by OITS differs in various respects to that elaborated here. However, you can get a good idea of the general principles behind it.

Figure 2. Let us assume there are two stationary bodies A and B and that a travelling spacecraft has to be at A at time t_A and arrive later at B at time t_B, where $t_B > t_A$.

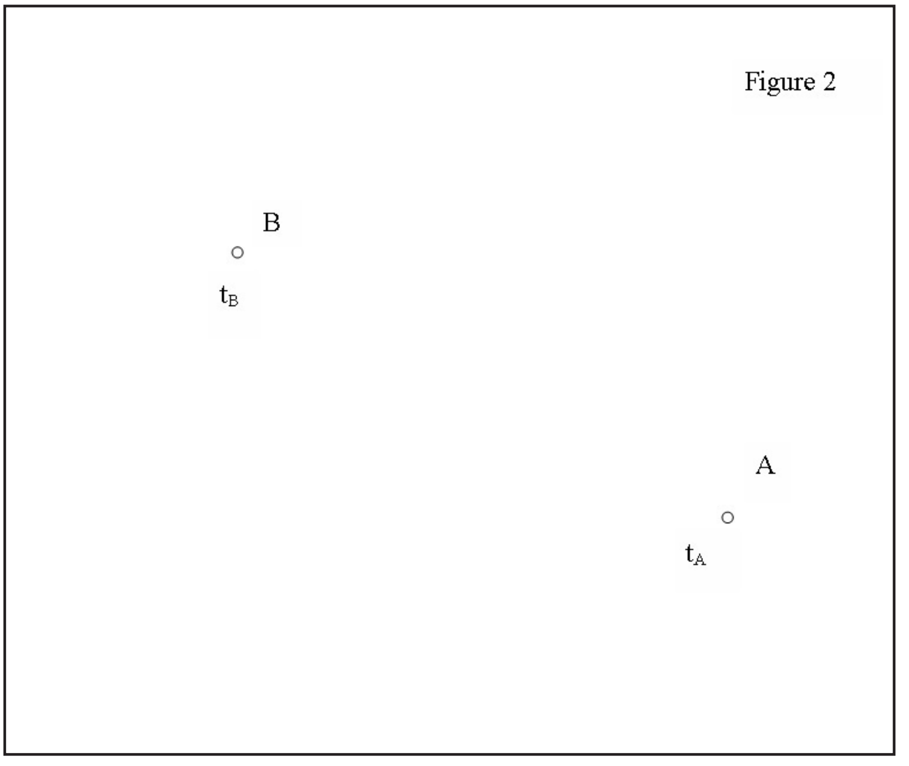


Figure 3. Furthermore we know the displacement between A and B is $\Delta\mathbf{R}$. We can ask what is the velocity we need at A to get to B?

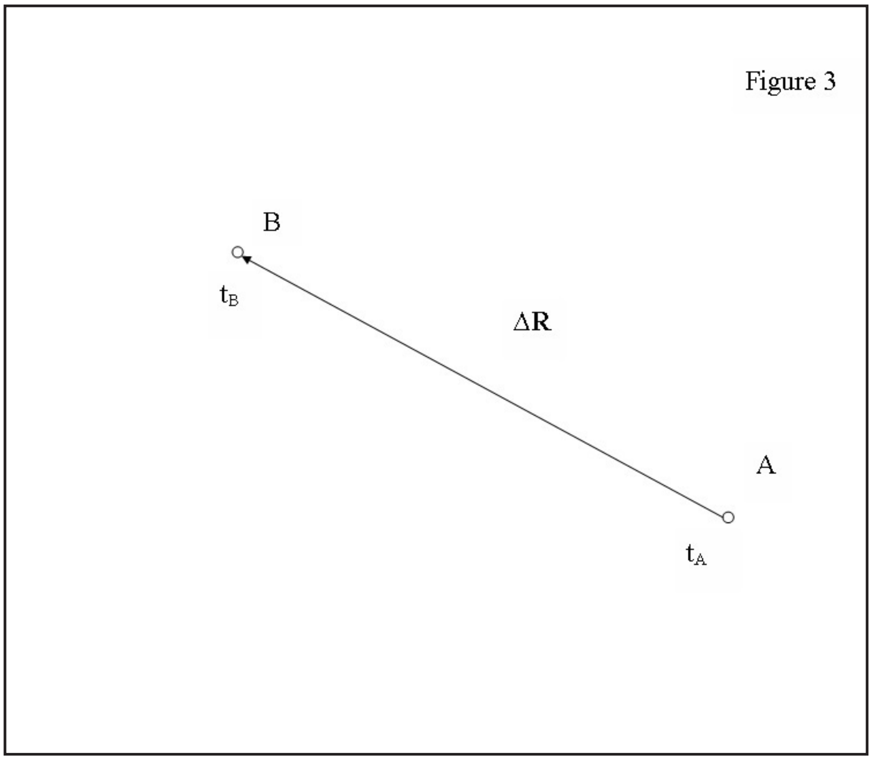


Figure 4. The answer is we need a velocity at A of $\mathbf{V}_{AB}$ given by $\mathbf{V}_{AB} = \Delta\mathbf{R}/(t_B - t_A)$.

But what if A and B are moving themselves? Take a look at Figure 5.

