

PRINCIPIUM

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Scientia ad sidera
Knowledge to the stars

Editorial

Welcome to issue 24 of **Principium**, the quarterly newsletter about all things interstellar from i4is, the **Initiative** and **Institute for Interstellar Studies**.

Our Introduction feature is *Project Glowworm: Testing Laser Sail Propulsion in Low Earth Orbit* by Zach Burkhardt, a member of the i4is Project Glowworm team.

Our front cover is a pre-encounter impression of Kuiper Belt Object, Ultima Thule, by David Hardy. The resemblance to an early New Horizons image of 2014 MU₆₉ is remarkable. Our back cover is Terry Regan's BIS Daedalus model with a background devised by Paul Kemp to go with *Project Daedalus – A Beginner's Guide* by Patrick Mahon in this issue.

We have *The TVIW Power of Synergy Symposium* reported by chair, Dr John D G Rather. You may recall the full programme in the last issue of Principium.

Territory in Outer Space by King's College London postgraduate Max Daniels examines the political and legal issues of exploration and settlement in space which will inevitably extend to interstellar when this is achieved.

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Amerigo: Brief Overview of a 1000 AU probe study by Jamie Bockett summarises the project at the i4is Starship Engineer Summer School in August 2018.

Our News includes the upcoming participation of Andreas Hein and Dan Fries in the MIT *Beyond the Cradle* event, Kelvin F Long interviewed for Universe Today, Professor Carl Murray of Queen Mary University of London on the Cassini mission at i4is HQ, The Mill, David Hardy at The Mill - *To the Stars on a Paintbrush*, our announcement that i4is will deliver a two-week elective on Chipsats at the International Space University, and Acta Astronautica published papers on i4is Projects Lyra

and Dragonfly. We also report a concert/lecture, *The Mystery of 'Oumuamua*, at Kings Place, London, and the Hein/Baxter paper, *Artificial Intelligence for Interstellar Travel* featuring in interstellar blog Centauri Dreams. We report on Interstellar in the Journal of the British Interplanetary Society (JBIS) - four issues including one devoted to the i4is Foundations of Interstellar Studies workshop in New York in 2017. And see also our thanks to *Astronomy Now* magazine for saying "Become a member of an interstellar community"!

Our News Features are - *Oumuamua*, *Project Lyra and Interstellar Objects*, John Davies & Adam Hibberd and the *69th International Astronautical Congress 2018 Follow-Up* - more in P25 in May.

The features, *Nomadic Planets and Interstellar Exploration* by T Marshall Eubanks is postponed to P25 when we will also feature the first part of an *Overview of Fusion Propulsion* by Kevin Schillo of the University of Alabama at Huntsville - plus a follow up on the *TVIW Power of Synergy Symposium* from David Fields and a final report on the *69th International Astronautical Congress 2018*.

