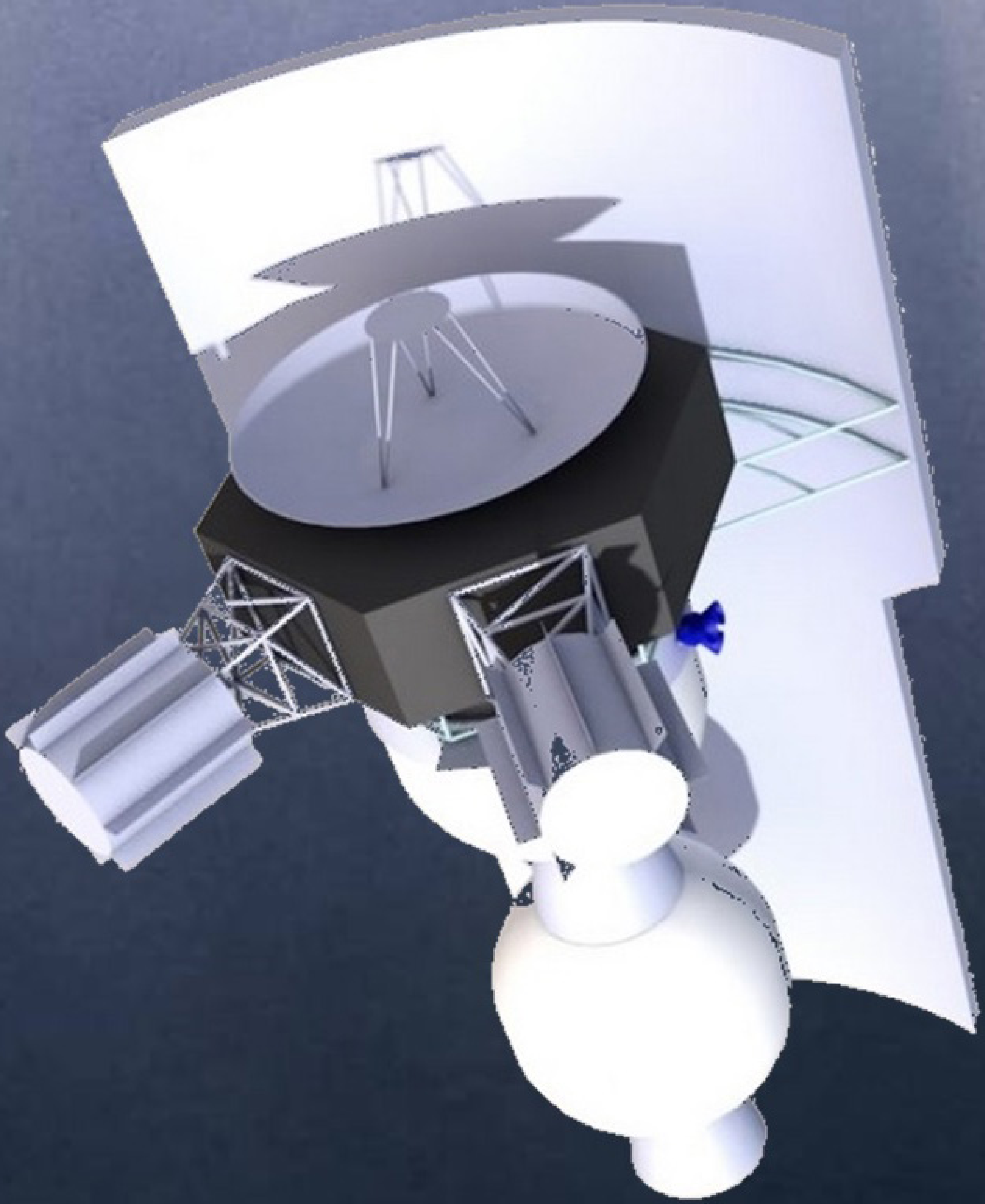
PRINCIPIUM

The Initiative and Institute for Interstellar Studies | Issue 37 | May 2022

SCIENTIA AD SIDERA | KNOWLEDGE TO THE STARS



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EDITORIAL

Welcome to issue 37 of Principium, the quarterly magazine of i4is, the Initiative and Institute for Interstellar Studies. Our lead feature this time is a review of *The Alien Communication Handbook* - Brian S McConnell - by Principium Deputy Editor Patrick Mahon - preceded by a "Stop Press" about a second running of our course *Human Exploration of the Far Solar System and on to the Stars.*

We have 9 pages of Interstellar News and our regular summaries of relevant peer-reviewed papers in *The Journals* (*JBIS* and *Acta Astronautica*).

The front cover image this time is *Project Lyra probe and the Pale Blue Dot*. The rear cover image illustrates the conclusion that the Milky Way's warp was caused by a galactic collision. More about both in *Cover Images* inside the rear cover.

We have a general interest in access to space and, most recently in the potential barrier around Earth resulting from proliferating space debris. In this issue our contributing editor, Samar AbdelFattah, reports on papers addressing this problem at the Intentional Astronautical Congress, IAC21.

Another long standing theme, reaching out to the rising generations we must interest in our interstellar objectives, is addressed in *Two Equations to the Stars*. In Part One we show how the Tsiolkovsky rocket equation can be made understandable to school students who have yet to study either the integral calculus in mathematics or the concept of momentum. We aim to give teachers the tools to achieve this by explaining both a simple numerical solution and a parallel derivation to justify the analytical approach possible in later education.

Another vital component of access to space is the legal framework to support resource utilisation and in this issue we have *Finding new ways to share resources in space* in which Max Daniels looks at how the idea of a *de jure* common-pool resource might be applied to materials in space.

As always we have the i4is members' page and another regular feature, *Become an i4is member*.

The next issue, in August 2022, will include -

• A report on the summer 2021 course *Human Exploration of the Far Solar System and on to the Stars*, delivered by i4is for the Limitless Systems Institute (LSI) - postponed from this issue. The 2022 course is announced in *The Second Interstellar Studies Summer Course* in this issue.

• The concluding part of *Two Equations to the Stars, Part Two: The Photon Sail Equation*.

• 72nd International Astronautical Congress 2021 - The Interstellar Papers

• Book Review: *Life in the Cosmos* (Minasvi Lingam & Abraham Loeb), by i4is Technical Director, Andreas Hein [1] also postponed from this issue.

- more in *Next Issue* at the end of this one.

If you have any comments on Principium, i4is or interstellar topics more generally, we'd love to hear from you. Write us an interesting - or challenging - letter and we'll publish!

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

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

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Please print and display our posters - one on page 33 and all our poster variants are available at i4is.org/i4is-membership-posters-and-video

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

[1] Associate Professor of Space Systems Engineering at SPASYS, Université du Luxembourg.

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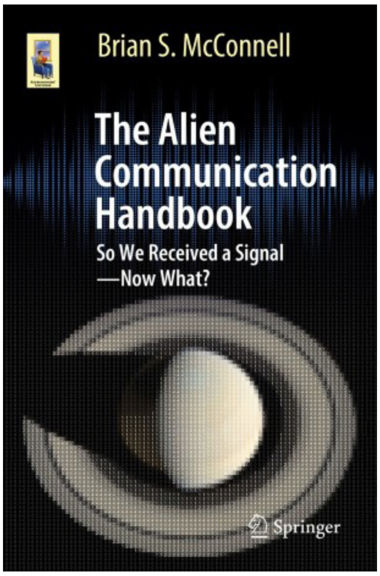

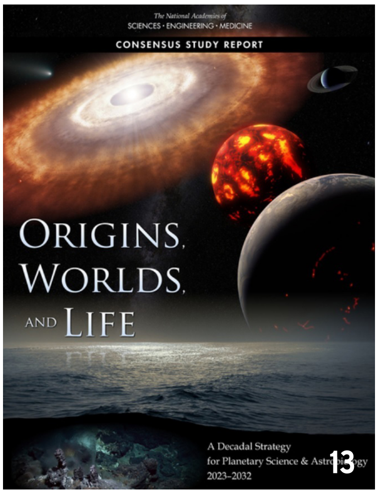

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REGULARS

The Second Interstellar Studies Summer Course

Human Exploration of the Far Solar System and on to the Stars

July 25th- 29th 2022

Rob Swinney

In 2021 the Houston-based Limitless Space Institute (LSI) commissioned the Initiative for Interstellar Studies to create a new course to educate and inspire the next generation to explore and travel beyond our solar system. New material was developed along with that previously delivered to the International Space University and on i4is' own 'Starship Engineer' courses. Following the success of the inaugural first course in the summer of 2021 the second course is being planned right now to take place July 25th-29th online.

The course provides a fundamental appreciation and basic knowledge of principal subjects, from setting the background and context through to advanced propulsion, systems, concepts, and designs. The course is predominantly (but not exclusively) a STEM-based course and targets the level of freshman/first year STEM university students. Attendees would benefit from a suitable background although the material will be useful even to the more experienced wishing to understand the principles. Whomever they may be, they will have a particular interest in the most ambitious opportunities for human exploration of space.

If you would like to know more, you should register your interest with Rob Swinney of i4is at info@i4is.org.

Poster for the First Interstellar Studies Summer Course

Credit: LSI / i4is

Videos of the First Interstellar Studies Summer Course are available via the i4is members page - **i4is.org/members/**

A video of the first presentation of the First Interstellar Studies Summer Course is open to all at - **i4is.org/videos/lsi-course-2021/**

BOOK REVIEW: The Alien Communication Handbook

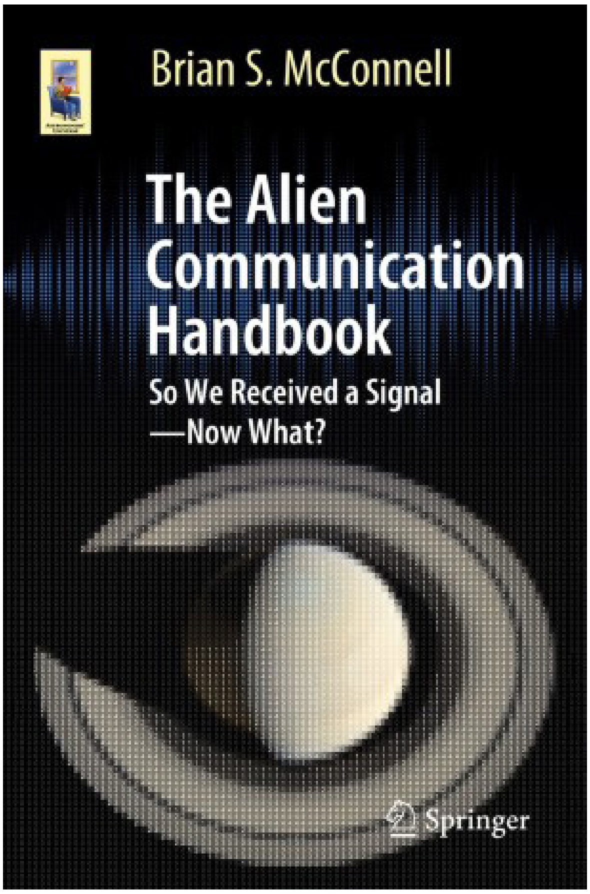
So We Received a Signal – Now What?

Patrick J Mahon

Most books about communications with extraterrestrial intelligences (CETI), the thing we might do after SETI has succeeded, are written from a scientific or linguistic point of view so when we spotted Brian McConnell's book [1], written by a communication systems engineer, we thought it deserved a review. Here Principium Deputy Editor Patrick Mahon gives us his thoughts.

If you are interested in the Search for Extra-Terrestrial Intelligence (SETI), you will probably be familiar with books that focus on the mechanics of search strategies, covering such issues as the pros and cons of radio versus optical SETI, the choice of wavelengths to search (eg the 21-centimetre line emitted from neutral hydrogen atoms), how to distinguish artificial signals from natural phenomena, and so on. Although these topics are briefly covered here, The Alien Communication Handbook [1] spends most of its time in rather different territory.

Author Brian S McConnell is an American computer engineer who has been writing about SETI for over two decades. He has discussed the issues I've just mentioned in earlier works. In this new book, as its subtitle makes clear, he poses an interesting thought experiment: if we were to receive a SETI signal that appeared to be genuine, what should our next steps be?



[1] The Alien Communication Handbook: So We Received a Signal – Now What?, by Brian S McConnell (Springer, October 2021) link.springer.com/book/10.1007/978-3-030-74845-6

This book has been published as part of Springer's "Astronomers' Universe" series of popular science books aimed at those who want to go beyond basic explanations of astronomical phenomena to gain a greater level of understanding and insight. From the very first pages, McConnell stresses the role citizen scientists will have in decoding a confirmed SETI signal. So this book is not just for armchair enthusiasts. If you'd like to get actively involved in SETI, it's full of information that will enable you to do just that, should the fateful day arrive when we find out 'we are not alone'.

The volume comprises nineteen chapters. Although not explicitly structured into different sections, the author's preface explains that they fall into five distinct parts:

• Part 1 (chapters 1 to 3) covers the basics of what SETI is looking for, what it might find and what we have learned about decoding non-human communications by studying how some other animals here on Earth share information with each other.

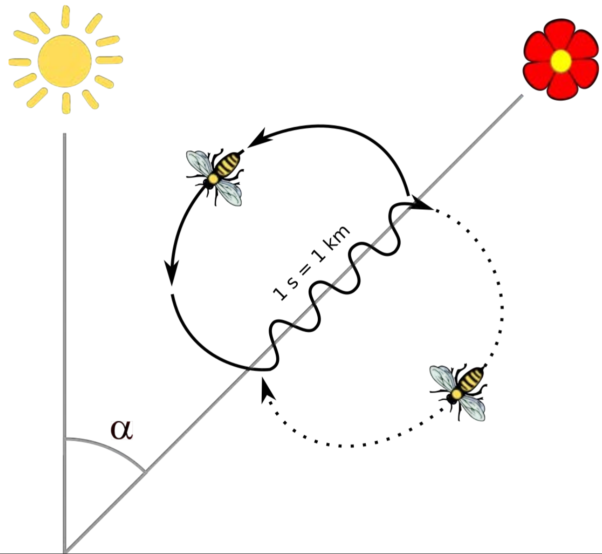
• Part 2 (chapters 4 to 7) discusses the early phases of work that would take place after a genuine alien signal was confirmed, covering a likely timeline of events, and the various ways in which useful information might be encoded into the signal.

• Part 3 (chapters 8 to 13) explores the various types of concrete information content that may be contained in a SETI signal and the ways that we might be able to differentiate between and decode them.

• Part 4 (chapters 14 to 17) considers how more abstract concepts might be encoded in a message in such a way that we might be able to build an understanding of these potentially very alien ideas over time.

• Part 5 (chapters 18 and 19) finishes things off by looking at the range of people and skills that will be needed to maximise the chances of success, and the sorts of information and knowledge that we could potentially gain from decoding the first SETI signal.

For me, the most fascinating material in Part 1 is found in chapter 3, which explores what SETI researchers can learn from academic studies of the ways in which animals communicate with others of their species. This chapter illustrates what McConnell does best, taking a complex subject, splitting it into bite-sized chunks and explaining each one clearly and simply. After summarising seven traits that any genuine language needs to contain, he explains how languages are typically structured and how that can aid the initial analysis of a new language. He then shows how such an analysis can be applied to the communications of several types of animals, from ants and bees through to prairie dogs (which have been extensively studied), dolphins and primates. Moving beyond animal research, McConnell then considers how a communications systems expert like himself might take a signal processing approach to the partial decoding of a new language of this kind. The chapter finishes with a discussion of how a similar approach might be of use in SETI and of the various ways in which this analogy between animal communication studies and SETI breaks down.



Bee waggle dance as cited by McConnell

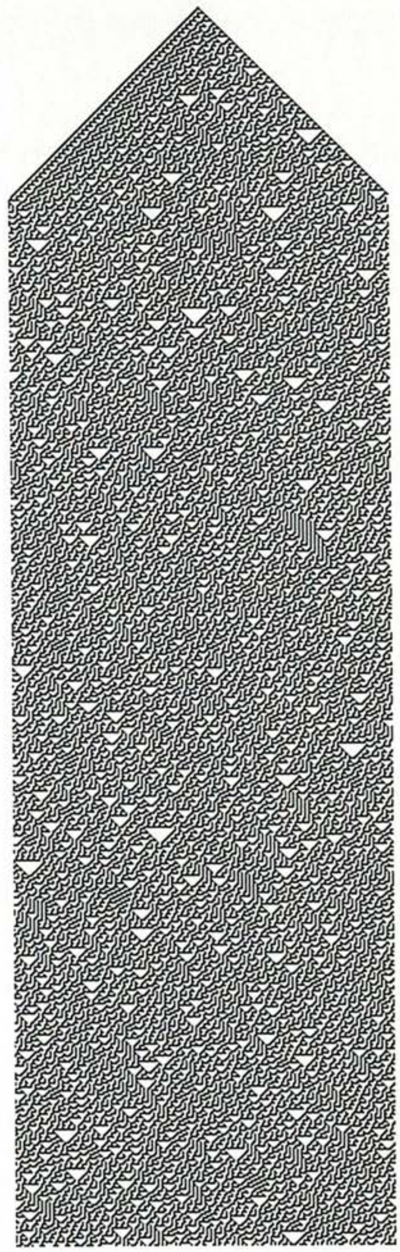
The bee waggles down a straight line pointing to the source it has found with the direction of the sun as reference and the duration of waggling indicating distance.

Credit: Emmanuel Boutet via Wikipedia
commons.wikimedia.org/wiki/File:Bee_dance.svg

Much of Part 2 will be familiar to SETI enthusiasts, covering as it does the numerous ways in which an electromagnetic signal can be modulated to carry information, and how error correction can be incorporated into the message to ensure that it can be accurately decoded at the other end, even if degraded on the way. The content that was new to me concerned the potential for SETI messages to be contained in 'inscribed matter' – that is, matter that has been altered in some way to encode information, with a CD and a DVD being two earthbound examples – rather than beamed through space via electromagnetic radiation. I was intrigued to learn that inscribed matter may in some cases be the better option, due to the extremely high density of information that can be encoded in this way.

Part 3 is the longest section of the book, covering six chapters and around one-third of the page count. This is where McConnell's expertise comes to the fore, as he explores how to decode an alien signal by looking for the data patterns that are typical of the different types of information content that an intelligent alien species might wish to share with others. His central contention here – and I imagine it may be contested by some in the SETI community – is that no matter how different the aliens who sent the signal may be, we can expect them to want to share some types of information we'll recognise, such as static and moving imagery. His basic argument is that if aliens send a signal through space at all, they will need to understand astronomy, electromagnetic radiation and some analogue of taking and sharing images. He explores the implications comprehensively, giving a clear idea of how such data might be encoded in, and decoded from, an alien signal.

An interesting departure from this discussion comprises a long chapter on the possibilities of aliens encoding algorithms or computer programmes of various kinds in their signals, since these might enable some limited level of real-time interaction between the recipients (us) and the signal, partially getting round the one-way nature of most electromagnetic communications over distances of light years. Such programmes could potentially be as simple as a Tic-Tac-Toe game (that's Noughts and Crosses to those of us in the UK), or as complex as a generalised artificial intelligence. Both would teach us something profound about the type of being that had programmed it.



Encoding of algorithms or computer programmes - McConnell's example above - and his explanation -

"Knowledge about digital computing is a de facto requirement for success in establishing a communications link, so it's not unreasonable to assume that the sender will know about computing and may incorporate algorithms into a transmission.

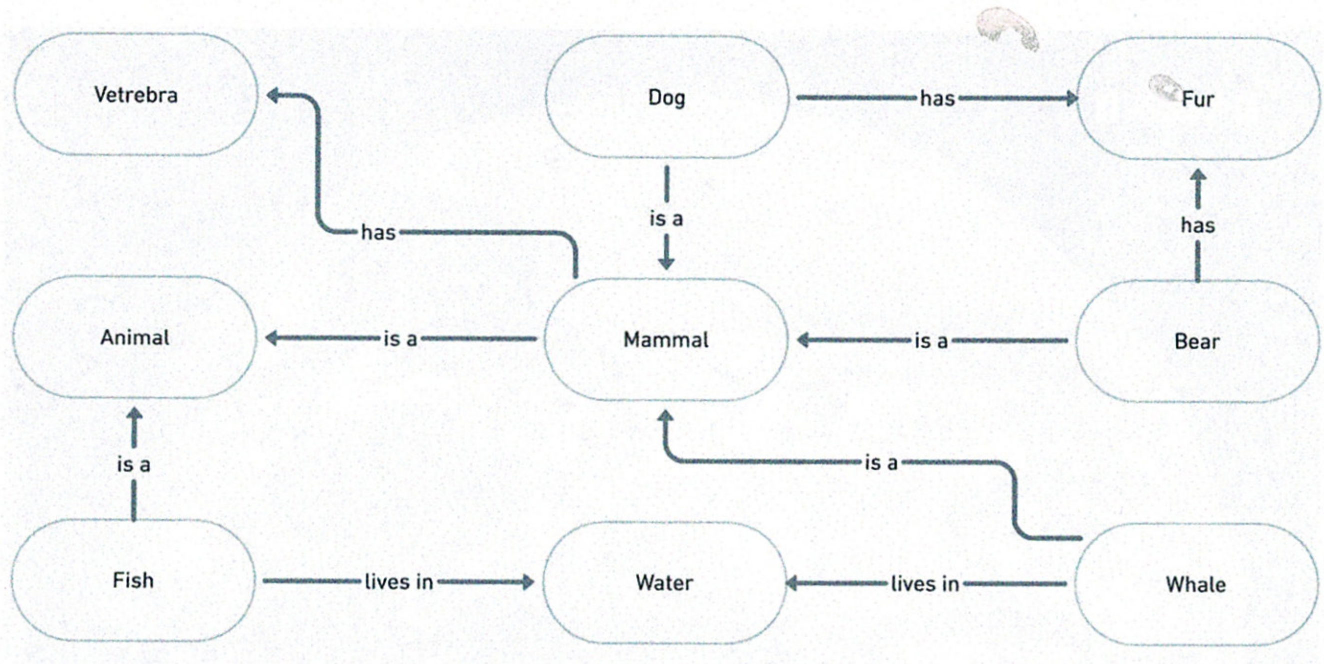
Algorithms, the procedures implemented in computer programs, are useful because they can implement arbitrarily complex instructions and math operations using a small and simple set of basic math and logic symbols. A program could represent something as simple as a tic-tac-toe game or something as complex as a climate model or machine learning system. The limits of communication are only constrained by the imagination of the sender.