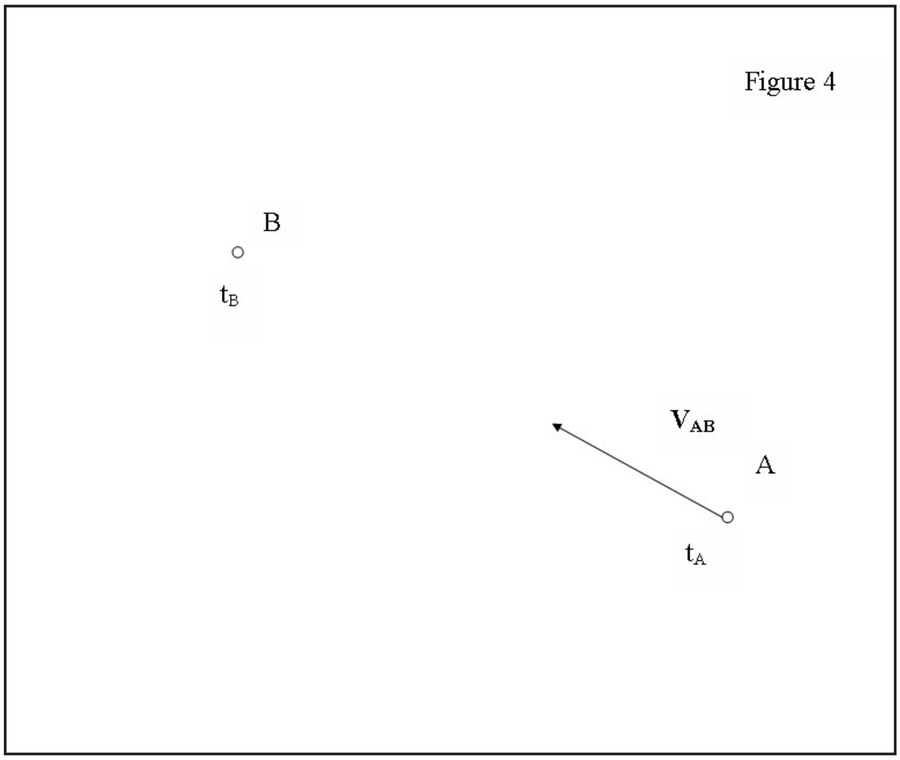
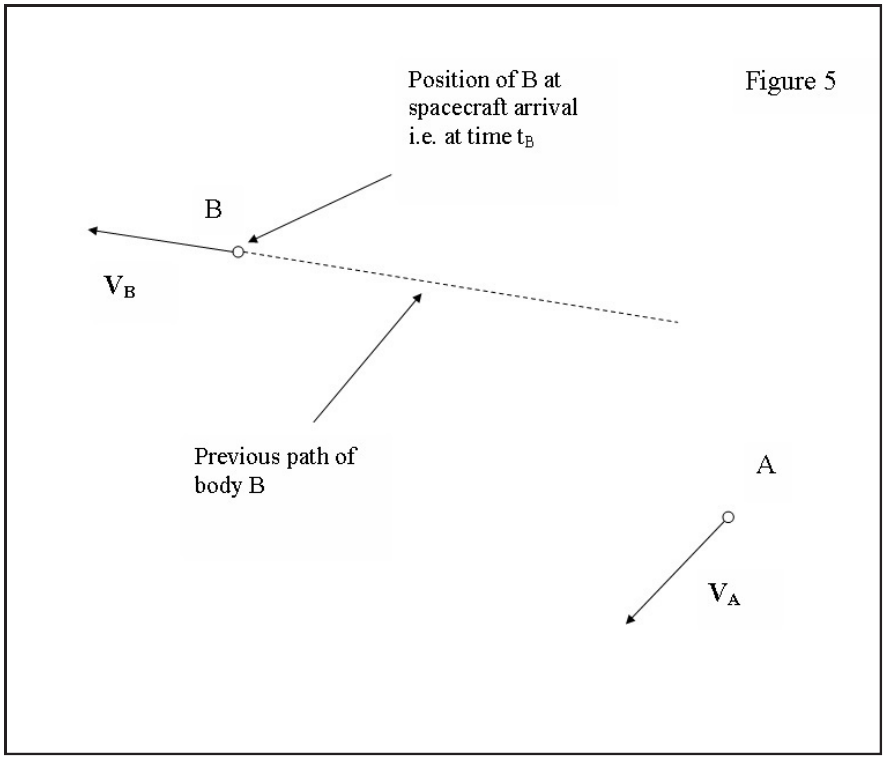


Figure 5. So we assume A and B are travelling in space with respective velocities $\mathbf{V}_A$ and $\mathbf{V}_B$. Also assume that our spacecraft originates from body A, so initially has the same velocity, $\mathbf{V}_A$.