Comments on i4is and all matters interstellar are always welcome,

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

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

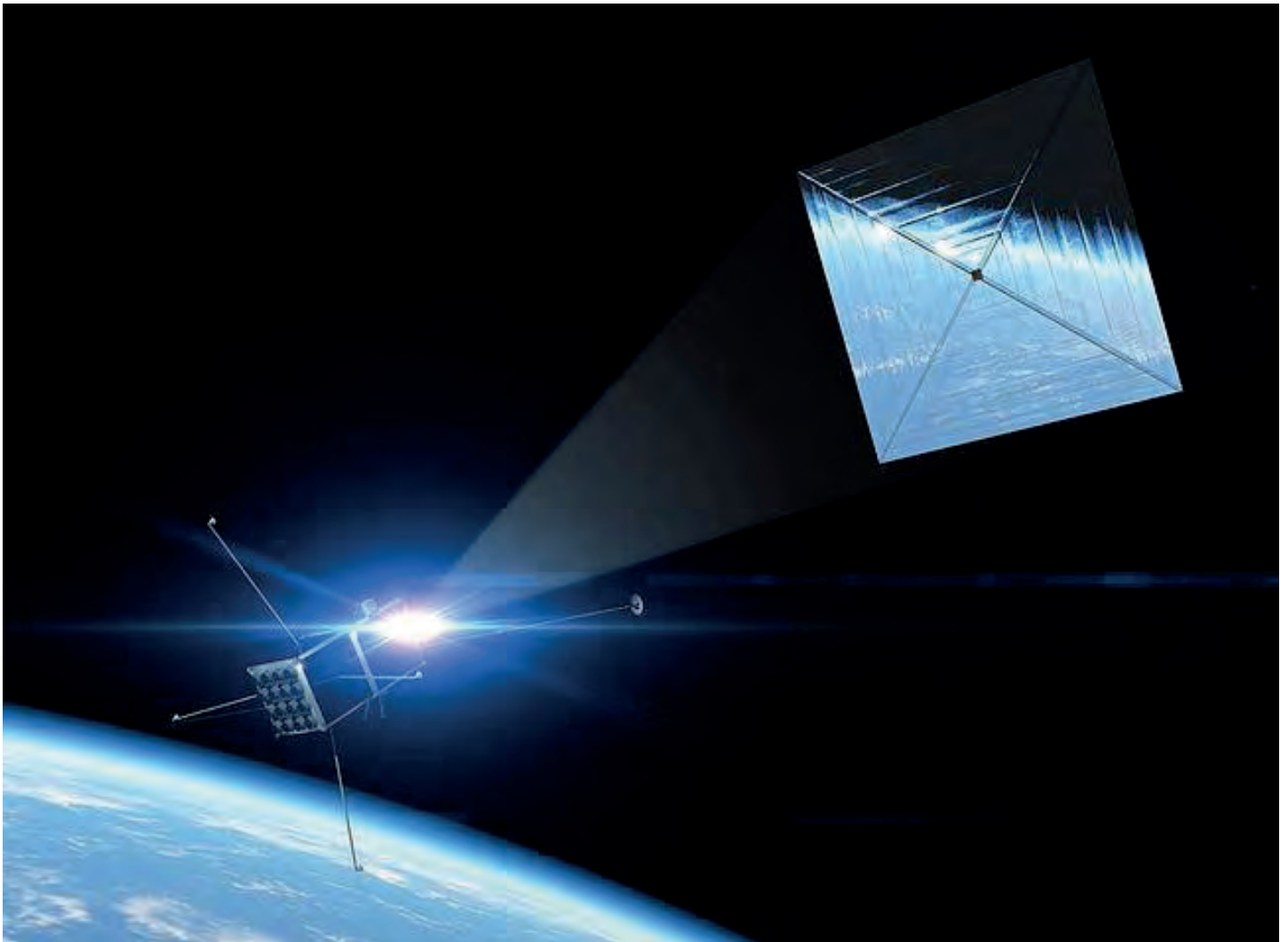
The views of our writers are their own. We aim for sound science but not editorial orthodoxy.

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Project Glowworm: Testing Laser Sail Propulsion in Low Earth Orbit

Zachary Burkhardt

In this article Zachary Burkhardt, a member of the Project Glowworm team of the Initiative for Interstellar Studies, describes the motivation for this near-term project and the results of work so far on this in-orbit demonstrator of laser sail propulsion, one of the two most currently feasible means of reaching the nearest stars. The last issue of Principium described one approach to the other feasible propulsion technology, reaction propulsion using nuclear fusion.

1. Introduction

Since the earliest days of spaceflight, many have desired to explore beyond the solar system. However, the massive distance between the Sun and even the closest stars has presented an insurmountable obstacle. Existing propulsion technologies are incapable of making the journey in timescales relevant to human beings, if at all. Major limiting factors include the level of thrust that can be provided by current propulsion technologies and the amount of propellant that can be stored for long duration flight. Lightsail propulsion is one way that these issues may be overcome.

Lightsail propulsion is a broad category of propulsion techniques which use the pressure exerted by photons to produce thrust on a spacecraft. While photons do not have a mass in the traditional sense, they do have momentum. When the photons strike an object, some of this momentum is transferred to the object; the momentum transferred is higher if the surface is reflective as the photons are reflected in the opposite direction of the incoming light which produces twice the change in momentum. A large flat reflective surface in space exposed to the Sun or another significant light source experiences many of these collisions, effectively creating a pressure. This pressure is very small, but by using a large sail with a high reflectivity, enough thrust can be produced to constitute a useful propulsive effect. One of the primary benefits of this propulsive technique is that thrust can be produced continuously without the need for any propellant. This circumvents the primary limitations of conventional propulsion methods which require sufficient fuel to be available to operate. However, the thrust produced

by a lightsail which uses a natural source of photons, such as the Sun, is very small which results in large travel times.