The data banner in this chapter [above] displays the output of a rule 30 cellular automaton, a simple algorithm that produces results that appear both orderly and chaotic.

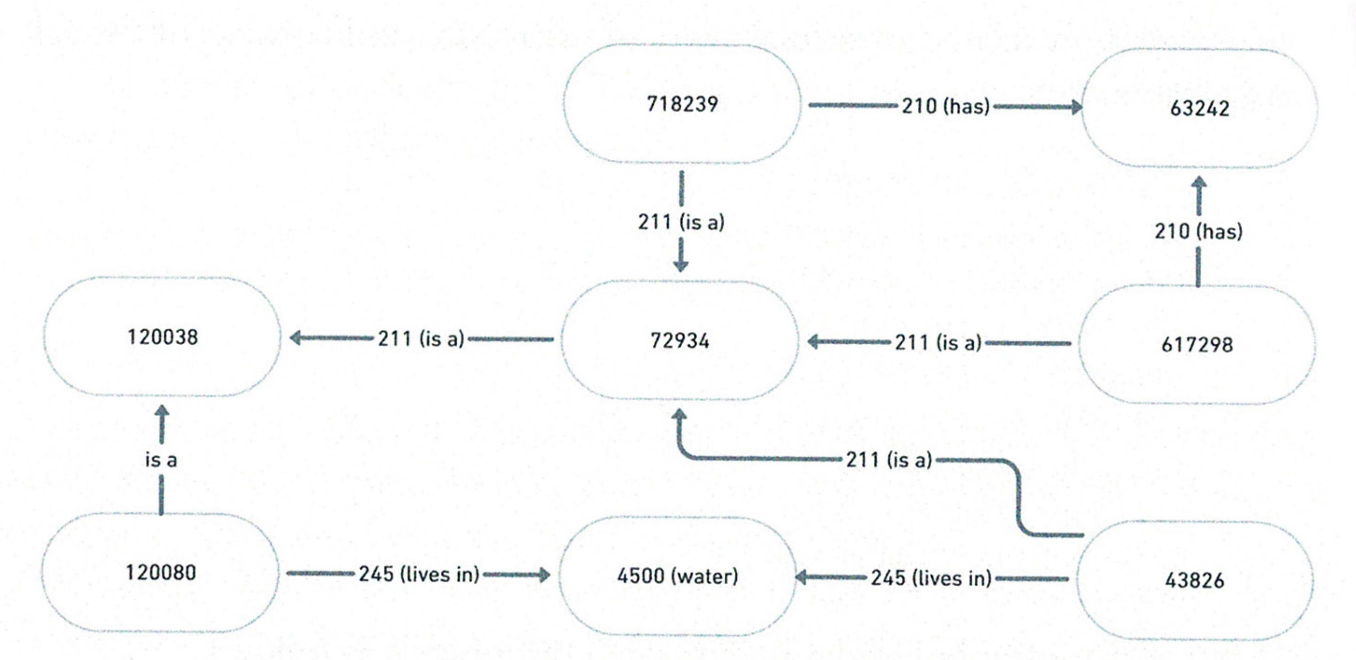
An algorithmic communication system is attractive because the amount of information that can be transmitted across an interstellar link is finite and possibly quite small relative to the amount of information the sender might want to share. If the sender can compress data using an algorithm and includes an algorithm that can be used to decompress it on the receiving end, the sender can increase the effective carrying capacity of the link manyfold."

Credit(image and caption); McConnell

In Part 4, the author considers whether and how it may be possible for aliens to encode more complex data and information into a signal. He starts with fundamental units of measurement of time, distance, mass, and so on, before moving on to the more complex question of how to communicate abstract ideas and concepts, through the development of a semantic network. Such a network links related ideas together, potentially allowing the recipient to move from descriptors of concrete objects to those for more abstract ideas.



McConnell: Fig. 15.1 An English representation of a small semantic network that describes the relationships between several types of animals.
Credit (image and caption): Brian McConnell



McConnell: Fig. 18.2 A diagram of a partially understood semantic network. Notice that even though only a few of the concepts are mapped to human language terms, we can still understand how the concepts are connected to each other.
Credit (image and caption): Brian McConnell

The following chapter discusses why a message might include information on the alien genome. Were this included – and decoded – it could help answer some profound questions, including how life started and whether it is possible for intelligent life to evolve with different genetic coding systems. This section concludes with a short chapter which considers whether the discovery of one alien species might lead us to find others, and the extent to which these aliens might communicate with each other via a galactic network of some kind.

The book concludes in Part 5 with two short chapters. The first identifies the different skills sets that could prove useful to the worldwide effort to decode an alien message, reinforcing the idea that citizen scientists and amateurs of many kinds could have a valuable role to play in this endeavour. The final chapter considers the central question, 'What could we learn from another civilisation?', exploring just a few of the categories of information that might expand our knowledge of the universe around us, and even of ourselves.

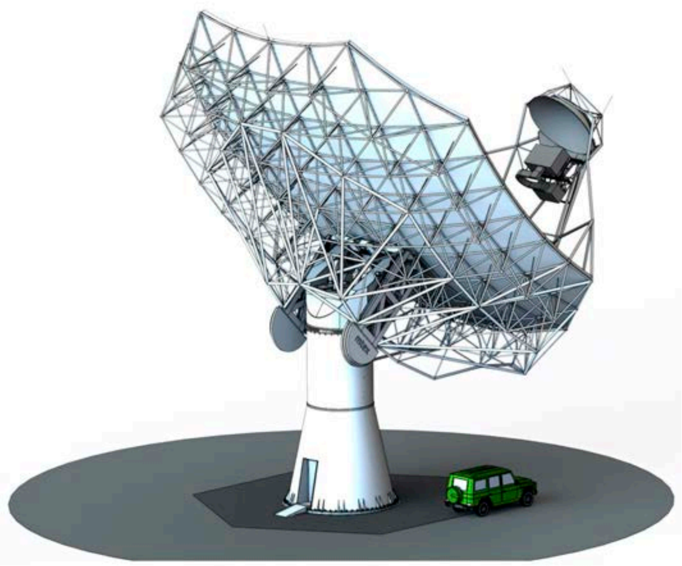
While this volume is, in my view, an excellent read, I do have a few minor criticisms to make. It seems odd that the five-part structure the author describes in the preface was not instituted in reality, as this would have split the material up logically and made it easier for the reader to navigate the book. Instead, we have nineteen chapters that follow one after the other, but they are somewhat uneven in both length and complexity. The longest chapter is 46 pages, while the shortest is just three. And whereas some – presumably those on subjects with which the author is most familiar – go into great detail, others rather skate over the topic, providing only the most basic information. In addition, the layout is not always as user-friendly as it might be, with the text sometimes referring to an important explanatory image that does not turn up until some pages later, while at other times the link between the text and a related image is not made clear.

The next-generation Very Large Array (ngVLA)
One of the 244 mtex antennas, each measuring 18 m in diameter, of the Main and Long Baseline Array of the ngVLA.
"The unprecedented capabilities of next generation radio telescopes, including ngVLA, will allow us to probe hitherto unexplored regions of parameter space, thereby placing meaningful limits on the prevalence of technological civilizations in the Universe (or, if we are fortunate, making one of the most significant discoveries in the history of science)." *Science with an ngVLA: SETI Searches for Evidence of Intelligent Life in the Galaxy*, Croft et al, 2018 arxiv.org/abs/1810.06568

Image credit: National Radio Astronomy Observatory (NRAO)

My final criticism is of the author's mindset, rather than the book itself, and is one I would make of many SETI advocates. There seems little place in McConnell's worldview for the idea that there could be any dangers to be found in an alien message. For example, despite dedicating a long chapter to the potential communication of algorithms of varied complexity, the author assumes throughout that these algorithms will be harmless, and suggests that decoding them will be one of the activities open to anyone. Given the near ubiquity of computer viruses here on Earth, I would have expected a few lines at least to be dedicated to a discussion of the need for some basic precautions, just in case any alien algorithms, whether deliberately or accidentally, had the potential to infect and cause damage to the IT equipment of those investigating them. As an occasional writer of science fiction, I found the inspiration for several short story ideas in this chapter – but in none of them did humanity come out well.

Criticisms aside, though, I applaud Brian McConnell for the efforts he has taken to explore this fascinating SETI thought experiment. His enthusiasm and natural prose style makes the book a remarkably easy read, given the complexity of the subject matter. He explains difficult ideas simply and clearly, and tackles a wide range of topics in a way that threads them all together as a coherent whole. Having read The Alien Communication Handbook, I am now desperate for a SETI signal to arrive during my lifetime, so that I can volunteer to take part in what could potentially become one of the great citizen science activities of our or any age. If the idea of getting involved in such a project excites you too, I'd encourage you to get hold of the book.

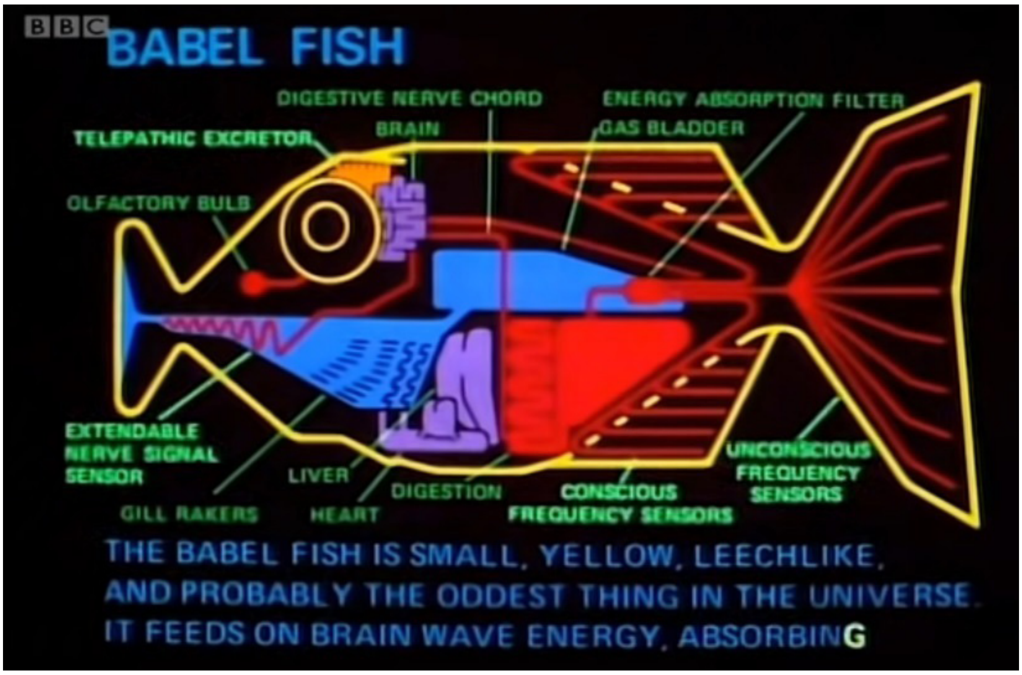


A couple of fictional examples of communication with ETIs - hostile and (mostly) harmless - neither cited by McConnell

Scene from A For Andromeda by Fred Hoyle.
Credit: BBC Television

Julie Christie as Andromeda and Peter Halliday as John Fleming with the computer in the background. The computer is constructed according to a message received from an ETI. The computer kills its operator, Christine, and creates Andromeda as its agent.
Note the flashing lights - those were the days! Cited in *Book Review: Extraterrestrial Languages* Daniel Oberhaus (P31 November 2020)

The Babel fish - as conceived by the late Douglas Adams.
Credit (image and quote): Douglas Adams / BBC



"The Babel fish is small, yellow, leech-like, and probably the oddest thing in the Universe. It feeds on brainwave energy received not from its own carrier, but from those around it. It absorbs all unconscious mental frequencies from this brainwave energy to nourish itself with. It then excretes into the mind of its carrier a telepathic matrix formed by combining the conscious thought frequencies with nerve signals picked up from the speech centres of the brain which has supplied them. The practical upshot of all this is that if you stick a Babel fish in your ear you can instantly understand anything said to you in any form of language.

...

Meanwhile the poor Babel fish by effectively removing all barriers to communications between different cultures and races has caused more and bloodier wars than anything else in the history of creation"

John I Davies reports on recent developments in interstellar studies

IAC 2022

We have a News Feature on this year's International Astronautical Congress, IAC 2022, elsewhere in this issue. We will have a full list of interstellar related items in our August issue, P38.

Here we note a couple of presentations by colleagues and friends of i4is which we can already mention -

Advanced Electric Propulsion Concepts for Fast Missions to the Outer Solar System and Beyond, Angelo Genovese, Initiative for Interstellar Studies

Wednesday 21 September 10:15

iafastro.directory/iac/browse/IAC-22/D4/4/

-and-

The Lunar Module Simulator: An Instructor's Account, Dr Albert Jackson, Triton Systems LLC

Wednesday 21 September 11:03

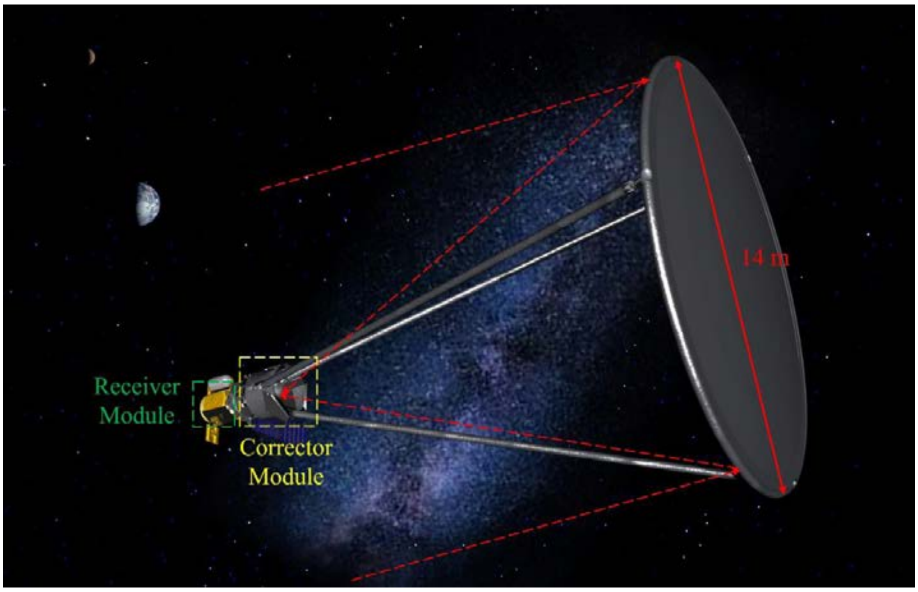
iafastro.directory/iac/paper/id/68471/summary/

We will be reporting in our November 2022 (P39) and February 2023 (P40) issues. We hope to see many i4is members, Principium subscribers and the workers and enthusiasts for the interstellar vision at this, the big space event of the year. ■

Inflatable infrared telescope to detect water

Engineers and scientists from University of Arizona, L'Garde Inc and Northrop Grumman have proposed an inflatable infrared telescope to detect water. In *Orbiting Astronomical Satellite for Investigating Stellar Systems (OASIS)* this instrument would perform high spectral resolution observations of water at terahertz frequencies [1]. A 14 metre inflatable primary reflector will have an inflatable metallised polymer membrane as the reflecting surface. It is designed to capture a wide range of infrared wavelengths from 63 μm in the mid-infrared (just beyond the range of the James Webb Space Telescope, 0.6 to 28.3 μm) to 660 μm in the very high infrared. 660 μm wavelength is 450 GHz frequency, which is not far beyond the highest radar frequencies [2].

The paper offers a systematic process to optimise the optical design and performance of space telescopes employing inflatable primary reflectors of various sizes. "Life as we know it" (as Mr Spock put it) seems to require water so detection of it is a necessary condition for such life. It is not a sufficient condition on its own but such a substantial instrument would be very attractive in terms of launch costs if inflatable mirror technology can be perfected - and this technical challenge is the main point of the paper. ■



OASIS mission concept showing the corrector and receiver modules (left side of the figure) and the fully deployed 14 m diameter primary reflective antenna A1 (right side of the figure), which is an inflatable membrane optic.
Credit (image and caption): Siddhartha Sirsi et al

[1] *Optical Design of the Orbiting Astronomical Satellite for Investigating Stellar Systems (OASIS)*, Siddhartha Sirsi et al, arxiv.org/abs/2203.05633.

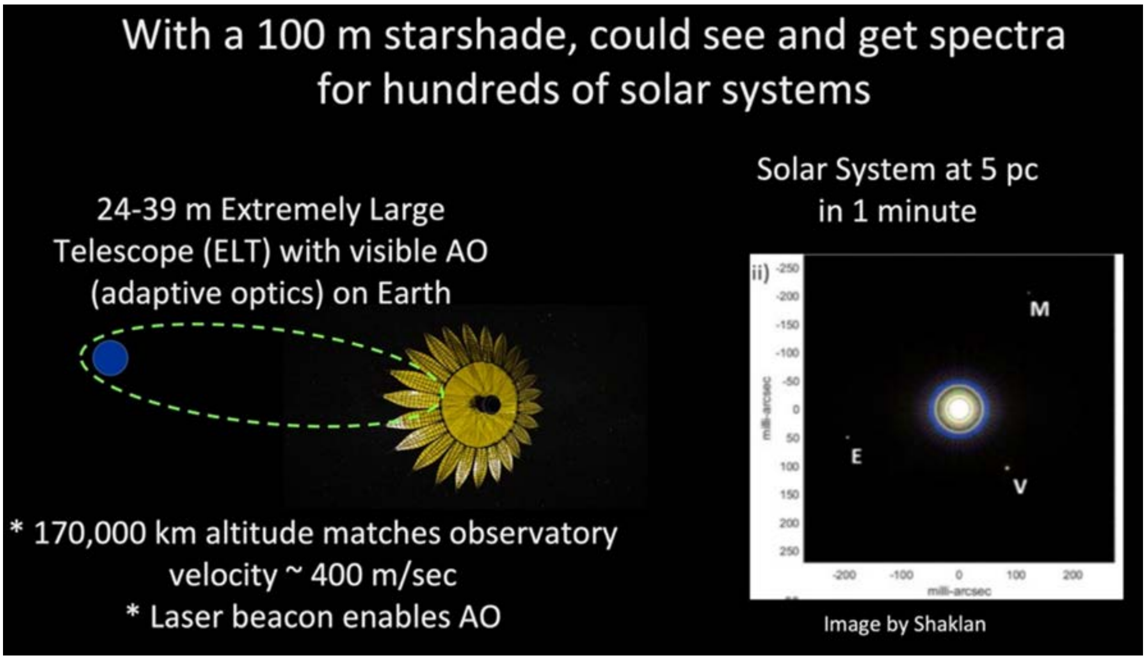
[2] Electromagnetic spectrum en.wikipedia.org/wiki/Electromagnetic_spectrum.

Engineering the Oberth Manoeuvre

Our Centaurian colleague Paul Gilster has a feature on implementing the idea of Herman Oberth (1894-1989) [1], of the Verein für Raumschiffahrt (Society for Spaceflight), back in 1927 in Wege zur Raumschiffahrt (Ways to Spaceflight).
The piece is based on work by Jason Benkoski and colleagues (Johns Hopkins Applied Physics Laboratory) of a combined heat shield and solar propulsion system. They used the test setup for the heat shield of the Parker Solar Probe, which was launched in 2018 and is designed to fly to 8.5 million km from the Sun.
The physics of flying close to the Sun and firing a rocket at closest approach, aphelion, shows that the most acceleration is achieved by delivering the maximum impulse as close to aphelion as possible and with the lowest aphelion achievable. Clearly the closer you are the Sun the hotter you get. But the heavier the heat shield you use the lower the available payload mass. Benkoski and the team "make a virtue of necessity" by letting the Sun provide the heat energy required to drive the rocket propellant while the propellant shields the payload by absorbing that energy.
Engineering is the application of ingenuity as the Latin root, ingenium implies. The JHU team thus exemplify their profession!
As Benkoski writes "The idea is to absorb all this heat with hydrogen, and shoot it out the back of the probe." [2] ■

A Starshade to help earth-based telescopes find exoplanets

In *Hybrid Observatory for Earth-like Exoplanets (HOEE)* John Mather of NASA Goddard Spaceflight Center (GSFC) proposes the first hybrid observatory, combining a 100m diameter starshade in space with a giant telescope on the ground (www.nasa.gov/directorates/spacetech/niac/2022/Hybrid_Observatory_for_Earth_like_Exoplanets/).
He tells us "The Hybrid Observatory for Earth-like Exoplanets (HOEE) would convert the largest ground-based telescopes now under construction (Giant Magellan Telescope, Thirty Meter Telescope, and Extremely Large Telescope) into the most powerful planet finders yet designed." These giants can deliver the best available resolution and contrast but are dazzled by the host star of the exoplanet. He notes the example of the sun, which is 10 billion times brighter than the Earth at visible wavelengths. He suggests "A starshade in an astro-stationary orbit would match position and velocity with the moving telescope, and cast a dark shadow of the star, without blocking the light of its planets. Active propulsion would maintain alignment during the observation." ■



Graphic depiction of Hybrid Observatory for Earth-like Exoplanets (HOEE)
Credit: John Mather

[1] *Engineering the Oberth Maneuver*, www.centauri-dreams.org/2022/03/03/engineering-the-oberth-maneuver/ .
[2] *Going interstellar with a sun-skirting probe*. hub.jhu.edu/magazine/2021/spring/apl-interstellar-probe/

i4is in US National Academies Decadal Survey

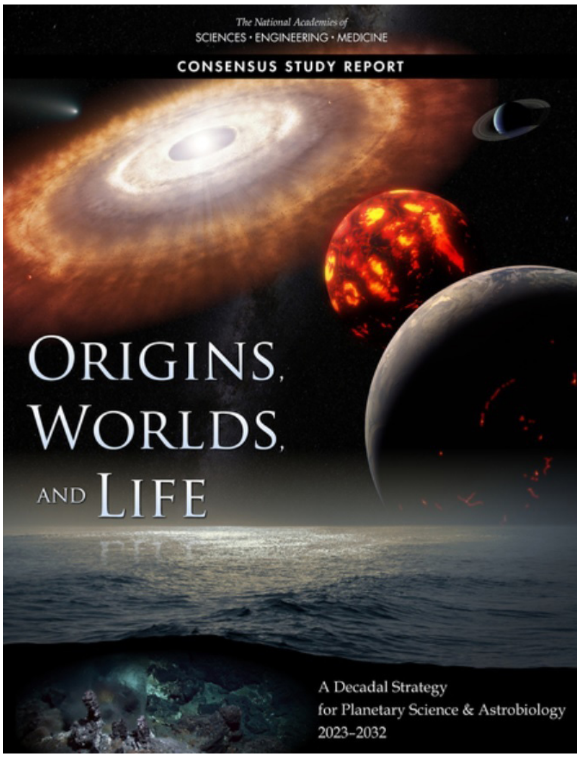
The Survey has been published as -
Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032 (nap.nationalacademies.org/catalog/26522/origins-worlds-and-life-a-decadal-strategy-for-planetary-science)
The most favoured projects are a Uranus orbiter (the least-visited of the planets) and the Mars sample-return but there is a mention for interstellar under the category - *Small Bodies* -

> The surprising discovery of two interstellar objects (ISOs) passing through the inner solar system, 1I/ 'Oumuamua and 2I/Borisov, raises the possibility of direct analysis of materials formed in the disks of other stars. 1I/ 'Oumuamua appeared asteroidal, in that it did not show cometary-like activity (Meech et al 2017), while 2I/Borisov exhibited evidence of a cometary color and tail (Guzik et al. 2020). Constraints on the mineralogy and elemental abundances of ISOs could provide insight into the composition of their parent disks. Improvements to Pan-STARRS1 and launch of the Vera Rubin Observatory will support detection of additional ISOs in coming years, and development of rapid launch capabilities could enable future spacecraft encounters with one of these extrasolar visitors.