Then as we can see from Figure 6, the spacecraft now needs to apply a change in velocity $\Delta\mathbf{V}_\mathbf{A}$ in order to arrive at the intended target B at time t_B.

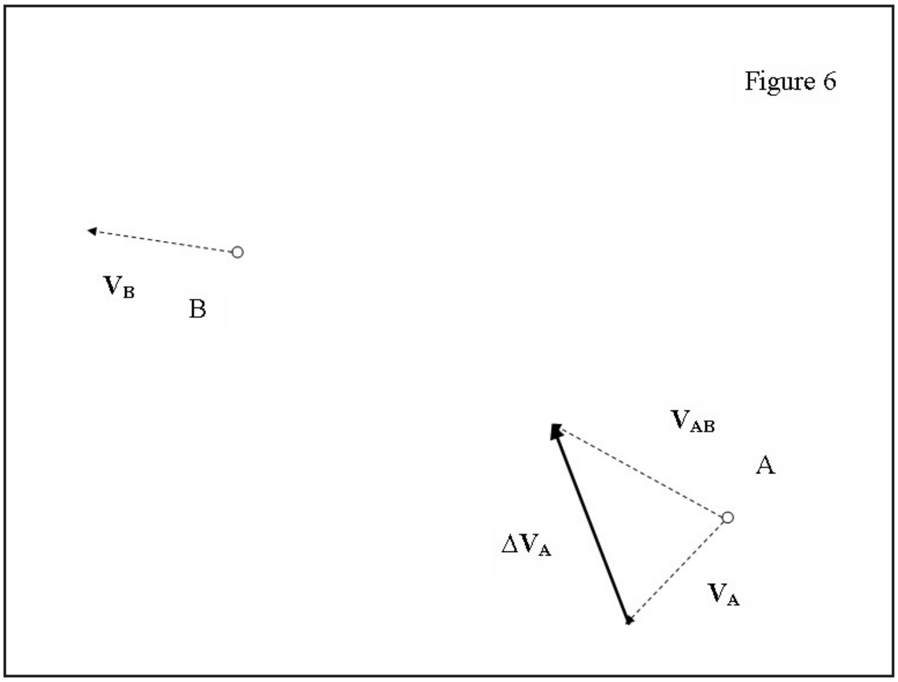
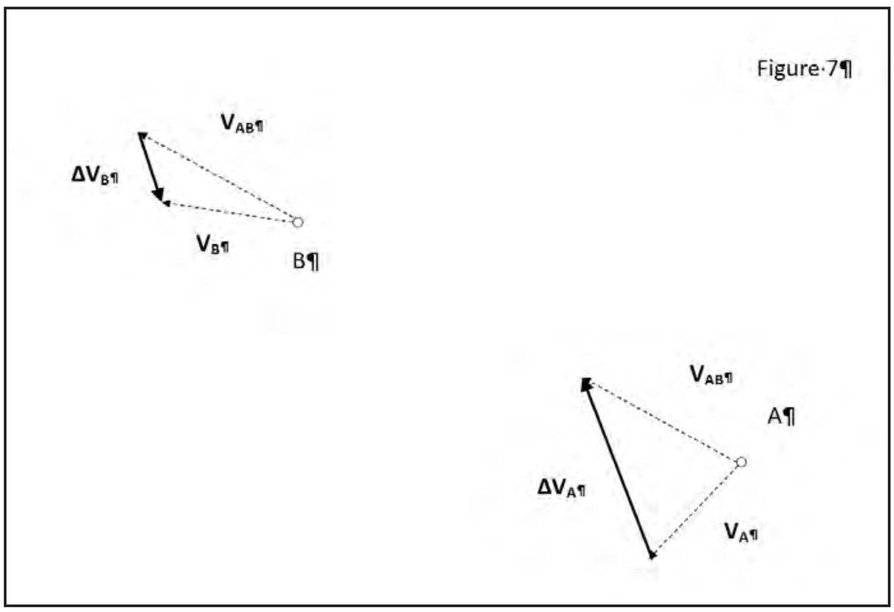