Laser sail propulsion is a variety of lightsail propulsion that aims to overcome this limitation by using high powered lasers to maximize the thrust generated by a lightsail. A laser can focus more energy on the sail, enabling higher thrust than would be produced by natural light sources such as the Sun. Laser sails were first proposed by Robert Forward [1], who imagined using a high energy laser with a massive optical lens of kilometers in diameter to propel spacecraft to the outer planets. This was expanded upon by Marx [2], who imagined using such a system to reach a rapid interstellar trajectory at relativistic velocities. While this idea showed great promise, the massive size of the lasers and optical systems involved made it impractical to pursue implementation and interest slowly faded.

Recent advances in high energy laser systems and spacecraft miniaturization have started to produce a revival of interest in the laser sail concept. Higher powers and lower masses could enable implementation of a laser sail system without massive optics; this has the potential to make laser sail propulsion feasible on a practical scale. One recent proposal that seeks to leverage this is the Breakthrough Starshot project. This project, initiated by renowned physicist Stephen Hawking and Russian billionaire Yuri Milner, aims to use laser sail propulsion to send a number of

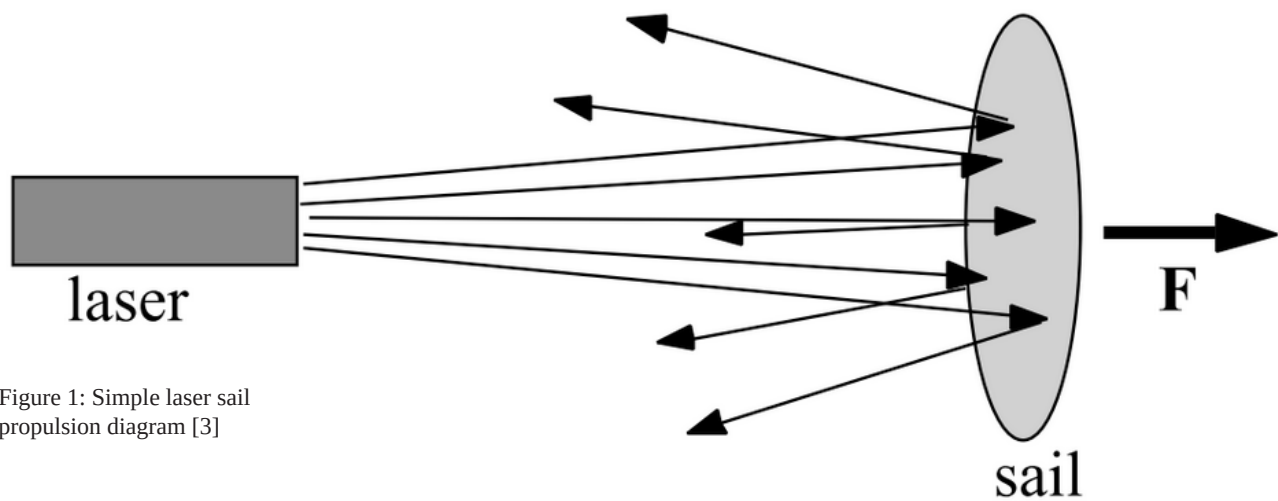


Figure 1: Simple laser sail propulsion diagram [3]

extremely small spacecraft called chipsats to the Alpha Centauri star system 4.2 light-years from Earth [4]. However, many significant barriers remain to its implementation. One of these is the fact that the concept of laser sail propulsion has never been demonstrated in space.

2. The Glowworm Mission

Project Glowworm is an attempt to advance interstellar laser sail concepts by providing the first in orbit demonstration of a laser sail. Glowworm will be a CubeSat that will deploy a small chipsat attached to a reflective sail. A CubeSat is a small satellite that is structured into one or more cubical units with sides approximately 10 cm in length. Commonly, CubeSats are referred to as being XU, where X is the number of units. A chipsat or femtosatellite is an even smaller classification of spacecraft. Generally, the mass of these satellites is less than 100 grams. This sailcraft will be pushed by a laser contained within the CubeSat.