- and mention of wider research into the interstellar medium (ISM).
It seems missions to ISOs might be a by-product of planetary defence -

> A critical next step is to develop a flexible implementation approach to quickly characterize threatening objects via reconnaissance missions in order to plan for mitigation if needed. Subsequent to NEO Surveyor, the next priority planetary defense mission is a rapid-response, flyby reconnaissance of an object representative of the most hazardous class of objects (~50 to 100 m diameter; see Planetary Defense chapter). A rapid response capability may also provide a template for responding to newly identified, high-value science targets such as interstellar objects or dynamically new comets.

However the selection panels rejected a "Interstellar Object Rapid Response Mission" (proposed by the Panel on Small Solar System Bodies) noting that the current structure of mission



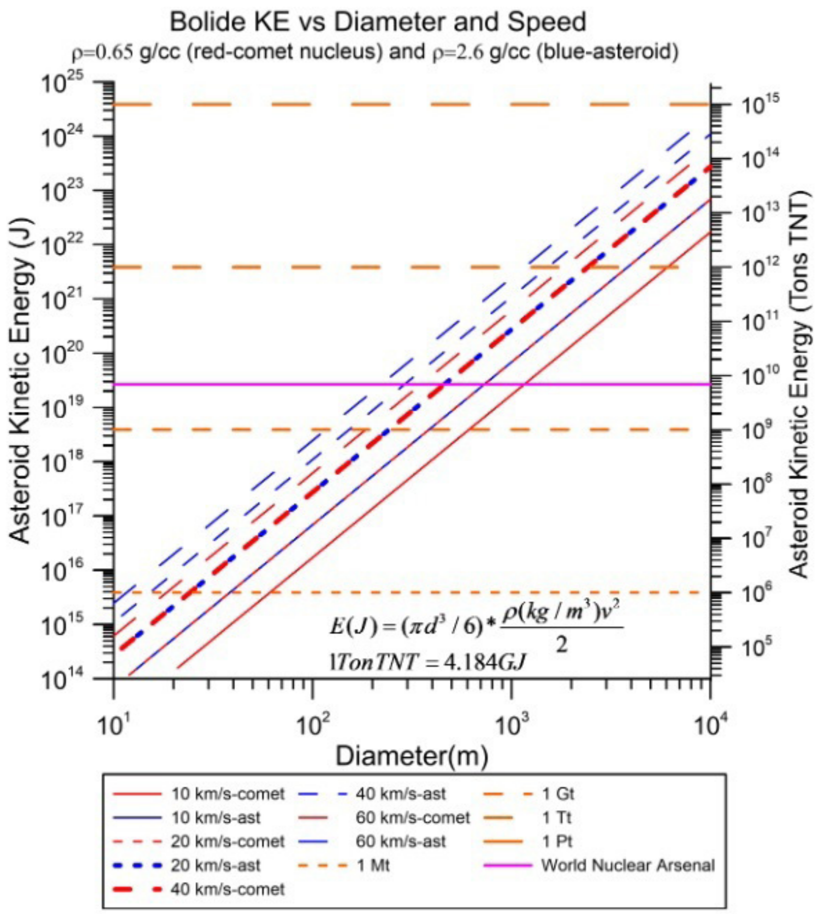
opportunities within NASA's Planetary Science Division does not lend itself to opportunistic, rapid response missions to newly identified targets of high scientific value - like 1I/'Oumuamua - including rapid launch capabilities to enable future spacecraft encounters.
Surprisingly there is no mention of ESA's Comet Interceptor, launching in 2029.
But notably two of the i4is Project Lyra team papers are cited -

- Eubanks, T, J Schneider, A M Hein, A Hibberd, and R Kennedy. 2020. *Exobodies in Our Back Yard: Science from Missions to Nearby Interstellar Objects*. Available at arxiv.org/abs/2007.12480
- Hein, A, T M Eubanks, A Hibberd, D Fries, J Schneider, M Lingam, R G Kennedy, et al. 2020. *Interstellar Now! Missions to and Sample Returns from Nearby Interstellar Objects*. Available at arxiv.org/abs/2008.07647 and published at Advances in Space Research, Volume 69, Issue 1, 1 January 2022, Pages 402-414 (www.sciencedirect.com/science/article/pii/S027311772100538X)

■

Don't Forget To Look Up

Professor Philip Lubin is a pioneer of interstellar studies, especially in the field of laser propulsion. With his UCSB colleague, Alexander N Cohen, he has now published a study looking at how existing and very near term technologies might mitigate or eliminate the extinction threat represented by a large comet or asteroid on a collision trajectory with Earth [1]. Such an object of order 10 km diameter hitting the Earth at a closing speed of 40 km/s for the comet and 20 km/s for the asteroid would have an impact energy of roughly 65 Teratons TNT, equivalent to the KT extinction event that made the large dinosaurs extinct about 66 million years ago. The scale of this (and lesser events) is well illustrated by their graph below.



Exo-atmospheric kinetic energy vs diameter and atmospheric entry speed for both typical comet and asteroid densities (0.65 and 2.6 g/cm^3, respectively). Relevant energy scales and total human nuclear arsenal shown for comparison. For diameters greater than 500 m, the bolide energy exceeds the world's nuclear arsenal. Humanity is good at building weapons, but nature is far better at it.

Credit (image and caption): Lubin and Cohen

While impacts equivalent to the KT event are very rare, roughly once per 100 million years, they argue that planetary defence should concentrate immediately on the much larger number of smaller but deadly threats, particularly those from about 20–500m in diameter. They suggest using an array of hypervelocity penetrators, either inert or using conventional explosives for these smaller objects - but being prepared to use the same technique with nuclear explosives for extinction level threats. Depending upon object size, a two-layer defence might be required with initial disintegration sufficient for most fragments to miss the Earth and with threatening fragments dealt with individually. For larger objects - larger than a few km in diameter, their own gravity must also be overcome while smaller objects are held together only by the mechanical strength of their material. They cite their earlier paper discussing this "Pulverize It" (PI) strategy [2] which makes the point that the shock waves from a fragmented object are spread out in both time and location and thus the total destructive effect is mitigated.

Lubin and Cohen consider a wide variety of scenarios and techniques but end with the ominous thought *Don't Forget to Look Down*, which recalls a thought that subterranean and sub-ocean refuges might be a last resort. These were suggested in the novel *Seveneves* by Neil Stephenson. Stephenson, who notably worked with Blue Origin for some time, also suggested a refuge for the eponymous seven Eves, who preserved the human species, based upon the International Space Station (ISS) [3]. Sadly the ISS is now recklessly under threat by the actions of the current Russian government. ■

[1] Don't Forget To Look Up, arxiv.org/abs/2201.10663

[2] PI – Terminal Planetary Defense, Philip Lubin, Jan 2022, arxiv.org/abs/2110.07559

[3] *The Orbits of Seveneves - A book review with a touch of orbital dynamics*, Sander Elvik, Principium 20 February 2018

Philosophy and Science of Space Exploration

Serife Tekin, Carmen Fies and Chris Packham (all University of Texas at San Antonio) propose a new interdisciplinary course, *Philosophy and Science of Space Exploration (PoSE)* [1]. They aim to "help overcome disciplinary silos to advance our understanding of space and critically examine its ethical ramifications, but also will better educate the public on how science works and help overcome the science scepticism that has unfortunately become more prominent in recent years".

They aim to "harvest space science enthusiasm and use it to generate an educated and critical engagement with progress in space science, while at the same time addressing and challenging growing distrust in science". They cite Descartes, Bertrand Russell and Karl Popper in support of the prevalence of a science-based world view. They aim to "take such historical and philosophical conversations a step further by referring to the recent advances in astronomy". Citing "inequities in science education" reported by the (US) National Science Foundation, they believe that their philosophy-based approach will overcome both scepticism and inequities. They will measure success by grasp of the content, development of critical thinking, change in students' interest in the subject matter and "will develop measures of the students' understanding of the tenets of ethics and of astronomy".

In their introduction the authors report that "growing distrust in science in the United States", exemplified by scepticism about Covid vaccines, contrasts with "growing enthusiasm for and excitement about astronomy and space exploration". In the latter they cite a paper from 2010, *The impact of astronomy*, by Andy Fabian [2]. I can find no such optimism in Professor Fabian's paper. He was President of the Royal Astronomical Society, 2008–2010 and, reporting on his presidency he was articulately pessimistic about the influence of science upon the UK public and government concluding "We have to have a survival strategy, because I really do think we are at an important time in UK astronomy." He reported that "Funding is shrinking" and that "Spreading the money to groups that are subcritical is not a good idea. We need, above all, to maintain intellectual leadership in our research." The premise of this proposal does not appear to be supported by Prof Fabian. My own country (UK) has, I believe, gone backward in its interest in, and respect for, science. Only four years after Prof Fabian's paper a senior government minister seriously suggested that "the British people have had enough of experts" and subsequent events have supported his view [3]. I do not believe that the USA is significantly less sceptical of science than the UK and other European countries. I wish Tekin et al well in their endeavour but I am not confident of their success. ■

Avoiding the Great Filter

In a recent paper *Avoiding the Great Filter: Predicting the Timeline for Humanity to Reach Kardashev Type I Civilization* (arxiv.org/abs/2204.07070), a team from the NASA/Caltech Jet Propulsion Laboratory, Beijing Normal University, Jagiellonian University (Kraków), two high schools in USA & India - and a retired executive from oil company Chevron, have attempted to project our human future to the point where we might avoid the suspected "Great Filter" often suggested as the explanation for the Fermi Paradox "Where are they (ETIs)?". They use Carl Sagan's formulation of the Continuous Kardashev Scale (in *The cosmic connection: An extraterrestrial perspective*, 1973) to estimate that we have achieved 0.728 - only 0.272 short of using all major forms of energy available from our home planet. They reject the simpler exponential growth models of earlier studies and include the United Nations Framework Convention on Climate Change (UNFCCC) alongside the five major types of energy sources (Coal, Natural gas, Crude, Nuclear and Renewable). They worry that achieving Kardashev Type I may not be sustainable long term. They quote Edward Osborne Wilson (RIP) from a 2009 debate at the Harvard Museum of Natural History - "The real problem of humanity is the following: We have Palaeolithic emotions, medieval institutions, and godlike technology".

The paper is quite detailed with respect to energy analysis but does not appear to justify its implicit assumption that achieving Kardashev Type I will deliver us from any Great Filter. ■

[1] *Teaching Philosophy and Science of Space Exploration (PoSE)*, Feb 2022, https://arxiv.org/abs/2202.11130
[2] *The impact of astronomy*, Andy Fabian, in Astronomy & Geophysics, V51 #3, June 2010, https://academic.oup.com/astrogeo/article/51/3/3.25/224270
[3] *The EU must learn from the anti-expert narrative that drove Brexit*, editorial in Nature 16 December 2020

Researching ‘Oumuamua as an Alien Craft

In *Research Programs Arising from ‘Oumuamua Considered as an Alien Craft* (arxiv.org/abs/2111.07895), Martin Elvis (Center for Astrophysics, Harvard & Smithsonian) analyses the controversial hypothesis that 1I/‘Oumuamua is an alien craft using a lightsail for propulsion - or the wreckage of one. He considers both a craft under control and one which is now an uncontrolled wandering interstellar hulk. He further subdivides the uncontrolled case into “anonymous METI” (messaging to extraterrestrial intelligence) and “inadvertent METI”. He takes no position on the alien craft hypothesis but considers options to further explore that hypothesis.

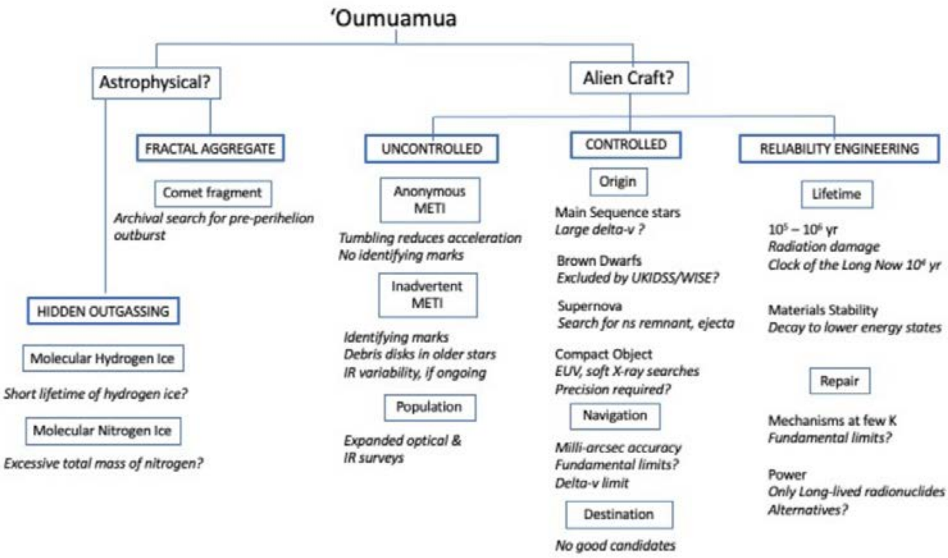
The anonymous METI case implies a sort of "message in a bottle". Since its velocity is very close to that of the Local Standard of Rest (LSR) - the velocity of the galactic crowd in our neighbourhood - this might imply an intention to disguise its point of origin. It might also imply a large population of such objects so that at least one "message in a bottle" will be found by another intelligence.

The Inadvertent METI case might imply something like the upper stage of the launcher for New Horizons, the probe to Pluto and beyond. Or perhaps just waste from a space-based factory of some sort.

If it was under control then can we discover its origin (or destination for that matter)? Here Elvis perhaps goes a little far since it is easy to disguise the intended long-term trajectory of a controlled object so speculation about this seems pointless? The longevity of such an interstellar explorer is clearly a major design issue and Elvis cites a human example of a mechanism with an intended lifetime of 10,000 years, the “Clock of the Long Now”.

A prototype of the Clock of the Long Now, on display at the Science Museum
Credit (image and caption): Science Museum, London

This is a detailed analysis (about 8,000 words) raising many interesting issues and, I believe, justifying its advocacy of a broad and well-defined research programme built around the hypothesis that 1I/‘Oumuamua is an alien craft. It includes a useful taxonomy of possibilities. ■



Taxonomy of possibilities for the nature of 1I/‘Oumuamua and later ISOs.

Credit: Martin Elvis

More from Centauri Dreams on Laser Sails and Ramping Up the Technosignature Search

Thanks again to the indefatigable Paul Gilster for drawing attention to two more papers stimulated by Breakthrough Starshot, *Delving into the Interstellar Sail* [1] - they are Campbell et al, *Relativistic Light Sails Need to Billow* [2]; - and - Brewer et al, *Multiscale Photonic Emissivity Engineering for Relativistic Lightsail Thermal Regulation* [3].

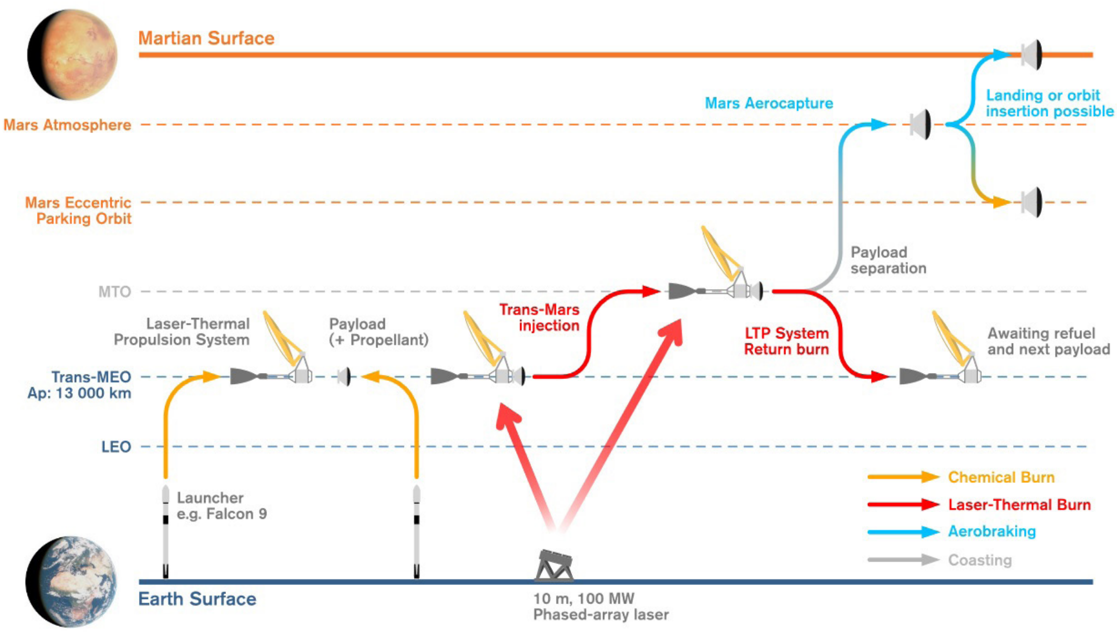
Paul also draws our attention to work to ramp up the search for technosignatures (www.centauri-dreams.org/2022/04/06/ramping-up-the-technosignature-search/). He celebrates the system upgrades to the Very Large Array (VLA) radio telescope, COSMIC (Commensal Open-Source Multimode Interferometer Cluster Search for Extraterrestrial Intelligence). COSMIC will have access to the complete datastream from the entire VLA, in effect an independent copy of everything the VLA observes. The VLA is an array of 27 dishes each 25 metre diameter in New Mexico, operating in a continuous frequency range from 1 to 50 GHz. We are truly in a golden age of SETI! ■

Riding a laser to Mars in 45 days

Phys.org draws attention to work at McGill University, *Riding a laser to Mars - in 45 days* [4] The paper is in Acta Astronautica, Volume 192, March 2022 and open publication [5].

The proposal is for a ground-based 10m wide 100 MW laser array to heat a core of hydrogen plasma. This would enable a 45-day transit time to Mars. They suggest a 1-ton payload and 706 kg of propellant delivering 8 g acceleration (1 ton looks a bit small for a human mission and 8 g is also a bit of a challenge for humans).

The claim is that this would yield unprecedented efficiency, specific impulse of 3,000 seconds and a mass to power ratio of 0.01 kg/kW or less. Longer transit times, probably for cargo rather than human missions, would allow greater masses. The paper cites a NASA solicitation seeking revolutionary propulsion for rapid, deep-space transit that identified a number of candidate missions of interest: traversing the distance between Earth orbit and Mars orbit in no more than 45 days, traversing a distance of 5 AU in no more than one year, traversing a distance of 40 AU in no more than five years, and traversing a distance of 125 AU in no more than ten years. ■

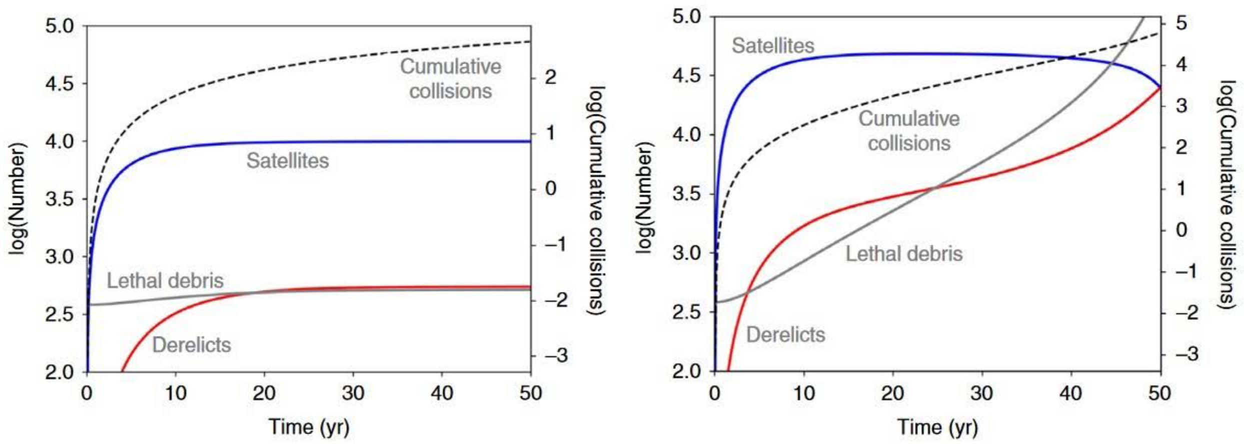


Concept of Operation diagram for a reusable Laser-Thermal Propulsion Systems.
Credit (image and caption): Duplay et al

[1] Centauri Dreams: www.centauri-dreams.org/2022/02/24/delving-into-the-interstellar-sail/
[2] Nano Letters 22, 1 (2022), 90-96 pubs.acs.org/doi/10.1021/acs.nanolett.1c03272
[3] Nano Letters 22, 2 (2022), 594-601 pubs.acs.org/doi/10.1021/acs.nanolett.1c03273 and arxiv.org/abs/2106.03558
[4] *Riding a laser to Mars - in 45 days* phys.org/news/2022-02-laser-mars.html
[5] *Design of a rapid transit to Mars mission using laser-thermal propulsion*, Emmanuel Duplay, Zhuo FanBao, Sebastian Rodriguez, Rosero Arnab Sinha, Andrew Higgins - all at Department of Mechanical Engineering, McGill University Acta Astronautica, Volume 192, March 2022 (www.sciencedirect.com/science/article/abs/pii/S0094576521006305?via%3Dihub)/ - there is an open publication version at arxiv.org/abs/2201.00244.