Figure 6

However in Figure 6, once it arrives at B it will simply flyby B. So this is an ‘intercept’. What if we wish to stay with B after arrival? Then we also need to apply a ‘ΔV’ at B, $\Delta\mathbf{V}_\mathbf{B}$, as can be seen in Figure 7. In other words a ‘rendezvous’.



Figure·7¶

The general idea behind OITS, is that we need to find the times t_A and t_B such that the ‘effort’ needed to get from A to B is minimised. This ‘effort’ is quantified as follows:

For Intercept:

Find t_A and t_B such that the magnitude of $\Delta\mathbf{V}_\mathbf{A}$ is minimised,

ie minimise $|\Delta\mathbf{V}_\mathbf{A}|$

For Rendezvous:

Find t_A and t_B such that the sum of the magnitudes $\Delta\mathbf{V}_\mathbf{A}$ **and** $\Delta\mathbf{V}_\mathbf{B}$ is minimised,

ie minimise $|\Delta\mathbf{V}_\mathbf{A}| + |\Delta\mathbf{V}_\mathbf{B}|$

But we have ignored the gravitational attraction of the Sun. In fact, this will 'bend' the velocity $\mathbf{V}_{AB}$, so that the s/c will be sent off-course. Refer Figure 8.

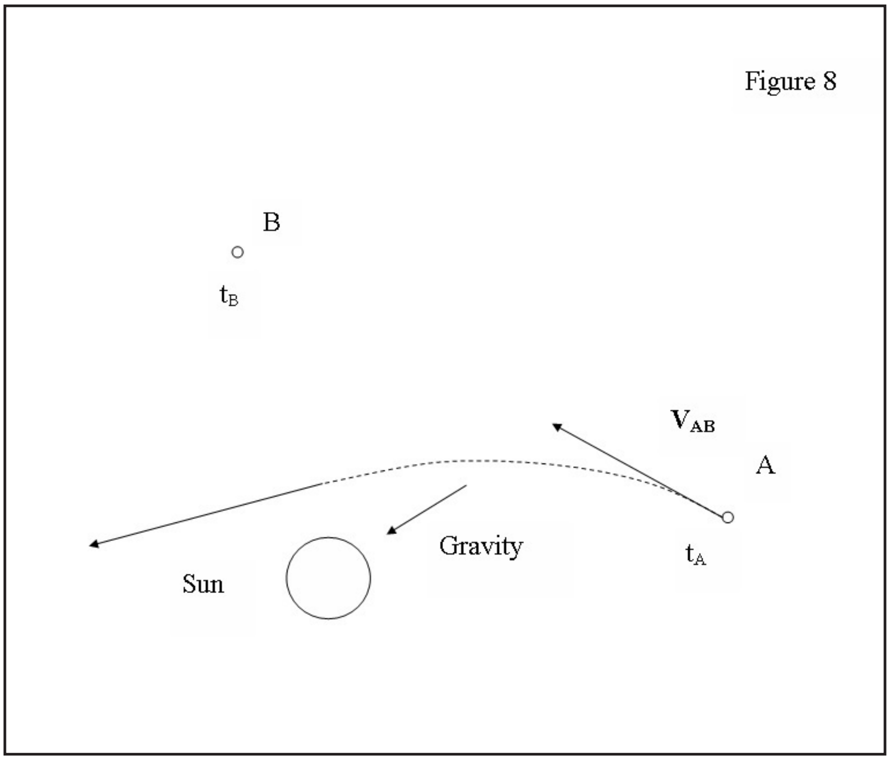
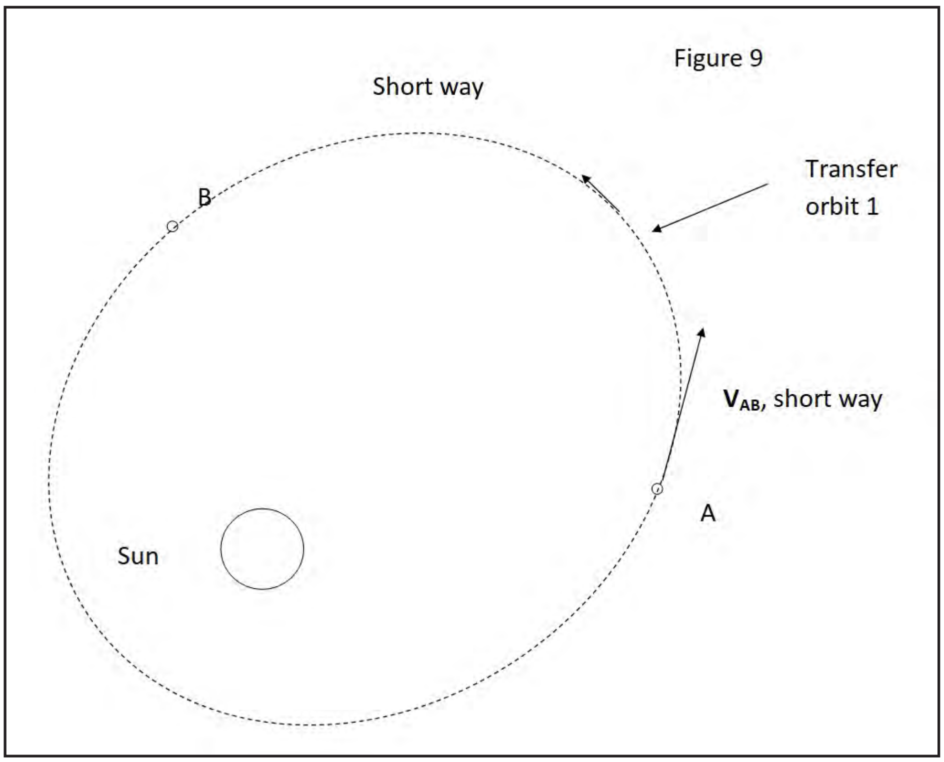
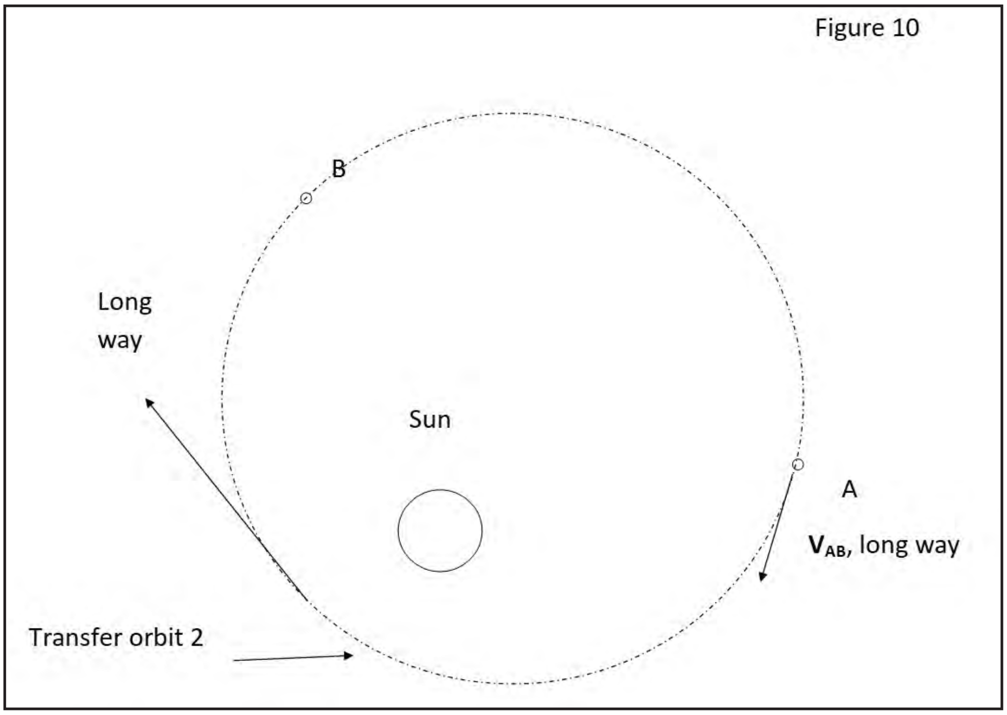


Figure 9 shows the solution to this problem.

In the presence of gravity of the Sun, there are actually two ways of travelling from A to B, 'short way' and 'long way'.