Two concepts of operation were initially proposed for the Glowworm mission. The first of these, referred to as the passive concept, would have the CubeSat remain in its original orbit throughout the entire mission. After deploying the sail, it would use the laser to push the sail away, moving it into a higher orbit. After several subsequent orbits, the two spacecraft would align again, and the CubeSat would again propel the sail with its laser. This would continue until the mission is complete.

In the second concept, the CubeSat would be equipped with a propulsion system that would allow it to follow the sailcraft as its orbital altitude is increased by the laser sail effect. This would allow the laser to be in continuous operation until the mission is completed, however, the addition of a propulsion system could significantly increase the complexity of development for the CubeSat.

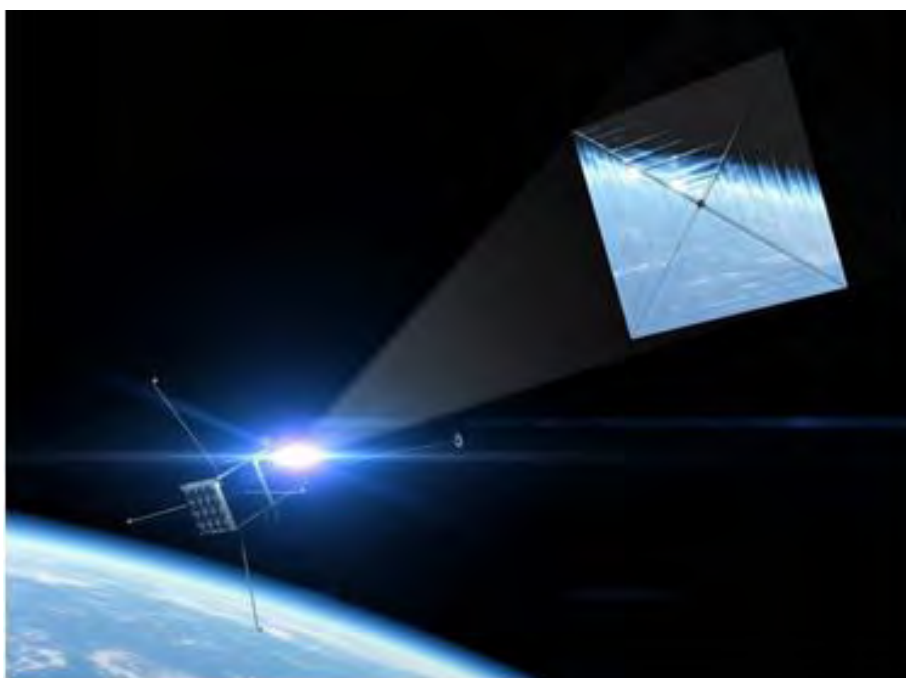


Figure 2: Artist's depiction of the Glowworm mission [5]

A recent study of the Glowworm mission was conducted as an individual student project at the International Space University. This effort set out to analyze the feasibility of the Glowworm mission and determine which of the two mission concepts should be pursued for further development. Several feasibility criteria were used to analyze the concepts:

1. The system must be able to achieve the mission objective of increasing the semi-major axis of the spacecraft's orbit by 10 km.
2. The system must be able to complete the objective within 50 days, a reasonable conservative estimate of the lifetime of a CubeSat in orbit.
3. The mission must be able to be completed with laser powers and optical diameters within the range achievable by a CubeSat.
4. Available components must be feasible for the design of a CubeSat and chipsat sailcraft capable of meeting likely mission requirements.

3. Orbital Simulations

A simulation of the mission was developed using the General Mission Analysis Tool (GMAT). GMAT is an open source orbital simulation software developed by NASA Goddard Space Flight Center. A script was developed to simulate the laser sail propulsion effect and applied as appropriate to the chaser and passive concepts.