The case for space environmentalism

An international team with lead author at the University of Edinburgh has published *The case for space environmentalism* (Lawrence et al, www.nature.com/articles/s41550-022-01655-6.pdf) in *Nature Astronomy*. They summarise the case for considering the orbital space around the Earth as an additional ecosystem, subject to the same care and concerns, and the same broad regulations as the oceans and the atmosphere. They suggest that damage to the orbital space environment has problematic features in common with other types of environmental issue. First, the observed and predicted damage is incremental and complex, with many contributors. Second, whether or not space is formally and legally seen as a global commons, the growing commercial exploitation of what may seem to be a 'free' resource is, in fact, externalising the true costs. They identify three categories of the space environment - the radio interference environment, the optical sky as an environment, orbital space as an environment and also cumulative effects and emergent behaviour. Their general term for everything we put up there is anthropogenic space objects (ASOs). They roughly classify collisions into minor, disabling, and disrupting or lethal. Noting that anything 1mm in size or larger can cause minor damage, such as perforating a solar array. The two scenarios they suggest -



The evolution of the satellite population, debris population and cumulative collisions for scenarios at a height of 600 km with frequent de-orbiting.
a. 2,000 launches per year aimed at a stable population of 10,000 satellites.
b. 10,000 launches per year aimed at a population of 40,000 satellites.
Calculations made using the JASON Report model [1]
See also fig 20 and equation 5-22 of the Jason Report, cited above.
Credit (image): Lawrence et al
Credit (caption above): adapted from Lawrence et al

- note the catastrophic trend of lethal debris in scenario b.

Principium is observing, reporting and commenting on Space Debris. For example in a News Feature, *Special on space debris at IAC21*, in this issue. Our principal concern is access to space but we will also keep an eye on the wider issues addressed in this paper. ■

[1] *Jason Report on the Impacts of Large Satellite Constellations*, www.nsf.gov/news/special_reports/jasonreportconstellations/ and www.nsf.gov/news/special_reports/jasonreportconstellations/JSR-20-2H_The_Impacts_of_Large_Constellations_of_Satellites_508.pdf

Studying an ISO using the Webb telescope

The JWST will gradually become operational over the next few months. A recent announcement from NASA, *Studying the Next Interstellar Interloper with Webb* (www.nasa.gov/feature/goddard/2022/studying-the-next-interstellar-interloper-with-webb) says that many, many more ISOs are thought to exist and -

> "The supreme sensitivity and power of Webb now present us with an unprecedented opportunity to investigate the chemical composition of these interstellar objects and find out so much more about their nature: where they come from, how they were made, and what they can tell us about the conditions present in their home systems".

If its trajectory intersects with Webb's viewing field then using the Near-Infrared Spectrograph (NIRSpec), observers will analyse the "chemical fingerprints" of gases released by the object as any ices present are vaporised by our Sun's heat and, with the Mid-Infrared Instrument (MIRI), they will observe any dust that the object is producing, from microscopic particles to pebbles. NIRSpec can detect emission from individual gas molecules including water, methanol, formaldehyde, carbon dioxide, carbon monoxide, and methane. MIRI will look for the heat spectrum produced by solid particles, dust grains or the ISO's nucleus.
The i4is Lyra programme will continue to explore the possibilities for intercepting ISOs near or far but a new ISO, especially one as mysterious as 1I/'Oumuamua, would be a real find. How lucky do we need to be to find another in the next few years while 1I is still a reachable target? ■

SETI in 2021

This second annual survey of SETI research from Pennsylvania State University researchers [3] lists 93 papers and books published or made public in 2021. Topic areas include search methods, technosignatures, theories of ETI and social aspects of SETI. The authors have aimed to be "usefully subjective" rather than comprehensive, excluding, for example, papers in which SETI is peripheral. ■

Non-terrestrial artefacts in the Solar System

Avi Loeb at Harvard is already driving a project to actively look for non-terrestrial artefacts in the Solar System [1], however a team led from KTH Royal Institute of Technology, Sweden, suggests that we may already have usable evidence in old astronomical data, including the photographic plates which were the main medium for capturing astronomical images up to a few years ago [2]. Pre 1957 plates are of special interest since Sputnik 1 was the first artificial intruder into astronomical observation. ■

Probability of Communicating ETIs

Wenjie Song and He Gao of Department of Astronomy, Beijing Normal University, discuss *The Number of Possible CETIs within Our Galaxy and the Communication Probability* [4]. Using Monte Carlo simulations they estimate the number of possible CETIs within our Galaxy and the communication probability among them. They suggest two poorly known parameters have a great impact on the results - the probability of life appearing on terrestrial planets (f_c) and eventually evolving into a CETI (F). Inevitably they start with that famous handy checklist, the Drake Equation. Despite the uncertainties they identify, they believe their results may quantitatively explain why we have not detected any alien signals so far (the even more famous Fermi paradox). In support they suggest that developments in the discovery of so many exoplanets and the data on star formation rate (SFR), it is now possible to conduct a quantitative study of this problem. Their simulation results result in a range of possibilities of humans achieving communication with an ETI based on plausible upper and lower values of f_c and F. ■

[1] *Galileo Project for the Systematic Scientific Search for Evidence of Extraterrestrial Technological Artifacts*, iq.harvard.edu/galileo
[2] *A glint in the eye: photographic plate archive searches for non-terrestrial artefacts*, Villarroel et al, 2022 arxiv.org/abs/2110.15217
[3] *SETI in 2021*, Macy J Huston, Jason T Wright arxiv.org/abs/2203.11172
[4] The Astrophysical Journal, 2022 April https://iopscience.iop.org/article/10.3847/1538-4357/ac561d/pdf

IAC 2022

The programme for the 73rd International Astronautical Congress (iafastro.directory/iac/browse/IAC-22/) has, as usual, a number of sessions of interest to interstellar studies. The dates are 18-22 September and it's in Paris this year. Unusually it's Sunday-Thursday this time and there are the usual educational and youth events in the previous week. Here's the items we find of special interest in the programme. More in Interstellar News in this issue.

IAF/IAA SPACE LIFE SCIENCES SYMPOSIUM: Astrobiology and Exploration IAC-22,A1,6 iafastro.directory/iac/browse/IAC-22/A1/6/
IAF SPACE EXPLORATION SYMPOSIUM: Solar System Exploration including Ocean Worlds (Special emphasis on missions to "Ocean Worlds", Enceladus, Europa, Titan) IAC-22,A3,5 iafastro.directory/iac/browse/IAC-22/A3/5/
51st IAA SYMPOSIUM ON THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI) – The Next Steps - with sessions -

- SETI 1: SETI Science and Technology IAC-22, A4, 1 iafastro.directory/iac/browse/IAC-22/A4/1/
- SETI 2: SETI and Society IAC-22,A4,2 iafastro.directory/iac/browse/IAC-22/A4/2/

IAF SPACE PROPULSION SYMPOSIUM - notably -

- Hypersonic Air-breathing and Combined Cycle Propulsion, and Hypersonic Vehicle iafastro.directory/iac/browse/IAC-22/C4/7/
- New Missions Enabled by New Propulsion Technology and Systems iafastro.directory/iac/browse/IAC-22/C4/9/

IAF SPACE TRANSPORTATION SOLUTIONS AND INNOVATIONS SYMPOSIUM - notably -

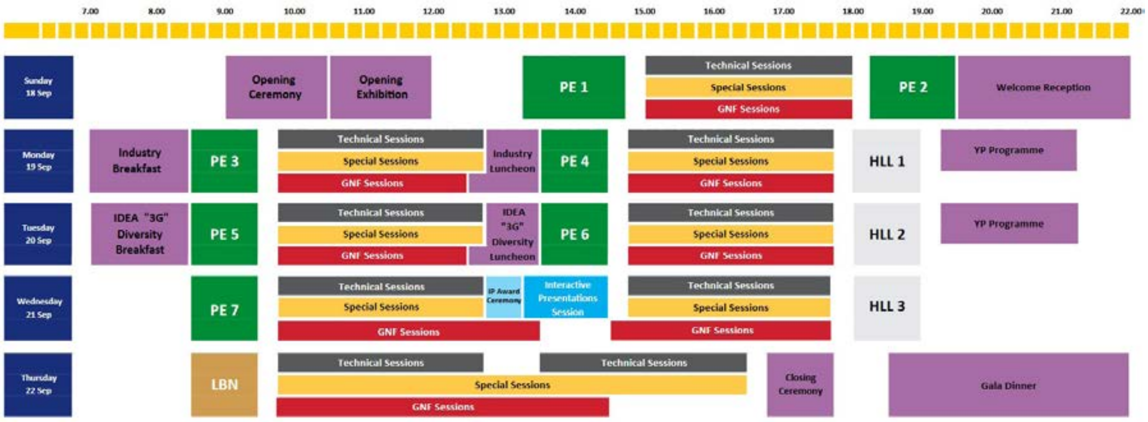
- Future Space Transportation Systems iafastro.directory/iac/browse/IAC-22/D2/4/
- Technologies for Future Space Transportation Systems iafastro.directory/iac/browse/IAC-22/D2/5/
- Space Transportation Solutions for Deep Space Missions iafastro.directory/iac/browse/IAC-22/D2/8-A5.4/

20th IAA SYMPOSIUM ON VISIONS AND STRATEGIES FOR THE FUTURE - notably -

- Innovative Concepts and Technologies iafastro.directory/iac/browse/IAC-22/D4/1/
- Modern Day Space Elevators Entering Development iafastro.directory/iac/browse/IAC-22/D4/3/
- Strategies for Rapid Implementation of Interstellar Missions: Precursors and Beyond iafastro.directory/iac/browse/IAC-22/D4/4/

20th IAA SYMPOSIUM ON SPACE DEBRIS iafastro.directory/iac/browse/IAC-22/A6/

Most also have associated - "IP" (Interactive Presentations) - open, parallel sessions which will encourage direct interaction with presenters.



Special on space debris at IAC21

Samar AbdelFattah

Principium has been increasingly concerned with the problem of space debris. The long term perspectives of interstellar studies inevitably lead i4is to consider the question - *How do we get there from here?* Until we develop an interplanetary culture, commerce and society the only "here" is the surface of our home planet. In P34 we illustrated the problem with our back cover image - a shot from ESA's latest space debris movie [1].

In P35, our November 2021 issue, we considered *Losing Access to Space - Are we building a fence around our planet?* [2].

Here Principium Contributing Editor Samar AbdelFattah summarises a selection of papers at IAC21 addressing this topic. A longer list of authors and papers follows - it is almost certainly incomplete.

Principium welcomes further discussion of this very significant potential barrier to our long term goals - email: John.Davies@i4is.org or Principium@i4is.org.

All figures are credited to the presenters and figure numbers are as in the presented papers.

Large Constellations

IAC-21,A6,5,9,x66275	Rendezvous and proximity operations design of an active debris removal service to a large constellation fleet	Mr Giacomo Borelli	Politecnico di Milano; D-Orbit SpA	Italy

IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/66275/
Open paper: www.researchgate.net/publication/355827730_Rendezvous_and_Proximity_Operations_Design_of_an_Active_Debris_Removal_Service_to_a_Large_Constellation_Fleet
Reported by: Samar AbdelFattah

The paper presents Active Debris Removal (ADR) service designed for LEO large constellation deployment which will safely deorbit the failed assets by performing a rigid capture. Since the growth of the region deployment is massively growing without any proof of the sustainability of these constellations in the space domain. The focus of the work here is the proximity and Rendezvous and Proximity Operations (RPOs) required during the ADR service mission to approach, capture, and deorbit the debris object. There were multiple mission architectures that introduced the ADR service. Some examples of these architectures were introduced in the paper as follows: The first mission architecture is the chaser mission, where the servicer is designed to approach each failed satellite in a constellation, capture the satellite and transfer it in a disposal orbit (complying with a five year re-entry time). Another concept is the mothership architecture, where the servicer approaches the failed asset and attaches the deorbiting kit. In this architecture the transfer from and to the disposal orbit is done using delta-v. In addition to these two, the chaser plus station architecture is considered where one servicer is used to capture and deorbit each target with a main station for refuelling.

[1] *Time to Act* www.esa.int/ESA_Multimedia/Videos/2021/04/Time_to_Act
[2] *Losing Access to Space* i4is.org/wp-content/uploads/2021/11/Losing-Access-to-Space-Principium35-print-2111260906-opt-9.pdf

With the Rendezvous as the main Concept of Operations (ConOps), the mission of the services first considered two types of constellation for the ADR design baseline:

1. Small class satellite (light target): OneWeb Arrow Spacecraft of 150 kg mass
2. Large class satellite (heavy target): EliTeBus- 1000 bus (GLOBALSTAR and Iridium-NEXT) of 750 kg mass

Second, the service were designed in the manner that provide the following requirements:

- Req-1: The servicer shall be able to rendezvous and capture the target. No cooperation or collaboration from the target shall be considered.
- Req-2: The servicer shall be equipped with onboard sensors dedicated to the measurement of bearing, range and pose of the target to enable and support the rendezvous operations.
- Req-3: The servicer shall be capable to perform the final operations in proximity regardless of the natural illumination conditions.

The envisioned ConOps is shown in Fig 1 with the following chronological sequence of the operations during one mission:

1. Absolute orbit phasing
2. Far-range rendezvous
3. Mid-range rendezvous
4. Inspection
5. Target preparation for robotic capture
6. Final approach forced motion
7. Robotic operations and capture
8. Stack stabilization and deorbiting

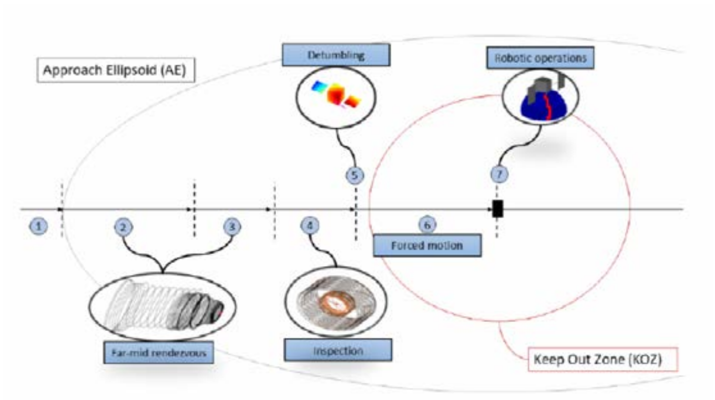


Fig 1 RPOs concept of operation for each service to a failed uncooperative satellite of the constellation fleet

For the ADR service, a suggested sensor payload was presented in the paper for visual object detection during the proximity operations. The payload includes mainly a Narrow Field of View (NFOV) Visible Camera with an additional Wide Field Of View (WFOV) camera. To enhance robustness to illumination conditions, an Infrared IR sensor is used to provide image measurement of the object in the closer range. At the last, the use of LiDAR sensor was to provide the range measurement of the target from mid-range. The detailed range performance of the payload is illustrated in Fig 2.

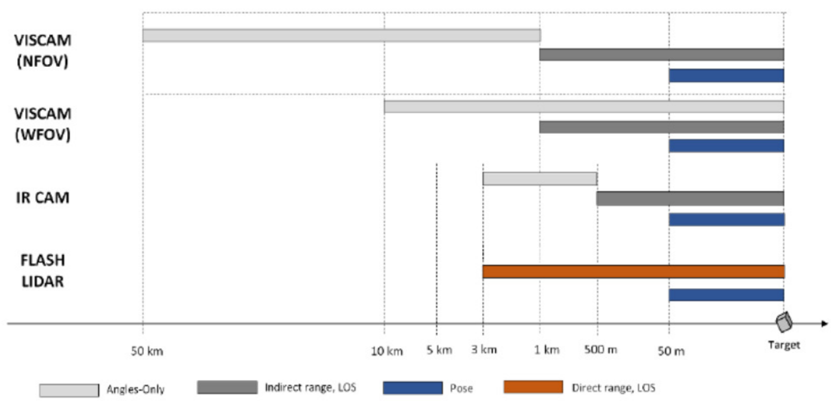


Fig. 2 Operation matrix of the sensor suite in function of the separation distance during the proximity operations

The authors discuss the far and mid range rendezvous design through analysing the Navigation and Guidance Control with the main objective for the servicer at this initial phase is to reduce the distance between the target and services for the rendezvous operations to run autonomously. They start Relative Guidance and Navigation Control (R-GNC) where each subfunction of the R-GNC servicer block is presented and simulated in a high fidelity environment.

After the analysis of the R-GNC, the authors discuss the onboard real-time navigation which is performed using an Extended Kalman Filter (EKF). In this case and during the mid-range operations the filter convergence is supported by the full observability conditions provided by the LiDAR range information. The GNC during the far and mid-range operations is implemented in a shrinking horizon Model Predictive Control (MPC), where at each GNC update, the guidance and control solutions are updated according to the filter estimate.

Fig 3 shows the table presenting the simulated far and mid-range rendezvous phases along with the R-GNC mode used.

Phases	Guidance and control	Navigation	Separation
Far-range 1	Observability enhanced (w)	AO	From 50 km to 10 km
Far-range 2	Energy optimal	AO	From 10 km to 1 km
Mid-range	Energy optimal	A+ range	From 1 km to 500 m

Fig. 3 Simulated ranges with R-GNC mode used results

After achieving the objective of reducing the rendezvous distance for a few hundred metres using the R-GNC at the end of the mid-range approach, the authors discuss in detail the inspection phase which will be required to proceed with the close-proximity operations. In this phase, the servicer performs a series of manoeuvres and fly-arounds which allows the onboard observation of the target pose and physical characteristics. This information will be a strict requirement for the ground go-command to proceed with the closer approach forced motion and operations.

Finally, the paper discusses the final stage of rigid capture. There are two possible scenarios during this phase depending on the tumbling status of the target object:

1. The target is not tumbling: the relative motion of the target capture point in the servicer body frame is limited and the rigid capture can be performed using the robotic arm (the capture point for the two targets used in the paper as a design baseline were defined and displayed).
2. The target is tumbling: contactless control of the target tumbling state is used employing the plume impingement effects of the servicer's onboard thrusters to prepare the target for the save rigid capture operations (the control algorithms for the servicer's thruster that will be used for detumbling were presented in the paper).

Authors: Giacomo Borelli - Gabriella Vittoria Maria Gaias - Camilla Colombo - Lorenzo Vallini

CubeSat in Debris Detection

IAC-21,A6,1,2,x66530	STRATHcube: The Design of a CubeSat for Space Debris Detection Using In-Orbit Passive Bistatic Radar	Lewis Creed, Julie Graham, Sebastian Diaz Riofrio, Ciaran Jenkins, Andrew Ross Wilson, Massimiliano Vasile	University of Strathclyde	UK

IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/66530/

Open paper: www.researchgate.net/publication/355808576_STRATHcube_The_Design_of_a_CubeSat_for_Space_Debris_Detection_Using_In-Orbit_Passive_Bistatic_Radar

Reported by: Samar AbdelFattah

This paper discusses a cubesat low altitude mission aimed as a Proof of Concept (POC) for the use of Passive Bistatic Radar (PBR) technology for space debris detection in LEO as an in-orbit operation instead of the ground-based tracking. The STRATHcube mission concept involves a radar receiver, an on-board antenna on the cubesat while orbiting at low altitudes. The idea is to detect the variations in radio signals transmitted by operational satellites orbiting at higher altitudes and known as illuminators of opportunities. In the normal case the bistatic angle is measured as 180 degrees and in case of interruption (variations in the radar signal) the signal processing algorithms can be used to detect the size and the shape of the object passing between the illuminator of opportunity and the cubesat, Fig 1.

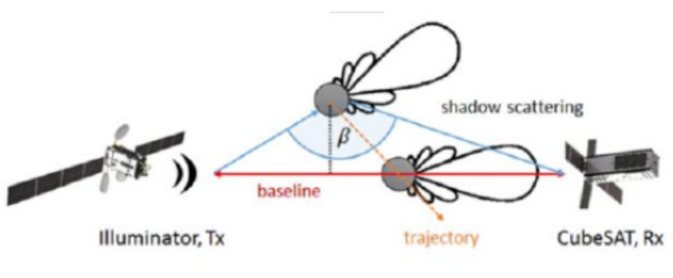


Fig 1 PBR cubesat concept

The team uses the effect of forward scattering to determine Radar Cross Section (RCS) of a target using the equation: $\sigma_{FS} = 4\pi U/\lambda^2$ (U=silhouette area of the target, λ is the wavelength [1])
Thus, the higher the frequency of the selected illuminator of opportunity (small wavelength) and belonging to a larger constellation, the better the chances of link availability and potential detection of smaller debris objects. Also, this will be essential in designing the cubesat payload so that the antenna is able to receive at the operational frequency of the illuminator.
The authors highlighted their preferences when it comes to selecting the illuminator of opportunity for their STRATHcube. Starlink was discussed as their most preferred for a constellation group, however, the frequency limitations eliminated a lot of interesting options. Since Starlink, Oneweb and TeleSat networks operate at high frequencies (Ku- and Ka-bands), the PBR experiment will not have suitable "Commercial off-the-Shelf" (COTS) batch antennas that can operate at these frequencies. Thus, older communication constellations like Iridium and Globalstar were more suitable for the mission frequency requirements. With 24 operational satellites only available with the Globalstar option, the selection was made for Iridium with its 75 operational satellites which were enough for the experimentation of the PBR technology. Although the authors discussed later on the availability for a custom designed patch antenna through Endurosat; However, this option was eliminated due to the limited budget for the student-led project nature of STRATHcube. As the main payload of the cubesat, the tradeoff of the antenna options considered two options, a 3D phased array antenna which is designed by a researcher in the university specifically for STRATHcube, and a commercial off-the-shelf patch antenna. Despite the fact that the custom phase array antenna was an optimum scenario to customize the operation frequencies, the design requirements for mass and power made it an unfeasible option compared to the commercial options. Table 1 shows the design requirements for the 3D antenna. Eventually, the team decided to use the PulseLARSEN Ceramic commercial antenna, Fig 2. In case of failing the radiation or vibration tests, the alternative would be a more conservative yet more expensive option which is the GNSS Active Patch Antenna by ISIS.
Authors: Lewis Creed - Julie Graham - Sebastian Diaz Riofrio - Ciaran Jenkins - Andrew Ross Wilson - Massimiliano Vasile

Fig 2 PulseLARSEN Ceramic Patch Antenna

Space-based Laser

IAC-21,A6,4,4,x66251	A Strategy for the Mitigation of Debris Shells in LEO using Space-Based Lasers	Lewis Walker, Massimiliano Vasile	University of Strathclyde	UK

IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/66251/
Open paper: strathprints.strath.ac.uk/79596/1/Walker_Vasile_IAC_2021_Mitigation_of_debris_in_LEO_using_space_based_lasers.pdf
Reported by: Samar AbdelFattah
The paper challenges the current solutions for space debris mitigation or elimination which rely on rendezvous, capture and deorbiting. Thus, these solutions are suitable for the removal of defunct satellites or large fragments. The presented solution uses a space-based laser in an approach to solve the challenges of ground based laser solutions which require a lot of power and lack the accuracy of object detection since it assumes the perfect alignment of the laser beam with the targeted fragment.
Similar to the L'ADROIT mission concept [2], the paper proposes a satellite constellation inserted into a shell around the Earth such that the constellation has access to all longitudes instead of the one large satellite placement in the polar orbit. In addition, the authors attempt to investigate L'ADROIT altitude, laser incidence alignment, and assumption on beam waist plane longitudinal alignment with the fragment.