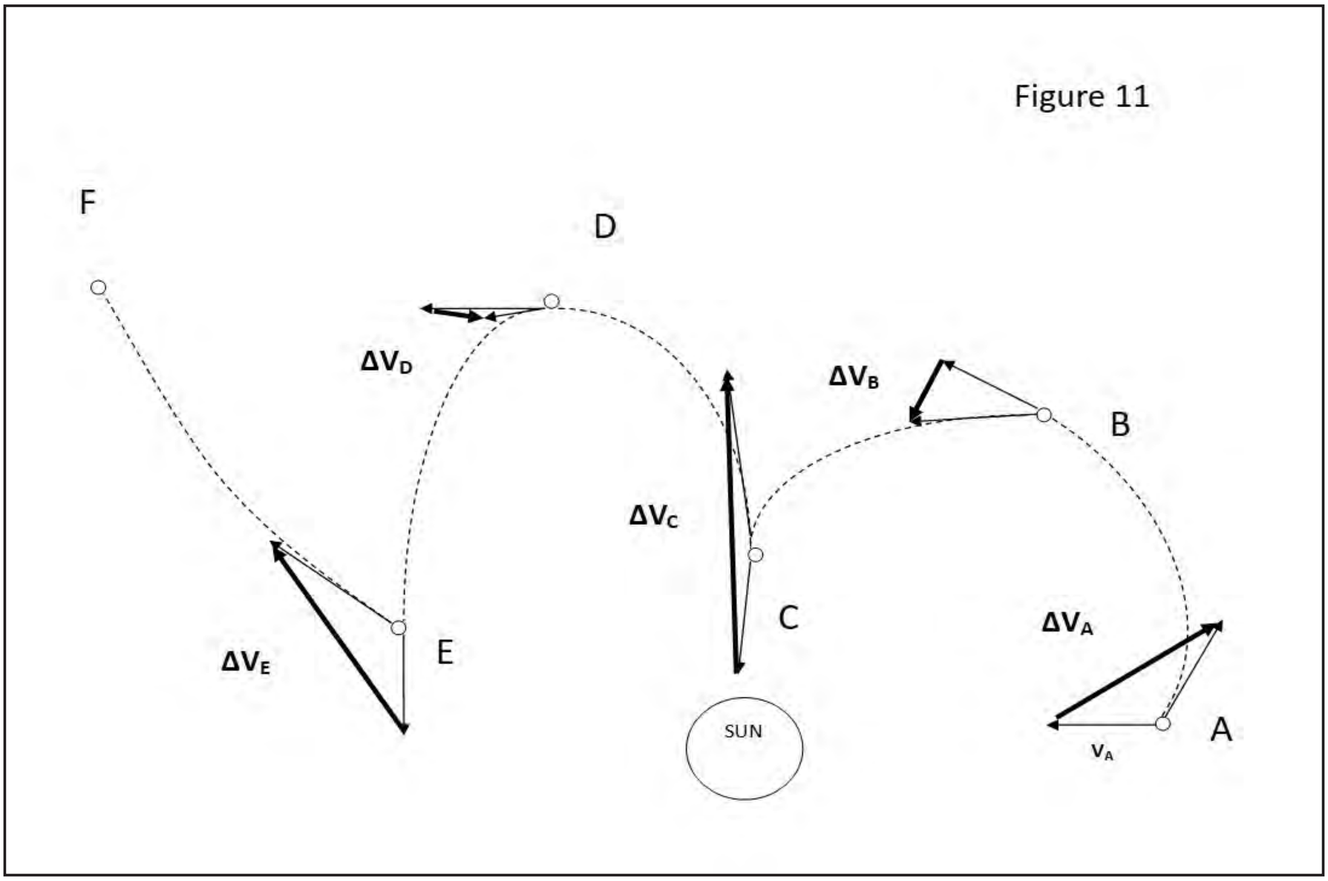


See Figure 10 for long way.



The solution to finding the two transfer orbits, short way and long way (see Figures 9 & 10), given departure time and arrival time and corresponding positions at departure and arrival, is a well-known problem of astrodynamics, known as the Lambert problem, and a possible numerical method of solution is provided in 'Fundamentals of Astrodynamics' (Bate, Mueller and White). The so-called 'Universal Variable Formulation'.

Figure 11, introduces the idea that there may be more than 2 bodies, the example given is for 6 bodies, labelled A, B, C, D, E and F.



So what OITS tries to do is find the times t_A, t_B, t_C, t_D, t_E, and t_F such that the cumulative ΔV_{TOT} (total deltaV - en.wikipedia.org/wiki/Delta-v_budget) is a minimum. ΔV_{TOT} is given by:

$$\Delta V_{TOT} = |\Delta \mathbf{V_A}| + |\Delta \mathbf{V_B}| + |\Delta \mathbf{V_C}| + |\Delta \mathbf{V_D}| + |\Delta \mathbf{V_E}| + |\Delta \mathbf{V_F}|$$

Given the known orbital paths of A, B, C, D, E & F around the Sun, ΔV_{TOT} is in fact only a function of the times t_A, t_B, t_C, t_D, t_E, and t_F.

In the general case, let there be 'Nbody' total number of bodies. From Figures 9 & 10, we can deduce there are in fact $2^{(Nbody-1)}$ ways of getting from body number 1 to the final body, ie there are this many permutations of short ways and long ways. Of all the possible permutations, we choose the one which minimises ΔV_{TOT}.

Problem Statement

So our problem can be stated as follows:

PROBLEM: Find times t_A, t_B, t_C, t_D, t_E, and t_F, such that $\Delta V_{TOT} = f(t_A, t_B, t_C, t_D, t_E, t_F)$ is a minimum.

The problem stated above is a 'Non-Linear Programming' problem, ie NLP. There may be some constraint functions also. There are various NLP solvers available on the internet which can solve such a problem. The function, f , is treated as a black-box and is user defined. The NLP then repeatedly feeds this black-box the input variables (in this case t_1, t_2, t_3 ...t_{Nbody}) and the user-defined function, f, is executed. It is the purpose of the NLP to so change the input variables iteratively until the global minimum of f is found, subject to satisfying all the constraints.

Given a sequence of celestial bodies i=1,2,3...Nbody, and a sequence of times t_i , i=1,2,3...Nbody, the corresponding positions and velocities of each of the celestial bodies need to be calculated. As well as holding a massive database of celestial bodies, the NASA SPICE toolkit also allows accurate determination of their positions and velocities (the ephemerides - en.wikipedia.org/wiki/Ephemeris) and can be linked in with the MATLAB software. Having so calculated the ephemerides, the Universal Variable Formulation can then be applied to calculate the value of ΔV_{TOT}, as previously explained. The NLP software can then be utilised to find the global minimum. I used a global NLP tool called NOMAD (editors note: see Adam's opening remarks and https://www.gerad.ca/nomad/).

Note that all of the variables t_i , i=1,2,3...Nbody are usually restricted to user-defined intervals, ie a solution is found subject to bounds on these variables. Also note that the celestial bodies i=1,2,3...Nbody, have masses and hence gravitational attractions of their own and in fact OITS incorporates the encounter dynamics of the spacecraft with each of these bodies. Thus in actuality the calculation of ΔV_{TOT} used by OITS is not precisely as described above.

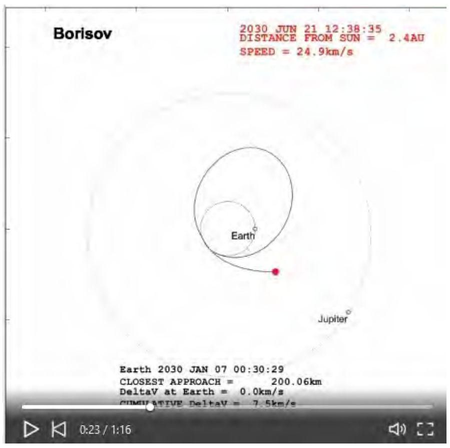
About the Author

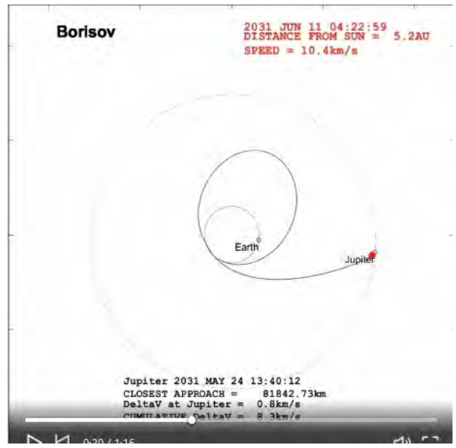
Adam Hibberd has already told his own story but a few additional notes may be of interest.