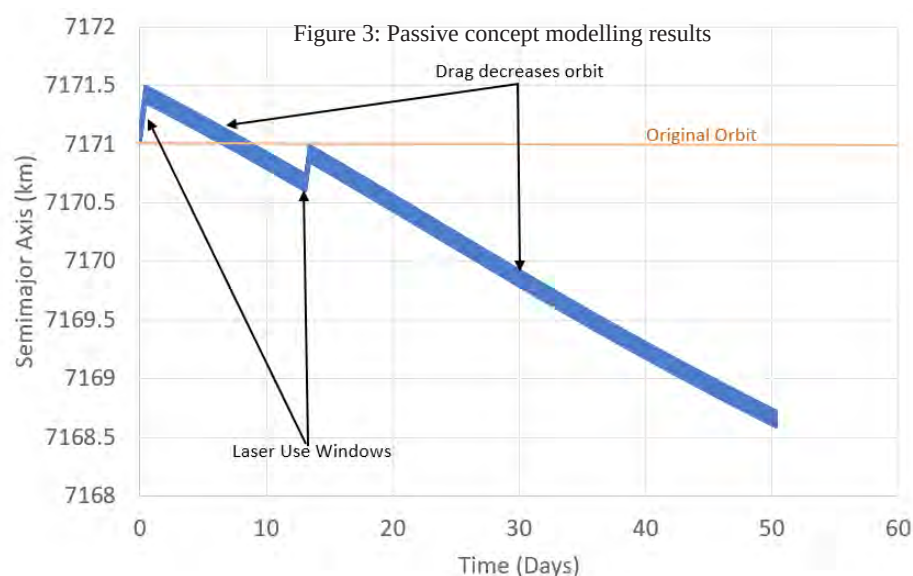
The simulation for the passive concept was used to determine the time it would take for the 10 km orbit raise to be achieved for a given laser power, sail size, and laser optical diameter. The latter two parameters are of critical importance; together they determine the maximum distance over which the laser can effectively propel the satellite. To generate an initial evaluation of the feasibility of the passive concept, best case scenario values were assumed for

both of these parameters, resulting in a maximum distance of just over 10 km. The GMAT script was set to only apply the laser sail thrust to the chipsat when it was within this distance of the CubeSat. The orientation between the laser and the sail is also a key parameter, as only certain relative orientations actually help to further the goal of increasing the altitude of the sail's orbit. Again, the script was set to only apply thrust in such cases.

The results of the GMAT simulation executed with these assumptions showed that, even in a best-case scenario, a CubeSat without propulsion would be unable to raise the orbit of the sail by more than 10 km. The laser is able to provide a noticeable increase in the orbit of the sail in its initial operation period, however the amount of time it takes for each spacecraft to complete a full orbit remains similar. On the surface, this may seem beneficial, as the spacecraft will return to the initial location of the propulsive event at similar times; however, the relative velocity that the propulsive effect created between the two spacecraft means that even when this does occur, the separation distance between the two spacecraft remains above the target value. The only way for the spacecraft to pass within 10 km of each other again would be for them to complete many hundreds of orbits; this would allow the small differences in position developed each orbit to compound upon each other, resulting in the sailcraft being one full orbit 'ahead' of the CubeSat.

While low Earth orbit is commonly referred to as a vacuum, it contains a small but notable quantity of particles. These particles produce a drag force which opposes the motion of spacecraft. This results in a decrease in the velocity of the spacecraft and a consequent reduction in the altitude of its orbit. This effect threatens to overwhelm the small propulsive forces produced by a small laser sail system such as Glowworm. Over the long period of time it

takes the spacecraft to align again, the influence of atmospheric drag causes the orbit of the sail to decay more than it was raised originally. Therefore, over time, the orbit of the sail decreases rather than increases and will never reach an increase of 10 km. Figure 3 shows the change in the semi-major axis of the sailcraft's orbit over a 50-day period for the best-case scenario described. The SMA initially increases in the first laser usage window then decays to below its initial value before the second usage



window. These are the only two windows to occur within the first 50-day period of the mission.

Atmospheric drag makes the passive concept of operations infeasible for the Glowworm mission, failing to meet the first feasibility criterion described above. It is possible that the concept could be revived by inserting the mission into a much higher orbit, but this is unusual for CubeSats. Moreover, even without the influence of drag, the orbit raise would take five or more years to achieve due to the infrequent nature of the laser usage windows. It is unlikely the CubeSat would survive in orbit for this long, as only about half of CubeSats have survived for more than 600 days [9]. Therefore, this notion would result in a failure to satisfy feasibility criterion 2 and achieving a 10 km laser sail orbit increase with a CubeSat that does not contain a propulsion system seems to be generally infeasible. A much larger spacecraft could accomplish the task but would be much more expensive. As a CubeSat form factor is targeted for the Glowworm mission, the passive mission concept is not feasible.