[1] This STRATHcube paper (see the Open paper link above) cites *SISAR Imaging for Space Debris based on Nanosatellites*, Theodorou et al 2015 (pure.strath.ac.uk/ws/portalfiles/portal/101404429/Theodorou_etal_RSN_2020_SISAR_imaging_for_space_debris_based_on_nanosatellites.pdf) for this equation.
[2] Claude R Phipps. *L'ADROIT–A spaceborne ultraviolet laser system for space debris clearing*. Acta Astronautica 104.1 (2014), pp 243–255 www.researchgate.net/profile/Claude-Phipps/publication/265338032_LADROIT_-_A_spaceborne_ultraviolet_laser_system_for_space_debris_clearing/links/60fc2f481e95fe241a87c5f0/LADROIT-A-spaceborne-ultraviolet-laser-system-for-space-debris-clearing.pdf

The solution is designed with two main payloads. A camera for fragment acquisition and tracking through continuous space scanning and a high-power Continuous-Wave (CW) laser to eliminate fragments and impart momentum. The payload is powered by an onboard battery pack which receives its charging supply from the solar panels incorporated in the satellite, which also powers electric thrusters used for orbit maintenance or adjustments.

"Beyond the power system, no detailed attempt to estimate the size and mass of the individual spacecraft is made, however the author expects these would be of the small-sat class, and between 100 and 300 kilograms each. To launch a constellation of one hundred 300 kg satellites, two Falcon 9 launches would be required, costing $100 million with reused boosters. This assumes onboard thrusters are used to transfer from the delivery orbit to the operational orbit."

The authors attempt to analyse the propagation of orbits semi-analytically using a tool called CALYPSO which was developed at the University of Strathclyde. However, for the sake of computational efficiency, propagations in this paper are performed with drag as the only perturbation.

Modelling Scenario

The modelled debris shell population of fragments is generated to simulate satellite breakup in a 1,200 km circular orbit at 45 degrees inclination. The selected model (2 cm Aluminium hex nut) which approximately coincides with the peak distribution of Iridium-Cosmos collision debris.

Due to computational demand, a representative population of 632 fragments is propagated over a 10-year mission span, as well as the orbit of a single satellite. The separation between the spacecraft and the fragments oscillates, generating many local minima, which represents candidates for the operation. However, the filtration criteria is conditioned by:

1. Visibility condition: fragment must be seen by camera at all times; such that the SNR is achievable before the object image moves by one pixel width in the sensor plane.
2. Reachability: fragment must be within 30 degrees of spacecraft negative velocity direction.

Optical Acquisition

At each encounter, a binary number will be given by comparing the minimum required exposure for SNR and the relative angular velocity, the binary number one indicates that the two conditions are achieved, Fig 1.

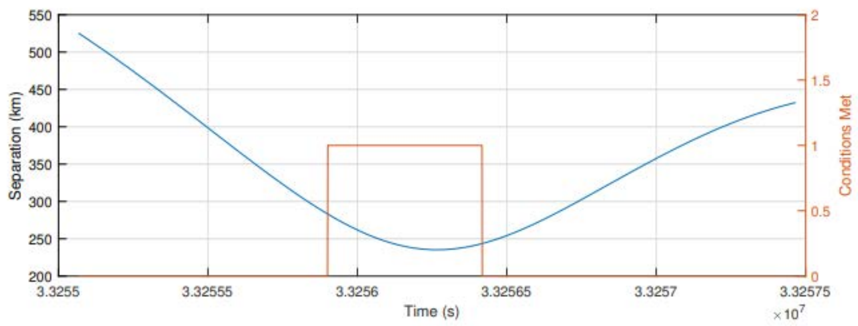


Fig 1 Example of information extracted on the dynamics of a single encounter

In their analysis, the authors were able to extract information on the rate of these interactions. On average, an encounter of 0.483 per day was concluded for the fragment representing a population of 632 fragments. For a more realistic population of 5,000 fragments, expected encounters are approximately 4 per day.

Laser Interaction Model

In this section of the paper, the authors attempted to define their Laser-Debris Interaction (LDI) model operations. Started by investigating the element illumination, system photon pressure force, longitudinal laser profile, to finally calculate the required impulse transfer. Using the database of encounter dynamics they obtained (only with the binary condition equal to one), they were able to feed the photon pressure model. And during the visibility window shown in Fig 2, the separation vectors are passed into the Laser-Debris Interaction (LDI) model to integrate the laser pressure force over the course of interaction.

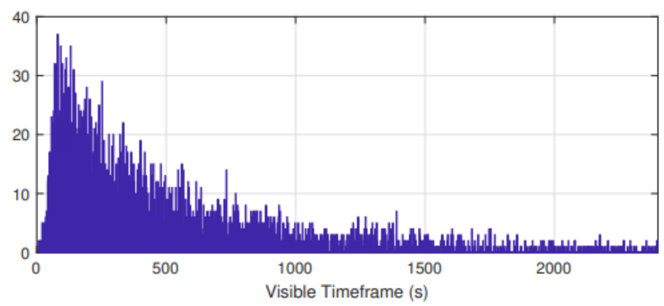


Fig 2 Distribution of visibility window duration

Long Term Mission Impact

The authors were able to scale up the fragments population to 5,000 at the 1,200 km altitude for a 10-years duration's worth of encounters for a single satellite, then modelled the results for a constellation of 100 satellites. In these results, only 417 fragments have been propagated to the end of the 10 years mission to gain an insight into the expected effect of any given fragment in the population. Thus, laser ablation method will be studied in their future work instead of the photon pressure mechanism.

Adaptation for Collision Avoidance

Orbit lowering is a potential use for the satellite constellation that was investigated by the authors at the end of their paper. A random population of 500 fragments were studied after 1 day of collision notice period and then the results were presented after repeating the analysis several times over different notice periods, Fig 3

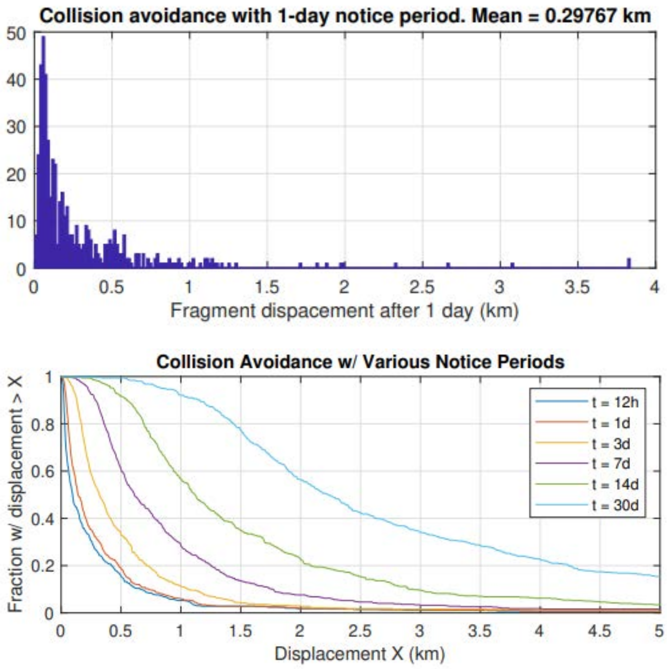


Fig 3 Fragment displacement scenarios

The concept was subsequently adapted and re-modelled using ablative interaction with pulsed lasers, leading to a far stronger effect on the orbits of fragments in the shell. Using ablation, it is possible to achieve lifetime reduction of decades for fragments in orbits with 1,200 km altitude, which could significantly reduce the risk posed by debris shells left behind after collision events at these altitudes.

Authors: Lewis Walker - Massimiliano Vasile

Policy and Legal Feasibility

IAC-21,E9,IP,3,x63533	Active Debris Removal Policy and Legal Feasibility	Josef Koller, Tyler Way, Mark A Skinner	The Aerospace Corporation; Space Policy Institute, George Washington University	USA

IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/63533/

Open paper: csps.aerospace.org/sites/default/files/2021-08/Way_Koller_ADR_20210422.pdf

Reported by: Samar AbdelFattah

According to the European Space Agency (ESA), there are approximately 29,000 pieces of debris larger than 10 centimetres and 670,000 pieces larger than 1 centimetre currently orbiting Earth. In addition, as of February 2021, there are over 6,500 spacecraft and over 2,000 rocket bodies in orbit. The paper addresses, from a regulatory perspective, this growth of space debris risk beside the future risks rising from proliferated low Earth orbit (pLEO) constellations for instance.

In the efforts to establish the obligation of law execution for debris mitigation and/or ADR services, the authors propose a framework based on two principal requirements:

1. Consent between debris owner and ADR service provider
2. Legally binding contract between parties that incorporates domestic law and international obligations

However, in case of multiple states to be involved, the framework adds to the above requirements ***a Memorandum of Understanding (MOU) between states***, which shall address the following:

- Authorization and licensing responsibilities
- Registration responsibilities
- Technical data exchange
- Liability Issues
- Ownership transfer, if any
- Transparent messaging responsibilities

The framework addresses an additional key political challenge which is the risk of using ADR as an anti-satellite weapon. The mitigation of such risk is achieved by the required consent by the launching state to the ADR service provider. Thus, a consent-based system draws, therefore, a clear line between prohibited and authorized operations.

Outer Space Treaty Obligations

Although the United States has incorporated OST Article VI provisions throughout its outer space regulatory authorities provided to NOAA, the FAA, and the FCC, none of these authorities yet, dedicated to regulating ADR operations.

Therefore the authors' affirmation on having a well funded entity within the United States government, which would require legislation and congressional approval, to resolve legal and policy problems can only be a longer-term solution. In the meantime, they suggest using their framework to promote ADR activities until processes and procedures become more mainstream and mature into sound policy or law that then can be implemented by the appropriate regulatory agencies.

Registration Convention

An important aspect of registration for ADR is the ownership principle of the treaty. The ADR framework here suggests that the typical responsibilities of the launching state for the ADR service provider would be to register the ADR servicer. And if the ADR service provider is part of a larger international conglomerate, the registration question could be resolved as part of the permission and consent-based contractual agreement, an MOU, or bilateral agreements. Also, in case of any damage/explosions caused by fuel on board, the MOU is used to define the responsible partner.

Liability Convention

Determining the liability of an accident is preceded by determining which launching state is the owner/operator and thus liability holder. Whether the liability should be held by the servicing satellite's launching state or the client's launching state, shall be defined in a contract between the ADR service provider and the launching state of the space debris.

Third Party Liability Regulations and Insurance

Following the insurance requirements in the United States for liability in space activities are covered under the Commercial Space Launch Amendments Act of 1988 which extend to the ADR service. The authors suggest extending the liability beyond launch and re-entry to extend to protection from accidents and mishaps as well.

Ownership Transfer Not Required

An example is given for a commercial launch provider that does not assume ownership of a payload that it places into orbit. In this case, providing a service is not considered a transfer of ownership and the client maintains ownership of its asset as well. Therefore, in the case of ADR, there is no precedent for the requirement of ownership transfers between client owner and ADR service provider, which removes a major obstacle to the legal conduct of international ADR operations.

Framework Analysis with Domestic and International ADR

1. Domestic Entity Removing US Objects

In the US, the current state of art requires a NOAA license for any camera capable of imaging Earth. Despite the fact that NOAA only regulates remote sensing and not the full extent of the space operations and how they are conducted, the remote sensing license and the associated interagency process will have to be sufficient for fulfilling the OST obligation for authorization due to the absence of such on-orbit authority.

2. International Debris Removal

The main challenge here is to answer the question on export control. The issues will depend on the countries involved, the capturing mechanism, and what level of technical data would need to be shared. Thus, agencies controlling the export of technical information will look at the amount of detail shared and decide on thresholds of technical information that would trigger restrictions.

Authors: Josef Koller - Tyler Way - Mark A Skinner

Risk Assessment

IAC-21,E9,IP,2,x64614	Mitigating Space Debris through Risk Assessment Framework	Anne Jing, Olivia Sun, Cindy Chen, Natacha Hughes, Dominik Adamiak	University of Toronto Aerospace Team (UTAT)	Canada

IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/64614/
Open paper: www.researchgate.net/publication/356579054_Mitigating_Space_Debris_through_Risk_Assessment_Frameworks
Reported by: Samar AbdelFattah

The authors in this paper are highlighting the growing presence and risk of space debris with 34,000 objects larger than 10 cm, currently orbiting the Earth. Since the first publishing for space debris mitigation guidelines by the Inter-Agency Space Debris Coordination Committee (IADC) in 2002, only 60% of the total payload mass nearing end-of-life in low Earth orbit is compliant with these guidelines. Thus, the paper aims at creating a proposal for a regulatory body centred on a risk assessment framework that will suggest a legal guideline for the Active Debris Removal (ADR) market. While reviewing the state-of-the-art for currently existing ADR and mitigation methods, the paper addresses the technical, legal, political and economic barriers to the creation of a space debris monitoring and removal market. To design and test this framework, the authors start the proposed regulatory system with a discussion on the current existing technical, legal political and economic barriers, explain in details the proposed regulatory system, then discuss the legal clarity provided by the proposed regulatory system. At the end of the paper, a case study on Cosmos-Iridium incident is made with high-level assessment of the two satellites under the proposed risk-rating scheme to apportion liability.

Proposed Regulatory System

A Risk Rating System is suggested to define the 1. monetary contributions (including operation, liability/insurance, ADR technology development costs), 2. liability conflict resolutions, and 3. A potential target list for ADR target- missions.

The risk rating system is divided into four main factors each having a different weighting out of a total of 20 risk points. The below table summarizes these factors weight and risk points:

Factor	Elements	Points Score
End of life plan considerations	1. ADR retrieval mission 2. Deorbit 3. Graveyard Orbit 4. Passivation	7/20 or 35%
Debris generating potential based on design factors	1. Propulsion system 2. Electrical or power generating systems including TT&C system (telemetry, tracking, communications) 3. Attitude and orbital control system 4. Structural system and thermal systems	5/20 or 25%
Orbital environment analysis		5/20 or 25%
Launch state considerations	1. 1pt - Average risk rating of all the launch states current satellites in orbit 2. 1pt - Estimated mass of debris released in the last 25 years (or since the implementation of the framework, whichever is earlier) 3. 1pt - Data sharing considerations	3/20 or 15%

After the risk rating outline, the authors discuss the monetary contribution. To ensure that the fees accurately reflect each signatory's orbital debris responsibility, in the first year of the organization's operations, the magnitude of each signatory's contribution to the common fund shall be determined via market-share liability. Thus, Market-share liability is suggested to resolve this issue of non-identifiability. The proposed regulatory system ends with an outline for funding the R&D of debris mitigation technologies.

Legal clarity provided by the proposed regulatory system

The authors follow their proposal by addressing current legal and political obstacles, then present a liability scheme supplemented by the risk rating system.

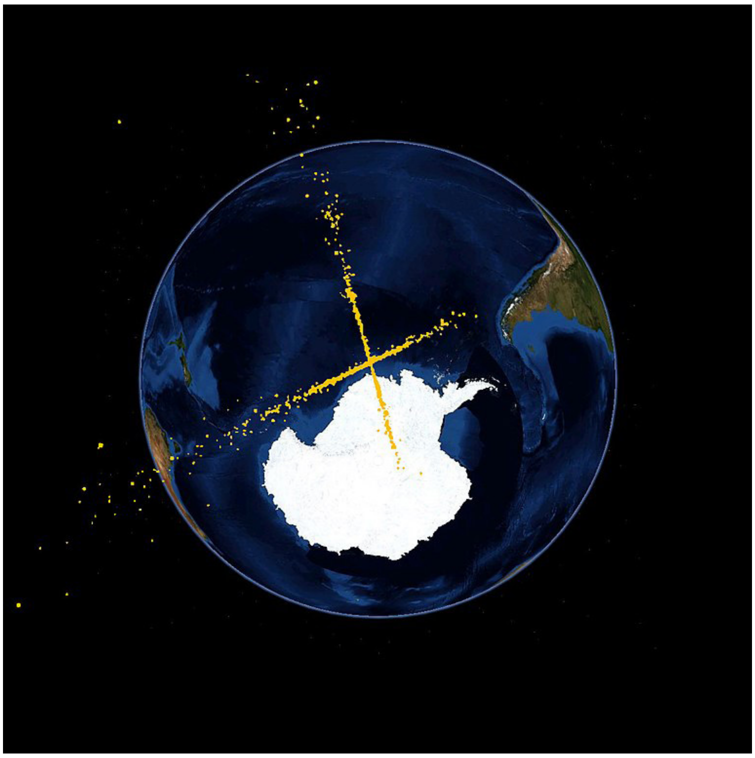
Finally, a display for the complete risk assessment per each of the factors is presented in the Cosmos-Iridium collision case study.

Authors: Anne Jing - Olivia Sun - Cindy Chen - Natacha Hughes - Dominik Adamiak

The effect of a single major collision

Collision between Iridium 33 and Kosmos 2251 -- debris field after 20 and 50 minutes.

Credit: Globe by NASA Worldwind in the public domain. Data based on work of Astronautics Research Group, University of Southampton (Wikipedia -en.wikipedia.org/wiki/2009_satellite_collision)



The Journals

John I Davies

Here we list recent interstellar papers in the Journal of the British Interplanetary Society (JBIS), published since the 1930s, and Acta Astronautica (ActaA), the commercial journal published by Elsevier, with the endorsement of the International Academy of Astronautics.

JBIS

Three issues of JBIS (December 2021, January and February 2022) have appeared since the General Interstellar Issue in November 2021. We have found no new papers of interest to interstellar studies. However the following has been published onlline -

Title (open publication)	Author	Affiliation
Abstract/Précis/Highlights		
online arxiv.org JBIS VOLUME 75 NO.2 February 2022		
Engineering an Interstellar Communications Network by Deploying Relay Probes	John Gertz1 & Geoff Marcy	Zorro Productions & Space Laser Awareness, USA
We develop a model for an interstellar communication network that is composed of relay nodes that transmit diffraction-limited beams of photons. We provide a multi-dimensional rationale for such a network of communication in lieu of interstellar beacons. We derive a theoretical expression for the bit rate of communication based on fundamental physics, constrained by the energy available for photons and the diffraction of the beam that dilutes the information by the inverse square law. We find that meter-scale probes are severely limited in their bit rate, under 1 Gbps, over distances of a light year. However, that bit rate is proportional to the 4th power of the size of the optics that transmit and receive the photons, and inversely proportional to the square of the distance between them, thus favoring large optics and short separations between nodes. The optimized architecture of interstellar communication consists of a network of nodes separated by sub- light-year distances and strung out between neighboring stars. (arxiv.org/ftp/arxiv/papers/2204/2204.08296.pdf)		

Acta Astronautica

Title	Number+date	Author	Affiliation
Abstract/Précis/Highlights			
Deceleration of Exoplanet Missions Utilizing Scarce Antimatter	Available online 16 March 2022	Gerald P Jackson	Hbar Technologies, USA
Antimatter-based propulsion for unmanned exploratory missions to exoplanets in such solar systems as Proxima Centauri and Epsilon Eridani. Deceleration of the spacecraft is accomplished by inducing fission of uranium-238 with antiproton annihilations. A low mass propulsion system is matched to a comparably low mass spacecraft architecture. Mission profiles emphasizing early science results are presented due to the long transit time to nearby solar systems. Antimatter production improvements and economics are enabling issues.			
Pulsed plasma rocket- developing a dynamic fission process for high specific impulse and high thrust propulsion	Available online 17 March 2022	Steven D Howe, Troy Howe, Francesca G Bennett, Nathan Blaylock, Gerry Jackson, Jason Cassibry	Howe Industries, USA
The Pulsed Plasma Rocket (PPR) is an advanced nuclear propulsion concept that uses a fission-based nuclear power system to rapidly cause a phase change in a fuel projectile from solid to plasma during a pulsed cycle. To create the plasma bursts that provide thrust, a highly moderated Low Enriched Uranium (LEU) projectile can be used in combination with an unmoderated LEU barrel to preferentially heat the projectile. A short section of High Enriched Uranium (HEU) at the barrel base, along with a novel control drum mechanism, allows for controlled and rapid neutron population growth to transition into a plasma state in a fraction of a second. The PPR concept is intended to provide fast transit to and from locations such as Mars, with the engine capable of providing 100,000 N of thrust and 5,000s of specific impulse. The pulsed plasma rocket is a revolutionary new technology that is much more efficient than traditional rocket engines. It creates a plasma field that can be used to generate thrust, allowing spacecraft to travel much faster and farther than traditional rockets. This technology is essential for future space exploration, as it will allow us to travel to other planets and moons in the solar system.			
Life beyond Earth: How will it first be detected?	Available online 6 April 2022	Chris Impey	University of Arizona
The search for life beyond the Earth is being carried out using a variety of techniques in three distinct realms of space. The best near-term prospect for the detection of life is the detection of biomarkers in exoplanet atmospheres. The next best prospect will come from the search for relic traces of life in ancient Mars rocks returned to the Earth. The strategy least likely to succeed, having indeterminate odds of success, is the search for extraterrestrial intelligence. The discovery of life beyond Earth, when it comes, will be one of the most important in scientific history.			