Adam has a Joint Honours Bachelor's Degree in Physics and Mathematics from Keele University, UK. His earlier education was at a state comprehensive school in Coventry in the English Midlands.

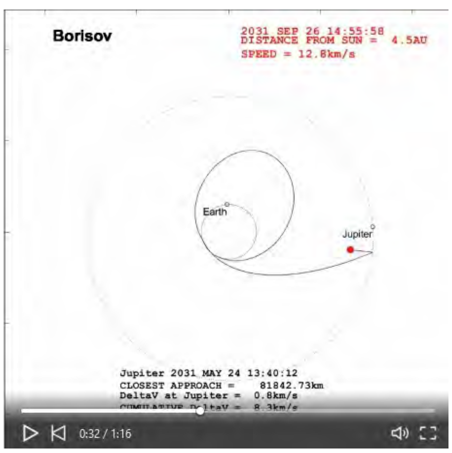
To see some of his most recent work in animated form look at www.linkedin.com/in/adam-hibberd-b73339136/detail/recent-activity/ showing a dramatic trajectory from Earth 2027, an Earth slingshot, a Jupiter slingshot, a precipitous dive into the Sun, an Oberth perihelion burn and an intercept with comet Borisov in 2051, when your editor will be 105 years old!

Here are some snapshots -





The probe leaves Earth on an elliptical trajectory, comes back to Earth and is slingshotted to Jupiter...



A Jupiter slingshot gives it a Sun-grazing trajectory to receive best Oberth effect at perihelion so that (with a considerable change of scale) the probe overtakes comet Borisov.

How low can you go? - The Benkowski equation

Adam Hibberd and John Davies

In this issue of Principium, we report the paper given by Dr Jason Benkowski of Johns Hopkins University Applied Physics Laboratory, *The Physics of Heat Shielding During an Oberth Manoeuvre*. Dr Benkowski quoted an equation for the Oberth manoeuvre, boosting a probe by firing a rocket at perihelion and thus adding velocities unattainable by planetary slingshot manoeuvres, even at the mighty Jupiter. The equation relates the Vescape or asymptotic velocity of the probe to the perihelion altitude above the Sun and the DeltaV imparted by the rocket at perihelion.

$$V_{escape} = 7.4142\frac{\Delta V^{1/2}}{r^{1/4}}$$

Vescape in AU/yr and DeltaV in km/s,
Credit: Benkowski

This equation assumes the incoming trajectory to the Solar Oberth Manoeuvre is in fact parabolic, ie the probe originated from a great distance from the Sun with near-zero velocity, in other words V-infinity is zero. In the trajectories from Jupiter to the Solar Oberth calculated for the Project Lyra research, this assumption is not necessarily valid.

The informal result is that -

- the closer you get to the Sun the better the Oberth effect and, of course -
- the greater the DeltaV imparted by your rocket the better the Oberth effect

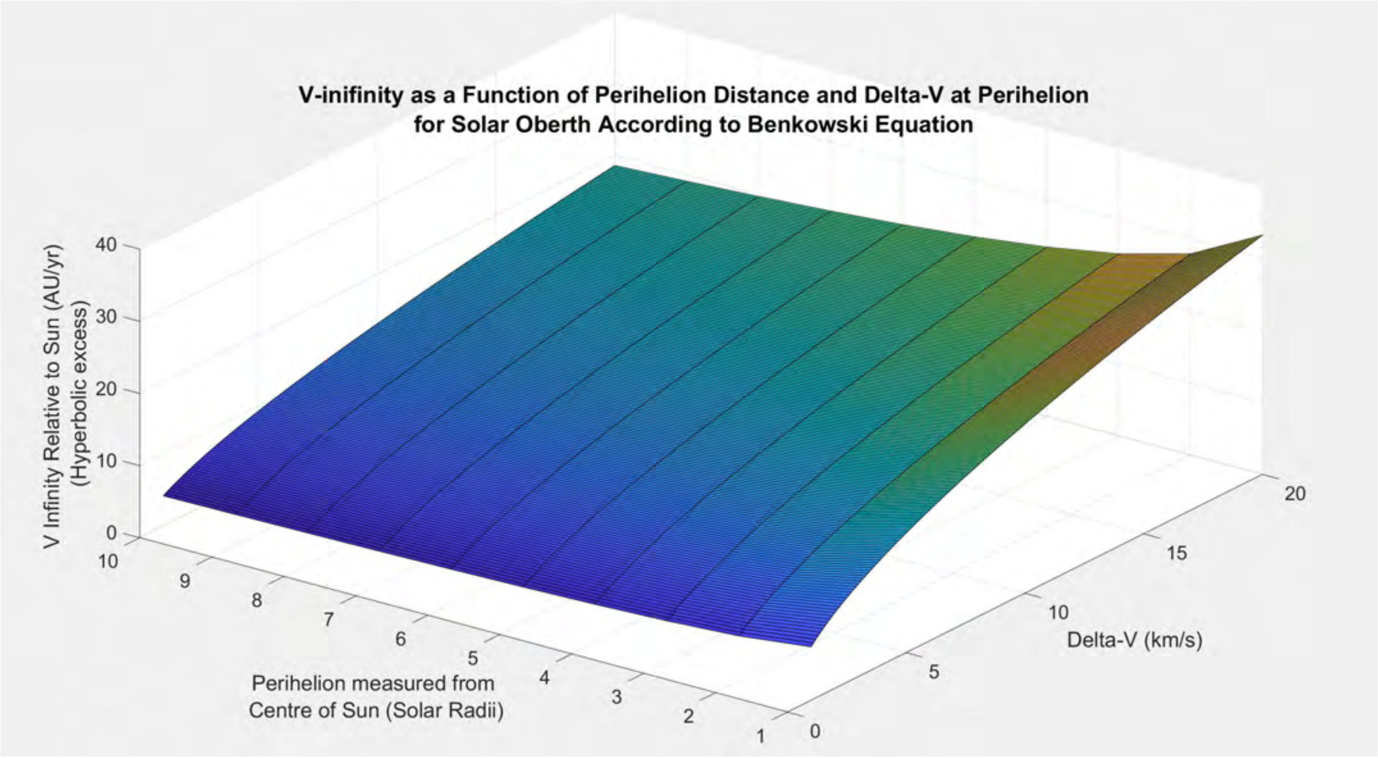
We thought that Principium readers would like to see some example results from the equation used by Dr Benkowski. Adam Hibberd is our i4is expert on this sort of calculation, see his piece on his calculations for the mission analyses for our Project Lyra team which have yielded mission plans to reach the interstellar comet, 2I/Borisov, and its more mysterious predecessor, 1I/Oumuamua.