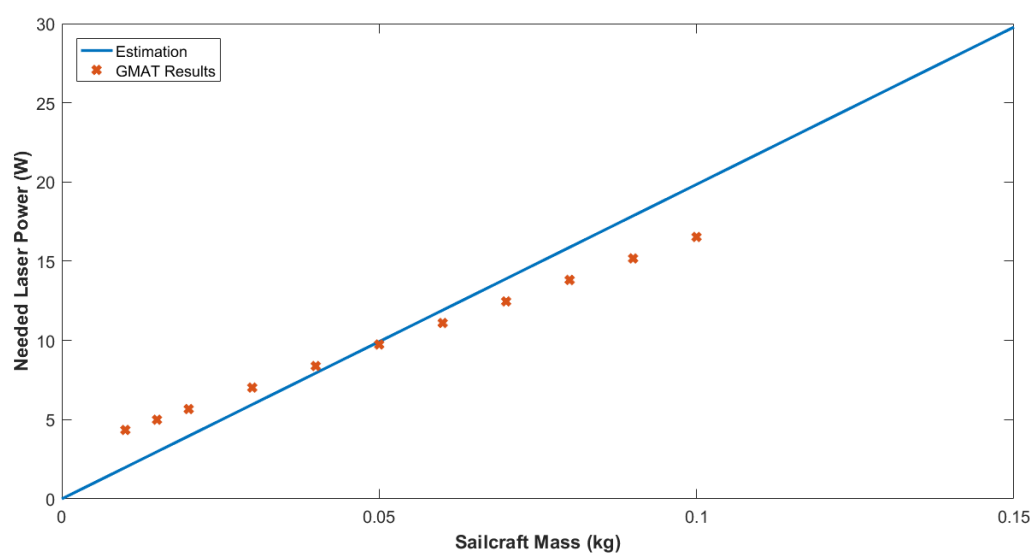
In the case of the chaser concept, an approximate estimate of the constraints placed on laser and sail sizes can be achieved without a detailed orbital simulation. Since the CubeSat will be following the sail, it will be able to apply thrust with the laser continuously, creating a continuous acceleration. The change in velocity to increase the orbit can be estimated to be 5.7 m/s using a simple low thrust orbit transfer approximation. This can then be used to find the needed acceleration to achieve the orbit raise in a given time. Because this case involves continuous acceleration, the orbit raise would only be limited by the amount of propellant on the CubeSat. As there is likely to be sufficient propellant for a mission of years in duration, it is logical to select a maximum mission duration. Among CubeSats that successfully deploy and

establish communication with the ground, around 90% survive for at least 50 days [6]. Therefore, this length of time was selected as a maximum for the mission to provide a reasonable degree of confidence that the mission could be successfully completed in the given timeframe. The calculated velocity change was used to determine the necessary constant acceleration and this was used to develop a function that describes the needed laser power as a function of the mass of the sailcraft.

To generate more precise values, a GMAT simulation was used. The simulation was run for a variety of sailcraft masses. In each case, the simulation was run for 50 days and GMAT's built in solver functionality was used to determine the thrust necessary to achieve the required orbit raise at the end of the 50-day period. These thrust values were then used to calculate the laser power.

Figure 4 shows the results of both the simplified calculation and the GMAT simulation. As expected, the influence of atmospheric drag means that more power is required for low sailcraft masses. For higher sailcraft masses, GMAT somewhat counter-intuitively predicted a lower laser power than the constant acceleration estimate. This occurred because the continuous orbital increase modeled in GMAT actually represents a more efficient transfer which requires slightly less than the calculated 5.7 m/s. Additionally, the influence of the drag force decreases as the mass of the sailcraft increases as less drag induced acceleration occurs given a constant force.

Figure 4: Chaser concept modelling results



4. Preliminary Design

The results shown in Figure 4 show that the laser power needed to produce a 10 km increase in average orbital altitude within 50 days falls within a range that may be achievable for a CubeSat mission. This demonstrates that the chaser concept can fulfil the first three identified feasibility criterion. Therefore, an initial design study for the Chaser concept was conducted. This served to advance the development of Glowworm and verify that the chaser concept met the fourth feasibility criteria.