Interstellar probe - Destination: Universe!	# 196, July 2022	Ralph L McNutt Jr (*), Robert F Wimmer-Schweingruber (University of Kiel), Mike Gruntman (University of Southern California), Stamatios M Krimigis (*/ Academy of Athens), Edmond C Roelof (*), Pontus C Brandt (*), Steven R Vernon (*), Michael V Paul (*),Robert W Stough (NASA Marshall Space Flight Center), James D Kinnison (*)	*The Johns Hopkins University Applied Physics Laboratory
An "Interstellar Probe" has been discussed in depth for almost 60 years. The results of a four-year long engineering, science, instrumentation, and implementation trade study for NASA are summarized. "Best" solutions are assessed and compared. Over 100 mission approaches using NASA's large new SLS super heavy-lift launch vehicle are quantified and assessed. Implementation costs are estimated and an example cost-loaded implementation schedule is published for an example mission.			
Quantitative characterization of photonic sail candidates using nanocantilever displacement	Available online 10 March 2022	Joseph E Meany	Savannah River National Laboratory, USA
Laser sources irradiating cantilever systems lead to measurable force deflection. Quantify spectral characteristics of light sails for mission qualification. Sail candidate materials may be directly tested for failure. Requires swatches on the order of μm^2. Allows for high-throughput iteration.			
Wind-pellet shear sailing	Available online 25 April 2022	Jeffrey K Greason (TZF) Dmytro Yakymenko & Mathias N Larrouturou (Electric Sky Inc) Andrew J Higgins (McGill University)	Tau Zero Foundation (TZF)
A new concept is proposed: a spacecraft overtakes pellets, transferring their energy to the spacecraft. The concept exploits the use of free energy sources available in space. Analysis suggests spacecraft may be accelerated from 2% to 5% of the speed of light. The technique may be combined with other propulsion devices to achieve greater speeds. A mission to return data from nearby stars within 30 years of launch may be possible.			

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Stephen Hawking, *Brief Answers to the Big Questions*, 2018 (published after his death)

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The opening session featuring Sonny White of LSI and Rob Swinney of i4is is open to all - i4is.org/videos/lsi-course-2021/

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Two Equations to the Stars - Part One: The Rocket Equation

How to explain rocket maths to mid-secondary school students

John I Davies

There are two currently feasible ways to propel a space probe to the stars, fusion rockets and laser sails - each governed by a simple equation.
Here John Davies explains the first of these equations and how middle secondary school students can be introduced to the mathematics, physics and engineering behind all rockets, including the ones that can propel us to the stars. In a separate Addendum on our website, Atholl Hay explains how teachers and advanced students can derive the equation from Newton's second law using the steps as used numerically in this article. Part Two, in the next issue of Principium, will explain the simple equation for laser and solar sail propulsion.

Who is this article for?

This article is primarily intended for teachers introducing school students to rocket physics, maths and engineering in mid-secondary school (middle school in USA). It avoids using calculus (integration) or momentum since these concepts are unlikely to have been introduced to students at this level - and many will never cover them. The objective is to give these students an accessible yet fairly rigorous understanding of the fundamentals of rocket propulsion. It uses a numerical approximation in a spreadsheet - thus avoiding those unfamiliar topics while introducing students to the consequences of the equation, the beginnings of calculus and the idea of numerical approximation as used elsewhere in physics, engineering and beyond.

Reading order

• **Teachers** should read the ***1-Introduction***, ***2-Background and Approach*** (2.1 and 2.2) - about 550 words. If the approach is interesting then read the rest of the article. If it is not interesting then perhaps tell i4is why (john.davies@i4is.org) so we can refine this. This article is accompanied by a derivation of the Tsiolkovsky equation using similar steps to the spreadsheet, RocketCalcSimpleForTsiolkovsky [1]. The derivation is in an Addendum [2] published alongside this issue.

• **School students** should read ***1-Introduction*** and ***3-For School Students - What you can achieve***. If they feel confident then read ***4-For School Students - The Spreadsheet*** - as far as possible and then report progress to your maths, science or engineering teacher and ask them to take a look at this article. If you don't feel confident then ask a teacher to help with the maths, science or engineering.

[1] RocketCalcSimpleForTsiolkovsky https://i4is.org/wp-content/uploads/2022/03/RocketCalcSimpleForTsiolkovsky.xls
[2] *The Tsiolkovsky Rocket Equation - A Parallel Derivation*, Atholl Hay https://i4is.org/wp-content/uploads/2022/04/The-Rocket-Equation-Principium_Addendum_7-converted.pdf

The work of a mathematician, Al-Khwarizmi (780-850 CE) - bottom right, a physicist, Newton (1642-1726 CE) bottom centre, and a maths teacher and engineer, Tsiolkovsky (1857-1935 CE) - top - gave us the way to understand what rockets can do

1 Introduction

This is the first of two articles for Principium explaining how to understand the equations which define our ability to reach both our Solar System and the stars. Our aim in this article is to provide a way to understand the Tsiolkovsky rocket equation without using mathematics beyond basic secondary school level. It is intended for teachers, self-motivated secondary school students and interested people in general. More about its objectives in section ***3 - For School Students - What you can achieve***.

The second article will explain the Robert Forward's laser sail equation - which governs the propulsion challenges of low mass probes such as i4is Project Dragonfly (2014) and the ongoing Project Starshot financed by Breakthrough Initiatives.

2 Background and Approach

This article follows from a presentation given to a number of UK secondary schools over recent years. This section is based on the material used for these presentations.

2.1 The Story

Our story begins with Al-Khwarizmi, Isaac Newton and Konstantin Tsiolkovsky, three heroes of Maths, Physics and Engineering. Al-Khwarizmi was the mathematician who taught us how to do algebraic manipulation. For example if x = y/z then it follows that xz = y - just multiply both sides of the first equation by z. Your multiplication is xz = (y/z)z but z/z = 1 so right hand side is just y.

Isaac Newton gave us his three laws of motion and the algebraic one is the second law. F = ma, Force = Mass times Acceleration [1]. Al-Khwarizmi tells us this must mean that a = F/m. Konstantin Tsiolkovsky applied a = F/m to a rocket where the complication is that the rocket gets lighter as it uses up fuel and gets lighter, so M keeps decreasing and acceleration (a) therefore gets bigger.

[1] Strictly speaking F is the *unbalanced* force or net force. Where multiple forces act then only the sum of these forces produces the acceleration.

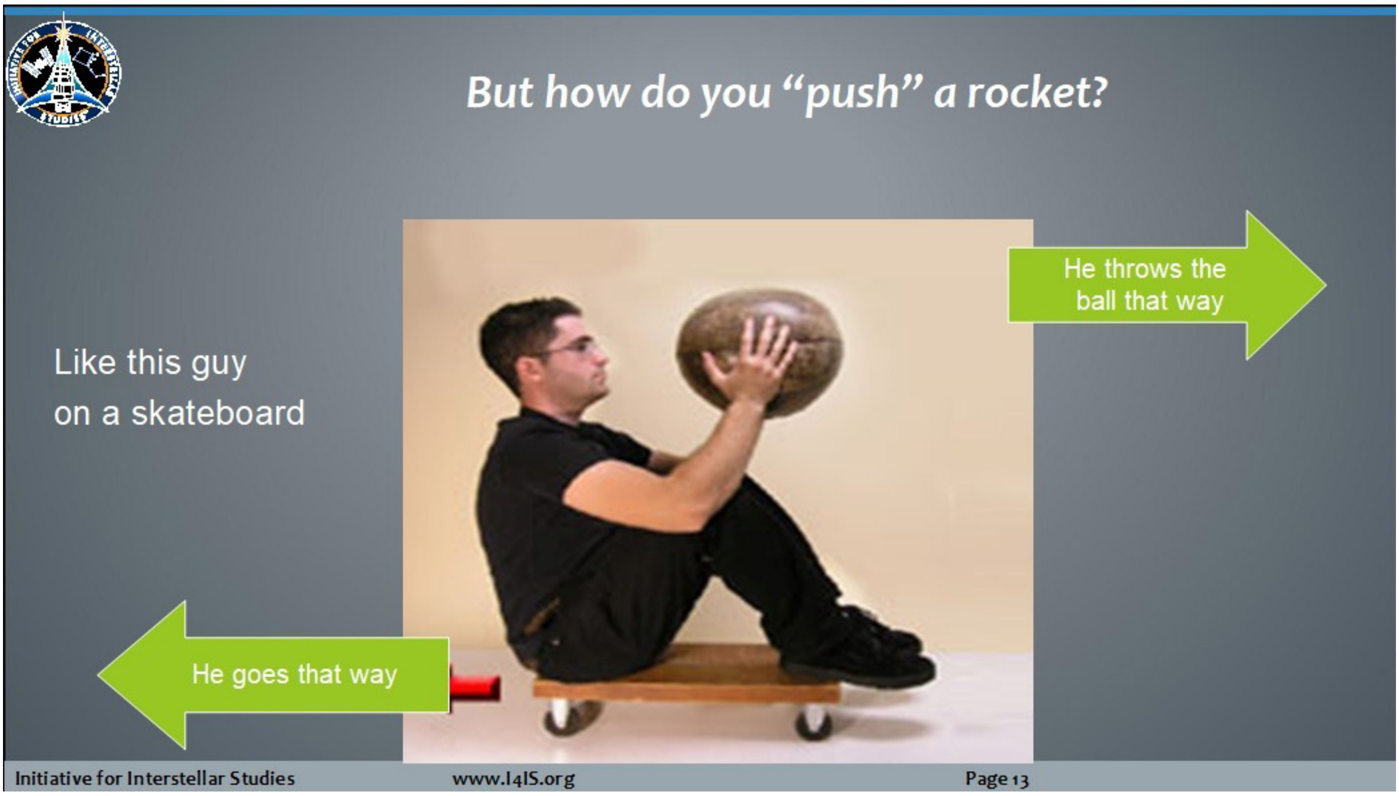
Tsiolkovsky wanted to know how fast the rocket flies after all the fuel is used so he used integration on a= F/m to add all the accelerations as the rocket uses up the fuel and got deltaV = Ve ln(Mo/Mf), which looks like a cousin to a = F/m.
His equation says -
Change in velocity[deltaV] = rocket Exhaust Velocity[Ve] multiplied by Natural Logarithm[ln] of initial mass of the rocket[Mo] divided by final mass of the rocket[Mf] when all the fuel is used [1]. This equation -
deltaV = Ve ln(Mo/Mf) [2]
- governs all rockets, in fact all reaction-propelled things from the mighty Saturn 5 which took humanity to the Moon to the tiny squid which can squirt water to propel themselves and even let them fly above the water for short distances.
It's important to remember that no rocket vehicle is immune from other forces such as gravitation and friction.

2.2 The Problem

But school students don't learn how to do integration until they get towards the end of school mathematics - and many never do it at all. And most derivations of the equation also use the concept of momentum which is also introduced late in school physics.
So how can school students get their heads around the rocket equation? The answer here is to use simple numerical methods - in fact a spreadsheet [3]. Here's how this works -

2.3 The Steps

First we need Newton's third, most "commonsensical", law - every action has an equal and opposite reaction. So if you try to push something it pushes you back, try it on ice where friction does not complicate things much. Here's an example with a skateboard, a man and a big ball -

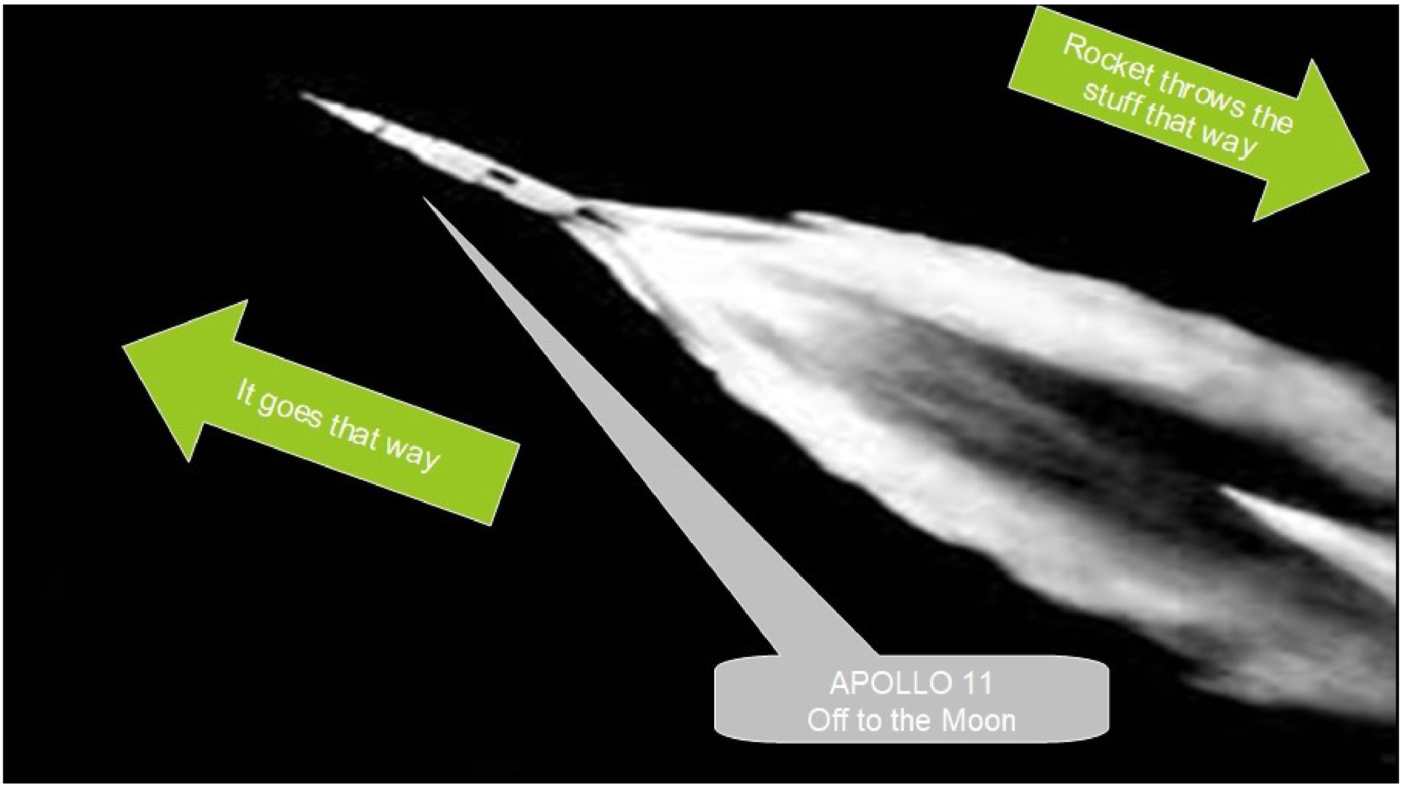


Newton's third law for a skateboard, a man and a big ball

You can also understand this using the idea of conservation of momentum - but this is only introduced late in UK secondary schools.

[1] Older textbooks will use the notation $\log_e$ for the natural logarithm.
[2] using capital M and V here to make the subscripts clearer.
[3] In UK schools spreadsheet work was standard up to a few years ago but some questionable political decisions have made it less common. Nevertheless in many UK schools and most schools elsewhere some facility with spreadsheets is still taught and spreadsheet skills are useful in life outside schools so it's easy to justify introducing it everywhere that basic computer skills are taught. School PCs will normally have a spreadsheet program installed, Excel or LibreOffice Calc.

And like the guy on the skateboard -



Newton's third law on a bigger scale - Saturn 5 lifting Apollo 11.

The force here is 34,000 kN but the mass keeps reducing as the fuel is burnt and pushed out of the back. So the initial acceleration is about 34,000,000 Newtons/2,965,000 kg= 11.5 metres per second per second minus gravity which is 9.8 metres per second per second. So the whole thing only accelerates at 11.5-9.8=1.7 metres per second per second - and it looks quite slow if you watch the video. But as the mass reduces the acceleration increases.

Newton's second law is - F = ma, force = mass times acceleration.
Al-Khwarizmi tells us this must mean that a = F/m, acceleration = force divided by mass.
Or "the harder you push, the greater the acceleration"!
As the Apollo 11 Launch video shows, big heavy rockets start slowly! And gravitation is the other powerful force operating here.
How do we convert rocket acceleration -
a = F/m
- into the velocity we get by using all the fuel?
We have to convert acceleration into velocity.
We can assume that the F from the rocket thrust is constant but the mass we are accelerating keeps reducing as the fuel is burnt and expelled as exhaust.
But we know the total mass of the rocket with all its fuel and the mass of the fuel so we know the initial and final mass of the whole thing.
We also know that F, the force produced by the rocket thrust, from F = ma. In this equation the mass (m) is the exhausted fuel and the acceleration of the exhausted fuel, acceleration (a), is constant because the rate of use of the fuel is constant.

Apollo 11 Launch video: www.youtube.com/watch?v=ygBxN5Ui0aM

If you know calculus you can integrate the equation - $\int a = \int F/m$
The integration limits are time interval so $\int a$ becomes the change in velocity, Δv, no integration required. The right hand side is more tricky. Tsiolkovsky did the integration and came up with his famous equation -

$$\Delta V = Ve \ln\left(\frac{Mo}{Mf}\right)$$

again using capital M and V to make the subscripts clearer

So the ΔV the rocket provides is the exhaust velocity, Ve, multiplied by the natural log (ln) of the mass ratio - the initial mass (Mo) divided by the final mass (Mf).
But how can we demonstrate that this works to the school students who haven't "done" integration and have not been introduced to the concept of momentum, as used in conventional derivations of the equation?
We have two tasks -
Convince students that the equation works while avoiding both momentum and integration.
Convince teachers that the method we use will allow the equation to be derived using only integration - avoiding the concept of momentum.
The sections ***For School Students - The Spreadsheet*** and ***For Teachers - Derivation - Paralleling the Spreadsheet*** below address these two tasks.

3 For School Students - What you can achieve

To understand how the physics of rockets lies behind the engineering which designs them you would normally need to understand both the concept of momentum and the mathematical operation called integration.
Neither of these is required by the approach we suggest in this article.
So if you want to understand the basics of rockets you only need some very basic algebra and how to use a simple spreadsheet on your computer.
We hope that the next section will give you the tools to do this and enable you to -
Work out how good any sort of rocket is - to achieve anything from moving or rotating your small satellite as it orbits the Earth to getting your starship to the star you want it to go to!
Understand the beginnings of calculus - which you will find useful to do things in subjects including rocket engineering, petrol and diesel engine design, construction engineering, accountancy, economics and just about all aspects of physics.
And, we hope, give you an idea of the power of mathematics and the satisfaction of understanding maths as a beautiful thing in itself and a pride in your membership of the human race which has accomplished such mighty things.

4 For School Students - The Spreadsheet

To understand rockets we need the work of Tsiolkovsky and two who came before him, Newton and Al-Khwarizmi. Here's how to use what they gave us.

4.1 Newton

Isaac Newton's three laws, in case you have not done them, are very simple but very powerful (I guess you have already heard of Newton ?).
The laws are -
#1 - an object will not change its motion unless a force acts on it;
#2 - the force on an object is equal to its mass times its acceleration;
#3 - when two objects interact, they apply forces to each other of equal magnitude and opposite directions.
In simple terms -
#1 - things don't move unless you push them;
#2 - the heavier (more massive) an object is, the more you have to push it, and the more you push the greater the acceleration you get;
#3 - when you push something you feel its pushing back on you.
The second law, #2, is the handy one for doing calculations. Mathematicians write is as -
F = ma
Force equals Mass times Acceleration.
On your computer it's -
F = m*a - computers are very literal; you have to tell them to multiply!
Schools will often use the idea of "balance of forces", adding and subtracting them to find out the net force. The methods in this article take one force at a time to keep things simple.

4.2 Al-Khwarizmi

So Newton has given us F = ma but we need to find 'a', the rocket acceleration. Changing the subject to 'a' will need algebra, the gift to us from Al-Khwarizmi [1]. A simple step leads to a = F/m. This is the equation we will use to calculate the acceleration of the rocket once we know the thrust F.
See the sidebar below, Step by Step Algebra, for a simple introduction to the algebra here.

Step-by-step algebra

So F=ma but if our rocket is m kilograms and we push it with F newtons of force then how much will it accelerate?
a=?
Here's how to understand this if you have not yet done algebra in maths. We'll use "*" as our multiply operator, as we do in computing.
You know that 3*6=18, what happens if we divide the left and right of this by 3 -
3*6/3=18/3
We don't really need to do the division on the left. We know that 3/3=1 and 6*1=6 so the left becomes just 6
On the right we started with just 18 and divided this by 3 too - which is also gives us 6.
Surprise surprise: 6=6!
So here's some simple algebra doing the same sort of thing -
x*y=z
What happens if we divide both sides by y?
x*y/y=z/y
But we know 3/3=1 and that anything divided by itself gives 1.
And anything divided (or multiplied) by one is just itself - unchanged.
So if x*y/y=z/y then x*1=z/y and so x=z/y
We have converted x*y=z into x=z/y
So let's take Newton's second law in computer form -
F=m*a
- and divide both sides by m -
F/m=m*a/m
Remember that m/m=1, so the right hand side will be -
F/m=a
- and so -
a=F/m
- which is what we need to calculate accelaration.

Not so clever? But doing maths without numbers is a big conceptual jump, it's algebra, and Al-Khwarizmi [1] made that jump. He was a mathematician who lived over 1000 years ago.