Adam has run the equation through his mathematical mill with the following results -

r solar radii	1	2	3	4	5	6	7	8	9	10
DeltaV (km/s)										
1	7.41	6.23	5.63	5.24	4.96	4.74	4.56	4.41	4.28	4.17
2	10.49	8.82	7.97	7.41	7.01	6.70	6.45	6.23	6.05	5.90
3	12.84	10.80	9.76	9.08	8.59	8.21	7.89	7.64	7.41	7.22
4	14.83	12.47	11.27	10.49	9.92	9.47	9.12	8.82	8.56	8.34
5	16.58	13.94	12.60	11.72	11.09	10.59	10.19	9.86	9.57	9.32
6	18.16	15.27	13.80	12.84	12.14	11.60	11.17	10.80	10.49	10.21
7	19.62	16.50	14.91	13.87	13.12	12.53	12.06	11.66	11.33	11.03
8	20.97	17.63	15.93	14.83	14.02	13.40	12.89	12.47	12.11	11.79
9	22.24	18.70	16.90	15.73	14.87	14.21	13.67	13.23	12.84	12.51
10	23.45	19.72	17.81	16.58	15.68	14.98	14.41	13.94	13.54	13.18
11	24.59	20.68	18.68	17.39	16.44	15.71	15.12	14.62	14.20	13.83
12	25.68	21.60	19.52	18.16	17.18	16.41	15.79	15.27	14.83	14.44
13	26.73	22.48	20.31	18.90	17.88	17.08	16.43	15.90	15.43	15.03
14	27.74	23.33	21.08	19.62	18.55	17.73	17.06	16.50	16.02	15.60
15	28.72	24.15	21.82	20.30	19.20	18.35	17.65	17.07	16.58	16.15
16	29.66	24.94	22.53	20.97	19.83	18.95	18.23	17.63	17.12	16.68
17	30.57	25.71	23.23	21.62	20.44	19.53	18.79	18.18	17.65	17.19
18	31.46	26.45	23.90	22.24	21.04	20.10	19.34	18.70	18.16	17.69
19	32.32	27.18	24.56	22.85	21.61	20.65	19.87	19.22	18.66	18.17
20	33.16	27.88	25.19	23.45	22.17	21.19	20.38	19.72	19.14	18.65

The spreadsheet cell calculation is - =7.4142*(POWER($C6,0.5)/POWER(D$2,0.25)) - where the $C6 column holds the deltaV values for the rocket and the D$2 row holds the perihelion values.

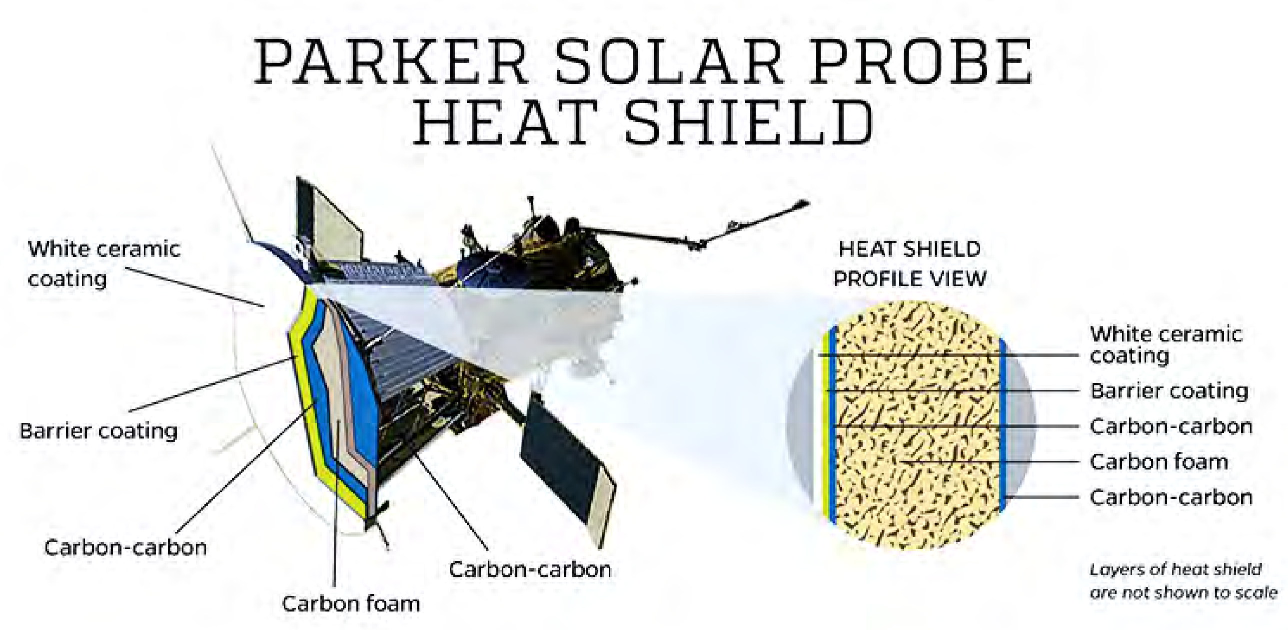
His Matlab tools also produced a 3D graph -