This process began with the definition of preliminary requirements for the mission. These requirements were used to determine what subsystems must be included on the CubeSat and the sailcraft and to guide the selection of components. Because the sailcraft is the target for the propulsive effect and must be initially stored within the CubeSat, the design of the sailcraft has a large effect on the design of the CubeSat. Therefore, the design of the sailcraft was considered first.

The requirements-based subsystem allocation indicated that the sailcraft would need to have several subsystems, including attitude determination and control, command and data handling, electrical power, and an acceleration measurement payload. The most complex chipsat to date has been Pocket PUCP, which was developed by Pontificia Universidad Católica del Perú, which included electrical power, communications, and temperature monitoring subsystems. Neither Pocket PUCP nor any other prior chipsat mission included any attitude control capability [7]. This means that the Glowworm sailcraft will need to advance the state of the art for chipsats and build a more capable system than previously developed chipsats.

To fulfil these proposed requirements, the sailcraft will at minimum need an attitude control system, as well as electrical power and command and data handling systems to support this. To measure the magnitude of the propulsive effect, it is also necessary to include some method of measuring the acceleration of the sail. Originally, an accelerometer was considered for this task but it was found that existing accelerometers suitably sized for a chipsat lacked the necessary precision. As an alternative, it was determined that the CubeSat component of the mission could carry a laser rangefinder which it could use to precisely measure the distance between it and the sail. To determine the attitude of the sailcraft, a magnetometer and rate gyro were selected. The former is able to determine the orientation of the spacecraft relative to the Earth's magnetic field

and the latter determines the rotation rate of the spacecraft. Three electromagnetic torquers were selected to allow the sailcraft to control its orientation. These produce a magnetic field which interacts with the Earth's magnetic field and causes the sailcraft to change its orientation. A small microprocessor was selected for command and data handling tasks. It was determined that the laser facing side of the chipsat could be dedicated to a single solar panel which could be specifically tuned to gather energy efficiently at the wavelength of the laser light. High reflectance dielectric mirrors were selected for the sail itself and the sail was sized to provide a total reflectance of at least 95% to the entire sailcraft including the influence of the non-reflective chipsat components. The current preliminary sailcraft chipsat design is shown in Figure 5.

The total mass of the sailcraft estimated based on the components selected is only 45 gm. However, a 100% margin has been applied to account for errors in mass estimation and currently unknown masses, such as that of solder used to attach components to the PCB. With a total mass of 90 gm, the current preliminary sailcraft design falls within the mass range that produced acceptable CubeSat laser powers shown in Figure 4.

A preliminary design for the CubeSat portion of the Glowworm mission was then created based on the preliminary sailcraft design. This resulted in a 3U CubeSat design that is theoretically capable of meeting all mission requirements. The design effort for the CubeSat aimed to select commercially available components wherever possible in order to reduce the cost and complexity of development. Suitable off-the-shelf options were identified for most major subsystems, however it was determined that the laser and solar panels would have to be custom developed; while lasers with the needed size and power range are available, none of them are space-qualified, and the total power needed for the mission is slightly out of the range that can be provided by commercial 3U CubeSat solar panels. It is possible that the latter concern, and potential volume limitations, could be ameliorated by switching to a 4U or larger design; this possibility remains to be studied in detail in the future.