4.3 Tsiolkovsky

You have probably heard of Newton and of algebra (though maybe not Al-Khwarizmi) but to understand rockets you need someone who wants to make things work, an engineer. More about this in the note ***What is a Rocket Scientist?*** at the end of this article.
You have probably never heard of Konstantin Eduardovitch Tsiolkovsky but he was a maths teacher who thought hard about the engineering problem of getting into space. His equation uses Newton and Al-Khwarizmi to solve the problem. He showed that it would be hard but not impossible. He died in 1935 so he never saw the results of his work - satellites, Mars probes, Moon missions and even probes beyond the Solar System.
Newton and Al-Khwarizmi give us a way to calculate the acceleration of a rocket -
a = F/m
- but how much speed do we get out of a rocket when the mass, m, reduces - by being expelled to get the force you need?
Tsiolkovsky wanted to know how fast the rocket would fly once all the fuel was used up. He added all the accelerations on the left hand side and used integration and the concept of momentum on the right hand side to get his famous rocket equation -

$$\Delta V = Ve \ln\left(\frac{Mo}{Mf}\right)$$

- multiplication is implied here - you would need to put a "*" after Ve to keep your computer happy.
ΔV (pronounced delta-vee) [2] is the new speed of the rocket after it burns out. Ve is the exhaust velocity - how fast the rocket exhaust comes out of the rocket. The tricky problem is that the mass of the rocket keeps reducing as the fuel is used up. That's why when you see a big rocket launch it seems to start quite slowly.
Tsiolkovsky's integration produces a function called the natural log (ln). He uses that function on the mass ratio of the rocket. That's the initial mass (Mo) divided by the final mass (Mf).

[1] Muhammad ibn Musa al-Khwarizmi en.wikipedia.org/wiki/Muhammad_ibn_Musa_al-Khwarizmi.
[2] The Greek letter Δ "delta" is used in maths, physics and engineering to mean "change in". So Δv is change in velocity.

Apollo 11 Launch - moon.nasa.gov/resources/288/apollo-11-launch/.
Credit: NASA
Video: www.youtube.com/watch?v=S3ufJ7lcr08

4.4 How do we avoid integration and momentum?

Most school students don't do integration and momentum until late in secondary school (high school in the USA) - and lots don't do them at all. So can we find a way to do what Tsiolkovsky did without these two bits of maths?
How about just "adding the acceleration for each second"? So calculate the speed added each second and add the extra speed every second. This is called a "numerical approximation". And it's used a lot in engineering – and practical sciences like meteorology. We would not get good weather forecasts (maybe not in UK!) without numerical approximation on massive computers. But you don't need monsters like the UK Met Office supercomputer to approximate the rocket equation. A simple spreadsheet will do the job.
Here's how -
Start with the **Mass of rocket** - starting (for example) with 100 kg
Let's decide to recalculate every 10 seconds
If we use 0.1 kg of fuel per second then in 10 seconds the **Mass of exhaust** used will be 10 times that, 1kg
Choose the **Velocity of exhaust** - even a firework rocket can manage 1,000 metres per second.
We already decided to recalculate every 10 seconds so between each calculation the **Time** interval is 10 seconds
We'll use our spreadsheet to calculate the **Acceleration of exhaust** in metres per second per second (note that extra "per second" - acceleration is the rate of change of velocity)
Here's the headings and first row of the spreadsheet -

Mass of rocket	Mass of exhaust	Velocity of exhaust	Time interval	Acceleration of exhaust	Force produced	Acceleration produced	Added velocity of rocket	Velocity of rocket
100	0.00	1000.00	10.00	100.00	0.00	0.00	0.00	0

Just the first four columns have results because the **Acceleration of exhaust** hasn't done its 10 seconds worth of pushing yet.
From that we can fill in the second row of the spreadsheet and calculate the effect of the **Acceleration of exhaust** on the rocket...

Force produced by the rocket using Newton's F = ma - mass (m) is the mass of fuel used [1]. **Acceleration produced** using the other way of writing Newton a = F/m but the mass (m) here is now the mass of the rocket, which we know is getting less and less as the fuel is used up. Now it's simple to take that **Acceleration produced** and work out the **Added velocity of rocket** in the 10 second interval we are using. For the first row of the spreadsheet the **Velocity of rocket** is just the **Added velocity of rocket** since it's starting from zero.

Mass of rocket	Mass of exhaust	Velocity of exhaust	Time interval	Acceleration of exhaust	Force produced	Acceleration produced	Added velocity of rocket	Velocity of rocket
100	0.00	1000.00	10.00	100.00	0.00	0.00	0.00	0.00
100	1.00	1000.00	10.00	100.00	100.00	1.00	10.00	10.00

- now display the calculations (press ctrl and ` for Excel) to see what we have done - Here it is with the row numbers and column letters also shown-

	A	B	C	D	E	F	G	H	I
1	Mass of rocket	Mass of exhaust	Velocity of exhaust	Time interval	Acceleration of exhaust	Force produced	Acceleration produced	Added velocity of rocket	Velocity of rocket
2	100	0	1000	10	=C2/D2	=B2*E2	=F2/A2	=G2*D2	0
3	=A2-B2	1	=C2	=D2	=C3/D3	=B3*E3	=F3/A3	=G3*D3	=I2+H3

But now we add a row to calculate for the next 10 second interval with the **Mass of rocket** now reduced by the **Mass of exhaust** used up in the first row. Calculate the whole row again and notice that the **Force produced** is the same but, because the **Mass of rocket** is less the **Acceleration produced** and the **Added velocity of rocket** have increased. More rows...

Mass of rocket	Mass of exhaust	Velocity of exhaust	Time interval	Acceleration of exhaust	Force produced	Acceleration produced	Added velocity of rocket	Velocity of rocket
100	0.00	1000.00	10.00	100.00	0.00	0.00	0.00	0.00
100	1.00	1000.00	10.00	100.00	100.00	1.00	10.00	10.00
99	1.00	1000.00	10.00	100.00	100.00	1.01	10.10	20.10

The rocket is accelerating faster.

[1] **A Note on the SpreadSheet Time Interval**
Sharp-eyed teachers and more advanced students will notice that the value of acceleration of exhaust, and thus force, calculated here depends upon the time interval chosen. This looks arbitrary. However, the length of the time interval Δt chosen affects the accuracy of the computation performed by the spread-sheet **but not the validity of the model of rocket propulsion**. If a "long" time interval is chosen the acceleration $a_e = v_e / \Delta t$ is decreased in value, but the amount of mass accelerated during the interval which is $m_e = k\,\Delta t$ where k is the burn-rate is increased. Conversely, if a "short" time interval is chosen, then the acceleration increases but the amount of mass accelerated in the interval decreases. So what matters is not the value of the acceleration per se, but the multiplication product,

$$m_e\, a_e = (v_e / \Delta t)\, k\, \Delta t = k v_e$$

which is constant since both k and v_e are constant attributes of the rocket motor. kv_e is the constant the "thrust force" which acts on the decreasing mass of the rocket plus fuel.

The length of the time-interval does affect the accuracy of the computation performed by the spreadsheet as the rocket's velocity is taken to be constant during this period, whereas in reality it is constantly increasing. In essence this is the old problem of approximating a curve by series of straight-line segments. The shorter the segments are the better the approximation, and the longer they are, the worse the approximation.

Keep adding rows and see the complete spreadsheet. Here's some sample rows -

Mass of rocket	Mass of exhaust	Velocity of exhaust	Time interval	Acceleration of exhaust	Force produced	Acceleration produced	Added velocity of rocket	Velocity of rocket
100	0.00	1000.00	10.00	100.00	0.00	0.00	0.00	0.00
100	1.00	1000.00	10.00	100.00	100.00	1.00	10.00	10.00
99	1.00	1000.00	10.00	100.00	100.00	1.01	10.10	20.10
98	1.00	1000.00	10.00	100.00	100.00	1.02	10.20	30.31
97	1.00	1000.00	10.00	100.00	100.00	1.03	10.31	40.61
...								
50	1.00	1000.00	10.00	100.00	100.00	2.00	20.00	708.17
49	1.00	1000.00	10.00	100.00	100.00	2.04	20.41	728.58
48	1.00	1000.00	10.00	100.00	100.00	2.08	20.83	749.41
...								
22	1.00	1000.00	10.00	100.00	100.00	4.55	45.45	1542.02
21	1.00	1000.00	10.00	100.00	100.00	4.76	47.62	1589.64
20	1.00	1000.00	10.00	100.00	100.00	5.00	50.00	1639.64
...								
5	1.00	1000.00	10.00	100.00	100.00	20.00	200.00	3104.04
4	1.00	1000.00	10.00	100.00	100.00	25.00	250.00	3354.04
3	1.00	1000.00	10.00	100.00	100.00	33.33	333.33	3687.38
2	1.00	1000.00	10.00	100.00	100.00	50.00	500.00	4187.38
1	1.00	1000.00	10.00	100.00	100.00	100.00	100.00	4287
Mass of rocket	Mass of exhaust	Velocity of exhaust	Time interval	Acceleration of exhaust	Force produced	Acceleration produced	Added velocity of rocket	Velocity of rocket

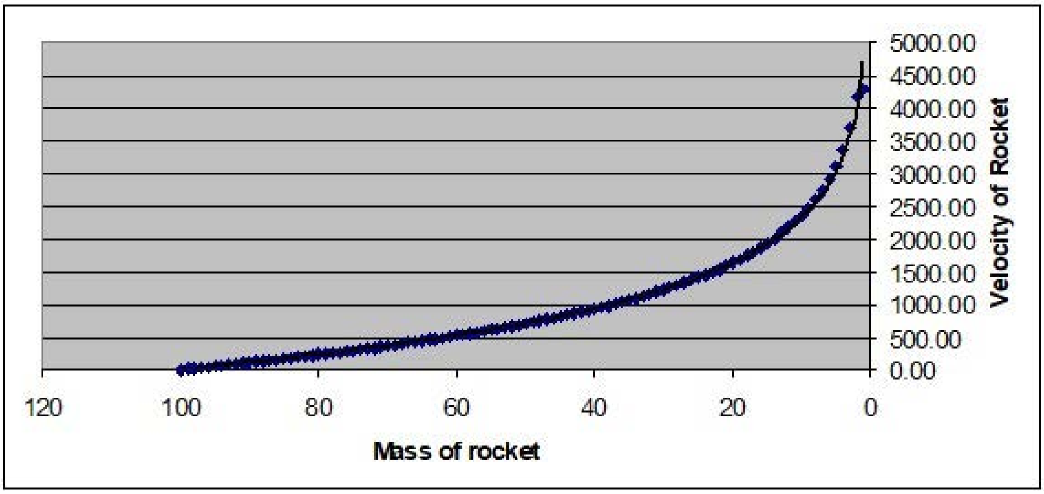
The header row is repeated at the bottom for clarity. Look at how the last row has the same Acceleration of exhaust and Force produced as in all the other rows but the Acceleration produced and Added velocity of rocket are much greater in each row - just because the rocket is getting lighter as the fuel is used up. The spreadsheet is available on the i4is website at i4is.org/wp-content/uploads/2022/03/RocketCalcSimpleForTsiolkovsky.xls.

4.5 Comparing Tsiolkovsky with your spreadsheet

Here's what Tsiolkovsky taught us -

$$\Delta V = Ve \ln\left(\frac{Mo}{Mf}\right)$$

The ln function produces something called a logarithmic curve. If you plot it as a graph, here's the curve you get from your spreadsheet ⇨



It looks a bit like an exponential curve but let us consult an "unbiased observer", Excel itself. Excel allows a trendline to be fitted to the curve and a function approximated. In this case Excel yields - y = -1015.1Ln(x) + 4683.3 - a natural log function displaced by the final value 4683.3. It's a logarithmic curve [1].
Let's take the same values you have in the spreadsheet and plug them in to -

$$\Delta V = Ve \ln\left(\frac{Mo}{Mf}\right)$$

Mo is 100 kg, Mf is 1 kg and Ve (the exhaust velocity) is 1,000 metres per second.
The mass ratio, the bit in the bracket, is 100/1 = 100. The natural log (ln) of 100 is 4.60 so the final (change in) velocity, ΔV, is 4.60*1000 = 4,600 metres per second.
This isn't exactly right but not a bad approximation for a spreadsheet! And you have a logarithmic curve just like the one produced by the Tsiolkovsky equation.

4.6 How to design better rockets

The Mf in the example, 1 kg, has to include the whole structure of the rocket and the cargo, called the payload, so it's a bit unrealistic! Imagine the rocket structure is 10 kg and the payload is 10 kg, total 20 kg. Looking at the 20 kg spreadsheet row -

Mass of rocket	Mass of exhaust	Velocity of exhaust	Time interval	Acceleration of exhaust	Force produced	Acceleration produced	Added velocity of rocket	Velocity of rocket
20	1	1000	10	100	100	5	50	1639.64

The velocity of the rocket is now 1639.64 metres per second but we are carrying a lot of structure we needed to hold the 80 kg of fuel we have used. Let's throw away that extra structure and start again with a 10 kg rocket, much lighter. This is the principle of the multi-stage rocket and you will notice that all real launches into space have more than one rocket stage.

[1] Mathematically a logaritmic curve is the inverse of an exponential curve. thirdspacelearning.com/gcse-maths/algebra/inverse-functions/

4.7 For Teachers - A better approximation and a two stage rocket

The spreadsheet approximation was first devised by John Davies of i4is but a better mathematician took a look and did produce an improved spreadsheet. Robert Freeland was the lead, with Michel Lamontagne, of the Firefly design - the most successful of the Project Icarus studies for probes propelled by a fusion rocket- extending the 1970s design of Project Daedalus of the British Interplanetary Society.

Robert saw potential in the original spreadsheet approximation and devised a better approximation with wider usefulness with -

- Two rocket stages
- More incremental steps in the spreadsheet for a better approximation
- Parallel use of the Tsiolkovsky equation to show the accuracy of the approximation

The Freeland spreadsheet is available on the i4is website at i4is.org/wp-content/uploads/2022/03/Incremental-Rocket-Example-Edited-by-Robert-Freeland.xls.

The columns in this version are -

Rocket Mass (tonnes), Exhaust Mass (tonnes), Exhaust Velocity (km/s), Time Interval (s), Acceleration of Exhaust (km/s2), Force Produced (MN), Acceleration Produced (km/s2), Added Velocity (km/s), Rocket Velocity (km/s), Elapsed Time (s), Tsiolkovsky Velocity (km/s)

4.8 More resources

There is a lot written about rocketry and the Tsiolkovsky equation. Here are just a few suggestions which may be useful background

The tyranny of the equation - a piece by NASA engineer/astronaut Don Pettit, almost cursing the limits set by Tsiolkovsky's equation [1] shows the frustration which Tsiolkovsky himself must have felt when he appreciated the consequences of his formula. As he said "Earth is the cradle of mankind but one cannot live in a cradle forever".

Other derivations of the equation - most use momentum and calculus -

NASA: www.grc.nasa.gov/WWW/K-12/rocket/rktpow.html
ESA: blogs.esa.int/rocketscience/2012/10/14/a-man-and-an-equation/
Wikipedia: en.wikipedia.org/wiki/Tsiolkovsky_rocket_equation#Derivation

Specific impulse is a measure of the efficiency of particular rocket technologies - both fuels and rocket motors. It is proportional to exhaust velocity [2].

Since it is measured in seconds it can be used instead of exhaust velocity to avoid numbers which differ between imperial and metric units. Exhaust velocity can, for example, be in feet per second or miles per hour versus metres per second and kilometres per hour but specific impulse is measured in seconds - which are the same in both systems of units.

Low mass/high exhaust velocity thrusters - ion propulsion gives high exhaust velocity and thus high specific impulse. So it uses less propellant to produce the same ΔV but ion thrusters are not scalable to the high thrust needed for launch from Earth [3].

4.9 Fission Rockets

Nuclear power has been advocated as a basis for rockets since at least the end of the Second World War in 1955. The difficulties of using a bulky and heavy device like the fission reactors used in power stations and ships has been much explored and solutions have been proposed that even go as far as suggesting an all-gas core. Recently interest has been revived as a way of speeding human Mars missions given the radiation load on astronauts inevitable with chemical rockets which would typically take about 6 months to get to Mars. More in a recent survey by NASA's Kurt A Polzin[4].

[1] The Tyranny of the Rocket Equation, www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny.html/
[2] Specific impulse: en.wikipedia.org/wiki/Specific_impulse
[3] NASA - Ion Propulsion, www.nasa.gov/centers/glenn/about/fs21grc.html
[4] Enabling Deep Space Science Missions with Nuclear Thermal Propulsion, assets.pubpub.org/gfaq1me4/01617915247833.pdf

4.9 Fusion Rockets

Fusion power offers much greater promise but remains to be demonstrated. An article in Principium 22 August 2018 *Reaching the Stars in a Century using Fusion Propulsion* [1] introduces the propulsion technology of the most developed of the *Project Icarus* fusion-based probes.

5 Conclusion

In this article I hope I have introduced school students and their teachers to a way of understanding the maths and physics of rocket propulsion without requiring concepts in both subjects which students may not have encountered and which many will never encounter. My objective is to both demystify rockets and to provide an early inkling of those more advanced concepts. I would be very pleased to hear from both students and teachers with both questions and suggestions for improvement (john.davies@i4is.org).

The second article in this Principium series will explore the maths and physics behind laser sails and solar sails. Human ingenuity faced with the hard reality of the Tsiolkovsky rocket equation has, as usual, found a "work around" and Tsiolkovsky himself, all those years ago, also dreamed that light might propel future spacecraft.

Thanks to Atholl Hay and Graham Paterson (City of Glasgow College) for their advice. Errors and omissions remain my own.

6 Final Note: What is a rocket scientist?

In the biography by Michael Neufeld of Werner Von Braun, *Von Braun: Dreamer of Space, Engineer of War* [2], his biographer says -

> One term you will not find in this book is "rocket scientist." There has been a deep-rooted failure in the English-speaking media and popular culture to grapple with the distinction between science and engineering. Although the boundaries are fuzzy, and a leading historian of technology has argued that all we have now is a unitary "technoscience," I still find it useful to think of a spectrum. On one end is basic science, which aims at achieving an understanding of the laws of nature without regard for their practical application, and at the other is engineering, which is about creating technological devices to shape the world to human purposes. Although Werner von Braun got a doctorate in physics in 1934, he never worked a day in his life thereafter as a scientist. He was an engineer and a manager of engineers, and he used that vocabulary when he was talking to his professional peers. Thus the correct term is "rocket engineer."
>
> In short the term "rocket scientist" contains a contradiction. But the world recognises it and we, as practical engineers, must live with it.

The term scientist is also misapplied to a whole, and very important, subject area "Computer Science". Alan Turing is often called the first "computer scientist". To adapt from Neufeld "Alan Turing never worked a day in his life as a scientist" and neither do modern "computer scientists". The field includes engineering, both hardware and software, and mathematics - often referred to as "theoretical computer science". Turing was a mathematician of the first rank and an ingenious engineer of both hardware and software. He was also a significant contributor to philosophy, as his 1950 paper in the journal *Mind* shows [3]. He was never a scientist - of computers or anything else. But we must live with the contradiction here too.

Science discovers how the world (and the universe) works. Mathematics discovers how to manipulate symbols and numbers systematically. Engineering creates and enhances physical and abstract structures and mechanisms for specific human purposes - often using maths and science but sometimes by pure invention. ■

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

[2] Von Braun was project leader of the team which designed the Saturn 5 moon rocket and before that the V2 rockets which bombarded Antwerp and London in the Second World War.

[3] *Computing machinery and intelligence,* Alan M Turing 1950, *Mind*, 59, 433-460, www.cs.ox.ac.uk/activities/ieg/e-library/sources/t_article.pdf

The Initiative for Interstellar Studies

image: ©ALEX STORER

JOIN US

Working towards the real Final Frontier

Help us to realise our mission to reach the stars - we need your help - physics to software engineering, graphic design to project management - and rocket engineering of course! ...and much more....
Some of us have PhDs, some masters and first degrees and others simply have talents! What we all share is enthusiasm for the interstellar future of humanity. We have about 20 active team members, led by -

» Dr Andreas Hein: Executive Director/Technical Director - andreas.hein@i4is.org
» Robert G Kennedy III: President i4is USA - robert.kennedy@i4is.org
» Rob Swinney: Education Director - rob.swinney@i4is.org
» John Davies: Editor Principium - john.davies@i4is.org
» Tam O'Neill: Manager Membership/Website team - tam.oneill@i4is.org

Join the team if you can help - become a member if you simply want to support our work.

Contact: info@i4is.org
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Web: i4is.org
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THE i4iS MEMBERS' PAGE

The i4is membership scheme exists for anyone who wants to help us achieve an interstellar future. By joining i4is, you help to fund our technical research and educational outreach projects. In return, members receive exclusive benefits, including our programme of talks, a newsletter and preprints, and access to the members-only area of the website, to which new material is added on a regular basis. If you aspire to an interstellar future for humanity, joining our membership scheme will allow you to get more involved while helping us take the vital early steps toward that goal.

Visions of our interstellar future.

Videos from our 2021 summer course *Human Exploration of the Far Solar System and on to the Stars*, delivered by i4is on behalf of Limitless Space Institute are now available to members.
The opening session featuring Sonny White of LSI and Rob Swinney of i4is is open to all at - www.youtube.com/watch?v=-J78I_J1NmE.
More about this on the second page of this *i4is Members' Page*.

Members' newsletter

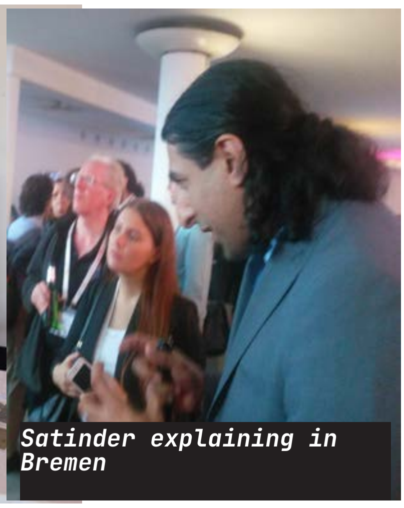
Members will have noticed that they have not received our newsletter for several months but a new edition should have arrived in your Inbox in mid-May. Get in touch if you did not see it - membership@i4is.org. As always it's also available via the website if you login i4is.org/members/.
We apologise to members for the interruption and aim to resume normal service in future.
We now believe we have the team in place to resume regular publication of the newsletter.

Getting more actively involved

There are lots of other ways you can help us take our programmes forwards, whether your skills are technical, scientific, educational, administrative or financial. If you think you could volunteer some of your time, please get in touch at info@i4is.org, and one of the team will get back to you.
And print our poster, on the previous page, to tell your friends and colleagues too.