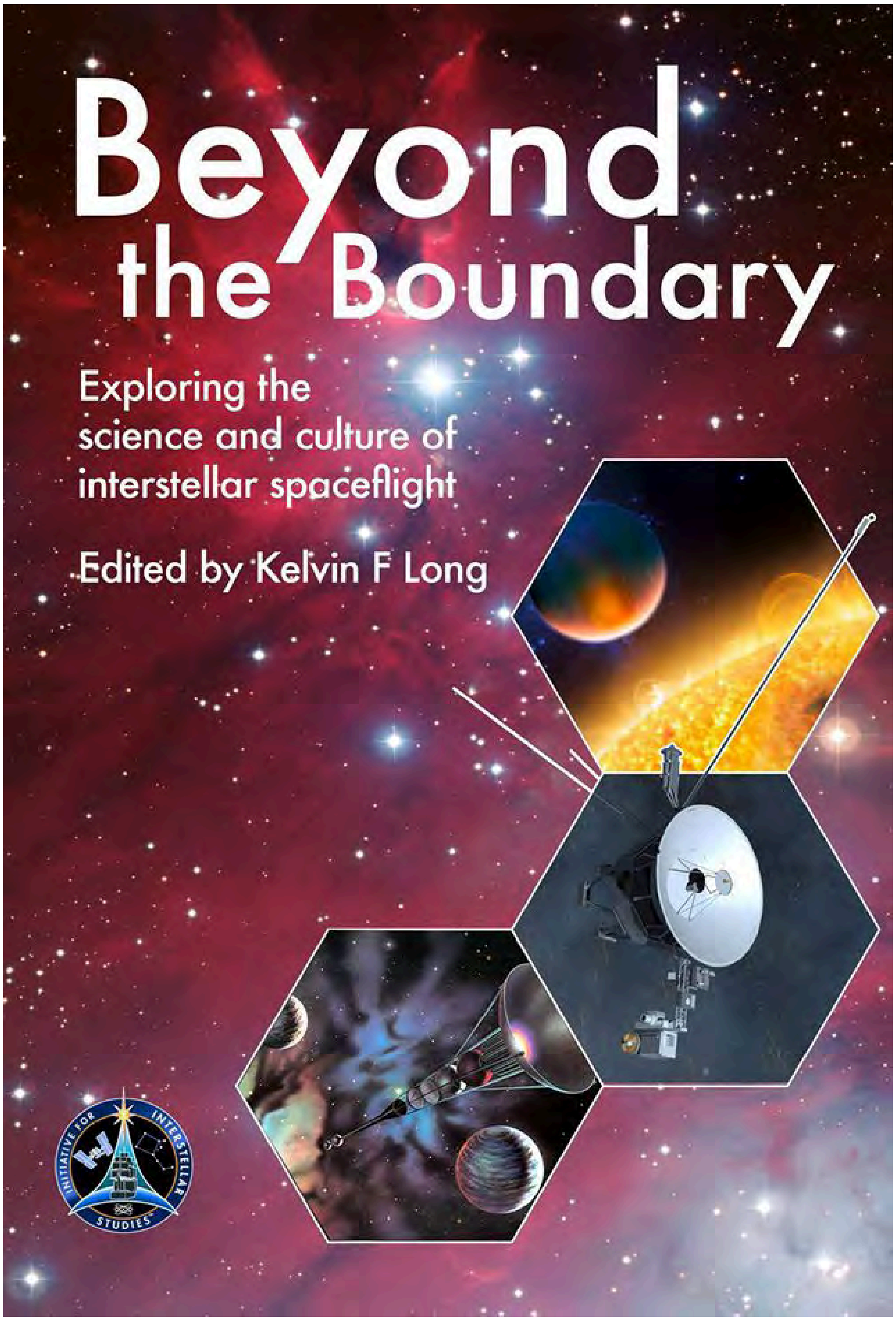
Dr Benkowski's paper quotes an example "To achieve a 20 AU/yr escape velocity from a 4 R s perihelion, a large ΔV of 14.6 km/s is required". This agrees with what appears in the table - in the 4 solar radii column and the 15 km/s row see a Vescape of 20.3 AU/year.

The next issue of Principium, P27, will include Adam's derivation of Dr Benkowski's equation.

The heat shield demands on an Oberth-accelerated probe are likely to be even more demanding than those on the Parker Solar Probe, currently spiralling towards the Sun (www.nasa.gov/content/goddard/parker-solar-probe).



Credit Greg Stanley-JHU-earthsky.org



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NEXT ISSUE

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Tennessee Valley Interstellar Workshop 2019
A memoriam of Chris Corner
What do we really know about the Outer Solar System?
News Feature - the i4is Education Team

Cover Images

Our front cover is "Urbium" - a new piece produced for Initiative for Interstellar Studies by our old friend Alex Storer of The Light Dreams. Alex dreamed this up partly as an homage to the Cities in Flight series of novels by James Blish. He exhibited the original at Novacon, a very long established UK SF convention. Read his report at https://thelightdreams.wordpress.com/category/news/.

Our back cover celebrates the passage of the second Voyager spacecraft out of the heliosphere and looks forward to probes venturing to that same region and beyond, as reported in the first part of our report from IAC 2019 in Washington DC in this issue.

It is from https://photojournal.jpl.nasa.gov/catalog/PIA17049.

Original Caption Released with Image: *This artist's concept shows NASA's Voyager spacecraft against a backdrop of stars. The Voyager spacecraft were built and continue to be operated by NASA's Jet Propulsion Laboratory, in Pasadena, Calif. Caltech manages JPL for NASA. The Voyager missions are a part of NASA's Heliophysics System Observatory, sponsored by the Heliophysics Division of the Science Mission Directorate at NASA Headquarters in Washington.*

For more information about Voyager, visit http://www.nasa.gov/voyager and http://voyager.jpl.nasa.gov.

Image Credit: NASA/JPL-Caltech Image Addition Date: 2013-09-12

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.

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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.

Front cover: Urbium
Credit: Alex Storer
Back cover:Voyager spacecraft artist's concept.
Credit: NASA/JPL-Caltech

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