Terry, John & Jeremy at a London school


Tishtry and Anna at a BIS event


Satinder explaining in Bremen

i4is volunteers at work... and there's lots to do remotely

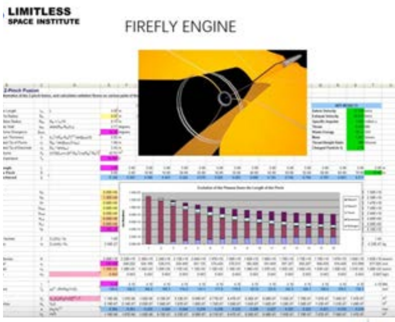
Exploring Equations

On the Members page of the website you will find - **Exploring Equations**NEW! (i4is.org/equations), a new public page where you can try out both the rocket equation and the light sail equation. For anyone who is new to them - or new to equations generally - we hope it's interesting and instructive.

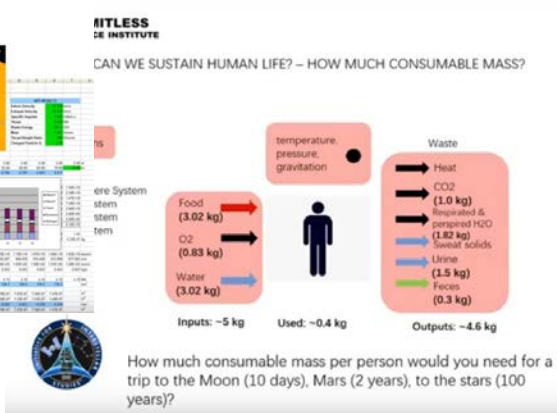
Human Exploration of the Far Solar System and on to the Stars

The presentations are now available to members at i4is.org/videos/lsi-course-2021/. They are -

Introduction and Background	Rob Swinney
Aspects of Science	Rob Swinney
Next Steps	Richard Osborne
In Situ Resource Utilisation as an Enabler	Satinder Shergill
Humanity's Power Basis for Starfaring	Robert Kennedy
Propulsion Introduction	Dan Fries
Electric Propulsion	Rob Swinney
Nuclear Propulsion - Fission and Fusion	Rob Swinney
Speculative Propulsion	Dan Fries
Spacecraft Systems	Andreas Hein
Case Studies: Power, Heat and Shielding	Michel Lamontagne
Case Study: Meeting the Human Requirements	Andreas Hein
Special Guest Panel	Brian Kelly / Gregory Johnson [1]
Deep Space Design Methods and Principles	Andreas Hein
Nuclear Rockets and other Large Concepts	Rob Swinney
Interstellar Starships in Science Fiction	Patrick Mahon
Space Habitats, Colonies and Worldships	Michel Lamontagne
Chipsats and Other Small Concepts	Andreas Hein
Visions of our Interstellar Future	John Davies
Participating Teams Presentations	teams [2]
Human Survivability: A Justification for Space Exploration	Team 1
Justification: Spiritual Insight	Team 4
Resource Utilisation for Interstellar exploration	Team 2
General Discussion and Course End	



Credit: Michel Lamontagne, Rob Swinney & Andreas Hein



[1] Brian Kelly (LSI, NASA Flight Operations), Gregory Johnson (Final Shuttle Hubble mission pilot - STS125) with Amelia Stanfon and Rob Swinney
[2] Team 3 did not present

Finding new ways to share resources in space

A review of Dennis O'Brien: "Is outer space a de jure common-pool resource?"

Max Daniels

Max Daniels brings us more policy analysis with implications for our long term space activities. Here he offers a critique of a recent paper by space lawyer Dennis O'Brien, *Is outer space a de jure common-pool resource?* [1] In our earlier issues, Max has discussed *Territory in Outer Space* (Principium 24, February 2019), *The Artemis Accords: what comes after the Moon?* (Principium 32. February 2021). The world is laying the foundations for a Solar System civilisation, without which we cannot extend our reach to the stars.

Dennis O'Brien is a lawyer and president of the Space Treaty Institute, a non-profit working to build a framework of laws in outer space. He has written extensively[2] in favour of the Moon Treaty [3], publishing his own agreement to accompany it. In his article, *Is outer space a de jure common-pool resource?*, which is the focus of this review, he continues along this theme.

O'Brien argues that we are approaching a critical moment when we can go into space and access its resources. This echoes the 15th-century Age of Exploration, and just like then, such activity needs to be governed. He says that space is indeed a de jure common-pool resource, where the Artemis Accords[4] are incompatible with international law.

This review disputes aspects of O'Brien's case. The creation of international law and norms in space is more complex than he describes, while the Artemis Accords will not be the final agreements ever made; rather, they are just a part of an evolving patchwork of space policy. First, a look at O'Brien's contributions to this debate.

A Model Implementation Agreement

O'Brien urges the Biden administration to sign the Moon Treaty, as it would support the private sector while protecting "essential public policies" [5]. The Treaty describes, "an international regime... to govern the exploitation of the natural resources of the moon" (Art. 11, para. 5).

[1] In *The Space Review*, 25 October 2021, www.thespacereview.com/article/4270/1 www.thespacereview.com/article/4270/1
[2] *The Space Treaty Project, Space Law* www.spacetreaty.org/space_law
[3] *IV. Resolutlons adopted on the reports of the Special Political Committee* www.unoosa.org/pdf/gares/
[4] The Artemis Accords, Principles for Cooperation in the Civil Exploration and use of the Moon, Mars, Comets, and Asteroids for peaceful purposes www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf
[5] *In the new spectrum of space law, will Biden favor the Moon Treaty?*, O'Brien in *The Space Review*, November 23, 2020 www.thespacereview.com/article/4073/1

This needs to be put into practice, and so the Space Treaty Institute has developed a 'Model Implementation Agreement' [1] to bring it into reality [2].

The Model Agreement is centred around four principles: it supports all private activities in space (and not just mining, as with the Artemis Accords); private property rights would be granted in exchange for public-policy obligations; significant policy issues should be addressed through an agreed governance process; and it would build upon existing institutions.

This is a modern and carefully formed proposal for the governance of a space economy. A problem is that no major spacefaring nation has ratified the Moon Treaty, which means none would need the Model Agreement. Instead, several States have already signed the Artemis Accords.

This review first explores "de jure" common-pool resources' before arguing that his analysis of safety zones does not appreciate what they offer.

Viewing space as a 'commons'

This concept is from the framework of Nobel Prize-winning economist Elinor Ostrom (Fig 1 [3]), who wrote extensively on how groups organise themselves to manage resources [4]. Ostrom's theories run counter to Garrett Hardin's 'tragedy of the commons' thesis [5], which held that individual users of a shared environment would degrade it - as in the oceans, rivers, or even outer space. She offered an alternative, where users find ways to manage these resources sustainably, avoiding the need for privatisation or for government to intervene [6].

Authors have applied Ostrom's framework to space. Common-pool resources can be observed where satellites are placed in specific orbits such as near-Earth orbit or use certain communications frequencies [7]. Both can threaten the availability of resources to other users and create unsustainable levels of debris [8].

		Subtractability of Use	
		High	Low
Difficulty of Excluding Potential Beneficiaries	High	Common-pool resources: groundwater basins, lakes, irrigation systems, fisheries, forests, etc.	Public goods: peace and security of a community, national defense, knowledge, fire protection, weather forecasts, etc.
	Low	Private goods: food, clothing, automobiles, etc.	Toll goods: theaters, private clubs, daycare centers

Figure 1: Elinor Ostrom's categories of goods and resources [3]

[1] Model Implementation Agreement for the Moon Treaty (January 2021) spacetreaty.org/modelimplementationagreement.pdf
[2] *Avoiding a New Age of Imperialism: An Article 11 Implementation Agreement for the Moon Treaty* youtu.be/i4Ayz1hy3YQ
[3] Elinor Ostrom Prize Lecture, *Beyond Markets and States: Polycentric Governance of Complex Economic Systems* www.nobelprize.org/prizes/economic-sciences/2009/ostrom/lecture/
[4] *Elinor Ostrom's work on Governing The Commons: An Appreciation*, Wyn Grant. 2012 blogs.lse.ac.uk/lsereviewofbooks/2012/06/17/elinor-ostroms-work-on-governing-the-commons-an-appreciation/
[5] *The Tragedy of the Commons*, Garrett Hardin (1968) in Science, New Series, Vol. 162, No. 3859, pp. 1243-1248, American Association for the Advancement of Science www.jstor.org/stable/1724745
[6] *Governing the Commons for two decades: A complex story*, Erling Berge & Frank van Laerhoven (2011) in International Journal of the Commons www.thecommonsjournal.org/articles/10.18352/ijc.325/
[7] An Introduction to Ostrom's Eight Principles for Sustainable Governance of Common-Pool Resources as a Possible Framework for Sustainable Governance of Space, T Chow & B Weeden, Secure World Foundation (2012) swfound.org/media/61531/isusymposium2012paper_tchowbweeden.pdf
[8] *Elinor Ostrom Goes to Outer Space - An Association of Space Appropriators*, Shane Chaddha (2013) papers.ssrn.com/sol3/papers.cfm?abstract_id=2293581

What is a "de jure" common-pool resource?

O'Brien argues that space is a "de jure" common-pool resource'. There are two parts to this definition. First, resources in space are 'subtractable': that is, when an individual uses a resource, such as Lunar ice caps, there is less of it for everyone else.

Second, these resources are not highly 'excludable'. If an individual takes resources (known as appropriation), it excludes others from doing the same. The Outer Space Treaty of 1967 (or OST) [1] prevents the appropriation, and so exclusion, of space and its resources. O'Brien combines these two aspects of space's resources – their subtractability and excludability under international law – to label them a "de jure" common-pool resource.

Safety Zones

This review breaks down O'Brien's support of the Moon Treaty with a focus on safety zones. It is argued that these are complex, and a useful attempt at forming effective approaches to governance.

The safety zones outlined in Section 10 of the Artemis Accords rely on the exclusion of other states, according to O'Brien. This would violate Art. I and II of the OST. There is justification to these fears, but safety zones are more complex than this.

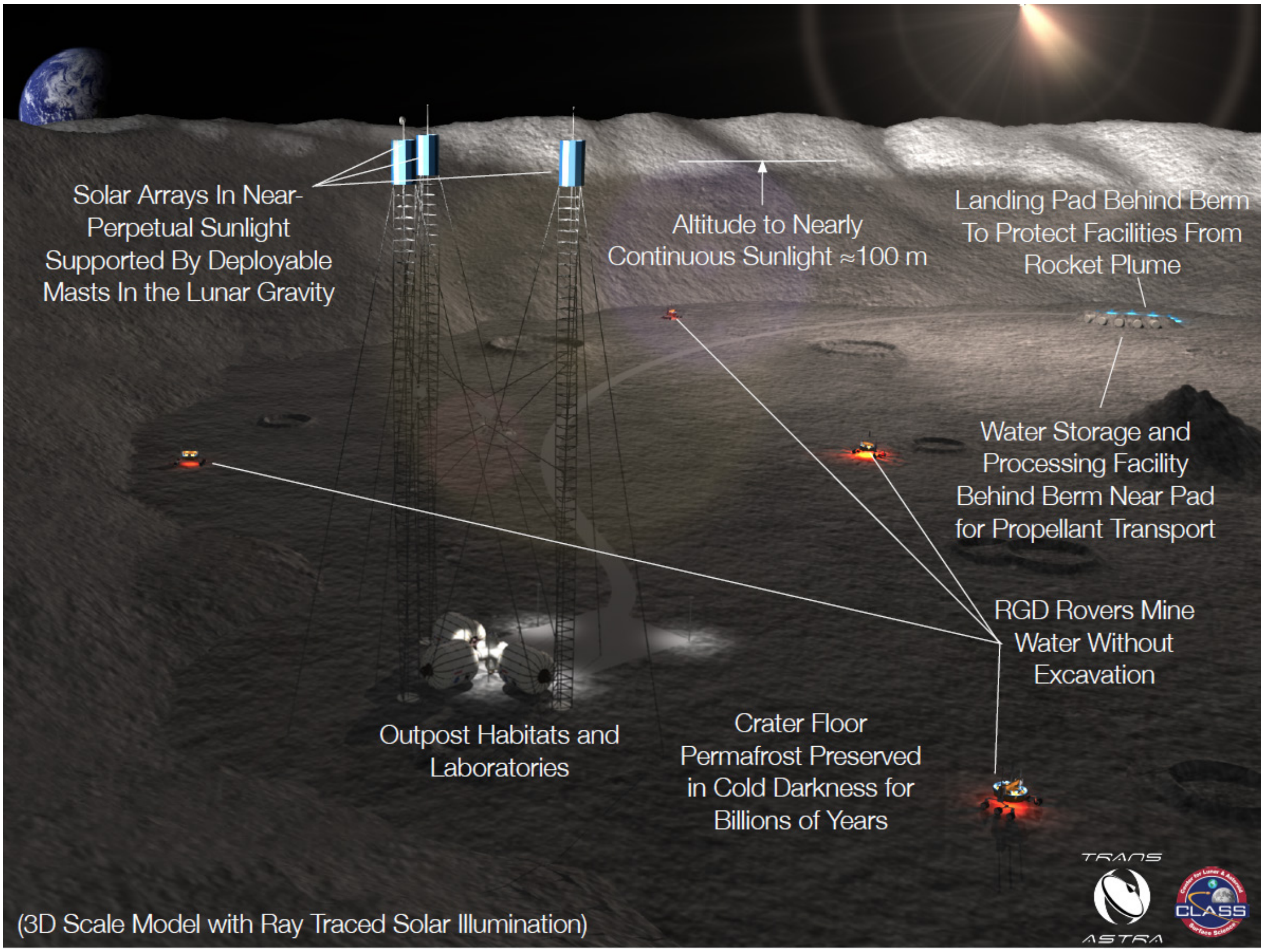


Figure 2: NASA depiction of extraction site of Lunar ice within a near-polar crater [1]

[1] Outer Space Treaty, 1967: www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html

At best, the term 'safety zones' is vague. In space they are a relatively recent concept, where Schingler warns: "there are no precedents here." [1] Some authors, however, have made a start. Newsome [2] and Stubbs [3] give safety zones three 'general principles': they should be transparent, they do not grant sovereign rights, and, "law that applies outside, also applies inside the zone." Schingler adds that they should be dynamic and respond to the mobile nature of assets in space.

They are not simply about land-grabs. They could be for practical reasons, as one state would not want another Lunar base (such as in Fig 2) right next to theirs which would blow up dust or interfere with transmissions and so disrupt operations[4]. Gilbert defines them by what they do: describing situations when mission operators believe third parties should "avoid harmful interference". [5]

Echoing this, Salmeri [6] argues that if resource-extraction were done in a well-communicated way that includes informing the UN, it would fulfil obligations under Art. IX and XI of the OST. Such transparency would provide a legal basis for the extraction of resources, as well as the sustainable use of the space environment.

This is not to say that the Artemis Accords are the ideal agreement, now or in future. Safety zones, as Gilbert concludes, are just the latest iteration towards building a sustainable lunar presence. Attempts to move towards agreed principles for operations in space should be welcomed.

O'Brien is right to apply Ostrom's framework in space. His suggestions that the Artemis Accords are a fundamental mistake and that this is our last chance are naïve. We can and should keep trying new approaches to space policy. ■

[1] *Imagining safety zones: Implications and open questions*, Jessy Kate Schingler (2020) www.thespacereview.com/article/3962/1

[2] *The Legality of Safety and Security Zones in Outer Space: A Look to Other Domains and Past Proposals*, Ted Adam Newsome, McGill University (2016) escholarship.mcgill.ca/downloads/zp38wg314.pdf

[3] *The Legality of Keep-Out, Operational, and Safety Zones in Outer Space*, Matthew Stubbs, in *War and Peace in Outer Space Law, Policy, and Ethics*, Cassandra Steer & Matthew Hersch (2021) https://oxford.universitypressscholarship.com/view/10.1093/oso/9780197548684.001.0001/oso-9780197548684-chapter-9

[4] *NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts* (2011) www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf

[5] *Safety Zones for Lunar Activities under the Artemis Accords*, Alexander Q Gilbert, Colorado School of Mines & Open Lunar Foundation (2022) uploads-ssl.webflow.com/5e4b7985a58df89b6c254001/6168af8319f5549af4dfc227_Pre-Print%20Safety%20Zones%20for%20Lunar%20Activities%20AQG%20Open%20Lunar%20Foundation.pdf

[6] NATO Legal Gazette, Issue 42 www.act.nato.int/application/files/5716/4032/2170/legal_gazette_42.pdf

About the Author

Max Daniels is Campaigns & Public Affairs Manager at Mid and South Essex NHS Foundation Trust. He was previously a Parliamentary Officer in the UK House of Commons. Max has an MA in Geopolitics, Territory and Security from King's College London, specialising in the political geography of outer space, and a BA in Geography from the University of Durham.

KEEP AN EYE ON OUR FACEBOOK PAGE

Our Facebook page at **www.facebook.com/InterstellarInstitute** is a lively forum much used by our own Facebookers and others active in our subject area.

NEXT ISSUE

Back in 1984. Robert L Forward published a paper entitled *Roundtrip Interstellar Travel Using Laser-Pushed Light-sails'* (Vol 21, No.2, J. Spacecraft, March-April 1984) [1] including the equation deriving acceleration from photon power, sail reflectance and vehicle mass.

• **Two Equations to the Stars - Part Two: The Photon Sail Equation:** Even using fusion, the capabilities of rocket propulsion remain limited by Newton's second law and thus the Tsiolkovsky rocket equation. Our second equation shows how probes propelled by light are limited only by the capacities of the photon source and the sail - up to the limit set by Einstein's light speed barrier, John I Davies

• **Human Exploration of the Far Solar System and on to the Stars:** A report on our summer 2021 courses, delivered by i4is for the Limitless Systems Institute (LSI) - reporter, Patrick J Mahon (postponed from this issue)

• **73rd International Astronautical Congress 2022 - The Interstellar Papers:** Your guide to all that's interstellar at the biggest world space conference of the year

• **Book Review: Life in the Cosmos (Minasvi Lingam & Abraham Loeb):** by i4is Technical Director, Andreas Hein [2]

- plus, of course. *Interstellar News* and interstellar papers in *The Journals*.

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[1] web.archive.org/web/20170808080011id_/http://interstellar-flight.ru/design/base_e/rit-1.pdf
[2] Associate Professor of Space Systems Engineering at SPASYS, Université du Luxembourg.

COVER IMAGES

Our cover images for this issue look near and far! A probe to 1i/'Oumuamua is a near term possibility, galactic warps and collisions are far far away.

FRONT COVER

Project Lyra probe and the Pale Blue Dot

i4is Project Lyra is an ongoing programme of work on the interception of interstellar objects (i4is.org/what-we-do/technical/project-lyra/). One major theme of this work is the use of gravitational slingshots to add velocity to a probe and a particularly effective way of doing this is a solar Oberth manoeuvre. Such a probe needs shielding close to the Sun and a rocket to add the perihelion kick required. The image depicts such a craft, with the Pale Blue Dot of the Earth in the middle of the misty band to the right, as it heads outwards to intercept the ISO 1I/'Oumuamua.

Credits: spacecraft: Malavika Patel (3D model), Adrian Mann (rendering). background: NASA (www.nasa.gov/feature/jpl/pale-blue-dot-revisited) composite: John I Davies

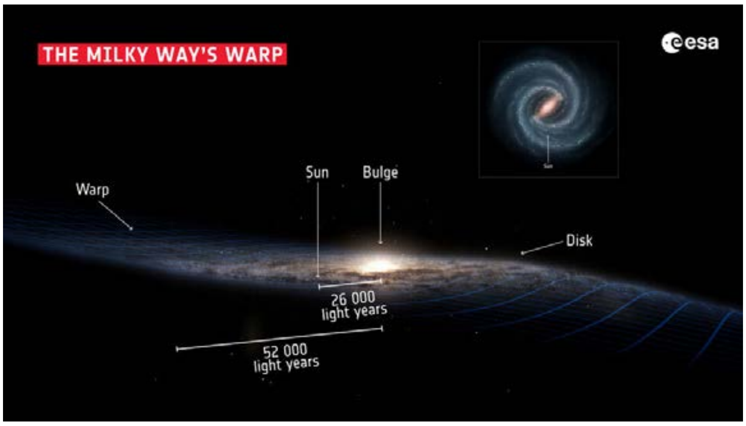
BACK COVER

Milky Way's warp caused by galactic collision, Gaia suggests

From ESA: Astronomers have pondered for years why our galaxy, the Milky Way, is warped. Data from ESA's star-mapping satellite Gaia suggest the distortion might be caused by an ongoing collision with another, smaller, galaxy, which sends ripples through the galactic disc like a rock thrown into water. www.esa.int/Science_Exploration/Space_Science/Gaia/Milky_Way_s_warp_caused_by_galactic_collision_Gaia_suggests

Image credit: Stefan Payne-Wardenaar; Magellanic Clouds: Robert Gendler/ESO

Paper: *Evidence of a dynamically evolving Galactic warp* - Poggio, E, Drimmel, R, Andrae, R et al. Evidence of a dynamically evolving Galactic warp. Nat Astron 4, 590–596 (2020). doi.org/10.1038/s41550-020-1017-3



We are not too close to the warp!
Credit: Stefan Payne-Wardenaar; Inset: NASA/JPL-Caltech; Layout: ESA.

MISSION

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

VISION

We look to a positive future for humans on Earth and in space. Our vision is to be an organisation catalysing the conditions in society supporting a sustainable space-based economy. Over the next century and beyond we aim to enable robotic and human exploration of space beyond our Solar System and to other stars. Ultimately we envisage our species as the basis for an interstellar civilisation.

VALUES

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

The Initiative for Interstellar Studies is a pending institute, established in the UK in 2012 and incorporated in 2014 as a not-for-profit company limited by guarantee.
The Institute for Interstellar Studies was incorporated in 2014 as a non-profit corporation in the State of Tennessee, USA.

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John I Davies, Carol Wright, Lindsay A Wakeman

Front cover: Project Lyra probe and the Pale Blue Dot
Credit: Malavika Patel. Adrian Mann, NASA, John Davies
Back cover: Milky Way's warp caused by galactic collision
Credit: ESA
Credit: ??
Back cover: ??
Credit: ??

SCIENTIA AD SIDERA
KNOWLEDGE TO THE STARS

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