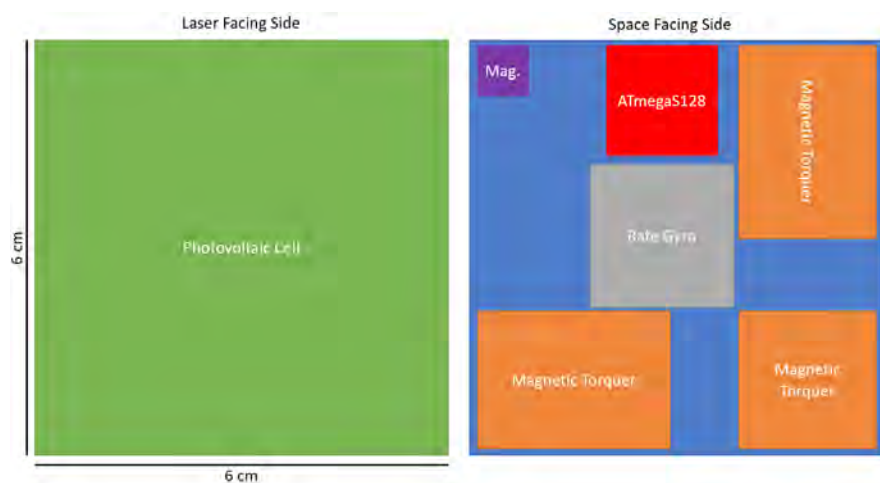


Figure 5:
Preliminary
chipsat design

5. Conclusion

Bridging the vast distances between stars is a major barrier for humanity's interstellar ambitions. With current propulsion technologies, it would take several centuries to travel to even the nearest stars. Laser sail propulsion is one of the most promising and credible potential interstellar propulsion solutions. By removing the need for fuel and still allowing high thrusts, a small laser sail vehicle could travel to the nearest star systems within decades. Before this can happen, however, the technology of laser sails must be demonstrated and validated.

Recent analysis of the Glowworm mission has determined that it is likely feasible to conduct a technology demonstration for laser sail propulsion using a combination of a CubeSat and a chipsat with current technologies. While this mission would require significantly pushing the boundaries of what has previously been achieved in chipsat missions, there do not seem to be any insurmountable obstacles. Future studies can refine the preliminary requirements and design work conducted thus far and begin to develop an optimized design solution. Ultimately, it should be possible to develop a robust design which will be able to provide a conclusive demonstration of laser sail propulsion. This will provide valuable data and confidence in the technology which will enable a serious push towards laser propelled interplanetary and interstellar flight.

The full ISU Glowworm project report can be accessed from the ISU library (isulibrary.isunet.edu/index.php?lvl=notice_display&id=10401).

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About the Author

Zachary Burkhardt holds a BS in Aerospace Engineering from the University of Alabama in Huntsville and a Masters in Space Studies from the International Space University, Strasbourg. He is a major contributor to i4is Project Glowworm and the co-author, with Nikolaos Perakis and Professor Chris Welch, of Project Glowworm: Testing Laser Sail Propulsion in LEO (www.researchgate.net/publication/328202365_Project_Glowworm_Testing_Laser_Sail_Propulsion_in_LEO)

The TVIW *Power of Synergy* Symposium

Promoting a Grand Transformation

John D G Rather

The Tennessee Valley Interstellar Workshop is a prominent contributor to the field of interstellar studies. In this article Dr John D G Rather introduces us to the organisation and especially to the latest of its major conferences. We published the full programme in the last issue of Principium (NEWS FEATURE - TVIW 2018). For a full list of events and people see tviw.us/tviw-symposium-on-the-power-of-synergy/ as more details are released in the near future.

Oak Ridge, Tennessee is the Secret City that changed the world in three years during World War II -- and literally won the war. In 1942 the city was founded in an obscure location that had huge amounts of electric power available from the Tennessee Valley Authority (TVA). Its purpose was to create and produce essential nuclear materials for the Manhattan Project. After the war, the huge technology facilities were transformed into the Department of Energy's Oak Ridge National Laboratory (ORNL) and the Y-12 National Security Complex -- both now \$1-2 Billion per year research and national security operations. For 75 years, Oak Ridge has been a hotbed of breakthrough science and engineering creativity, now being celebrated as part of the new Manhattan Project National Historic Park created in 2015. Extending south from Oak Ridge, the Tennessee River valley embraces huge industrial growth in Chattanooga, Tennessee and burgeoning high-tech development in Huntsville, Alabama. Huntsville hosts NASA Marshall Space Flight Center (MSFC), the birthplace of the Saturn rockets that took us to the moon in 1969, as well as the US Army Aviation & Missile Command and many supporting industries. The Tennessee Valley Interstellar Workshop (TVIW), a tax-exempt educational corporation, is the creation of highly motivated people in Oak Ridge and Huntsville who are inspired to develop meaningful steps toward a space-faring interstellar civilization. The most recent example was our symposium, *The Power of Synergy*, held in Oak Ridge, Tennessee October 23-25, 2018 at the Y-12 New Hope Center. It advocated aggressive near-term goals for accelerated space development, emphasizing how synergistic government and private industry capabilities can catalyze

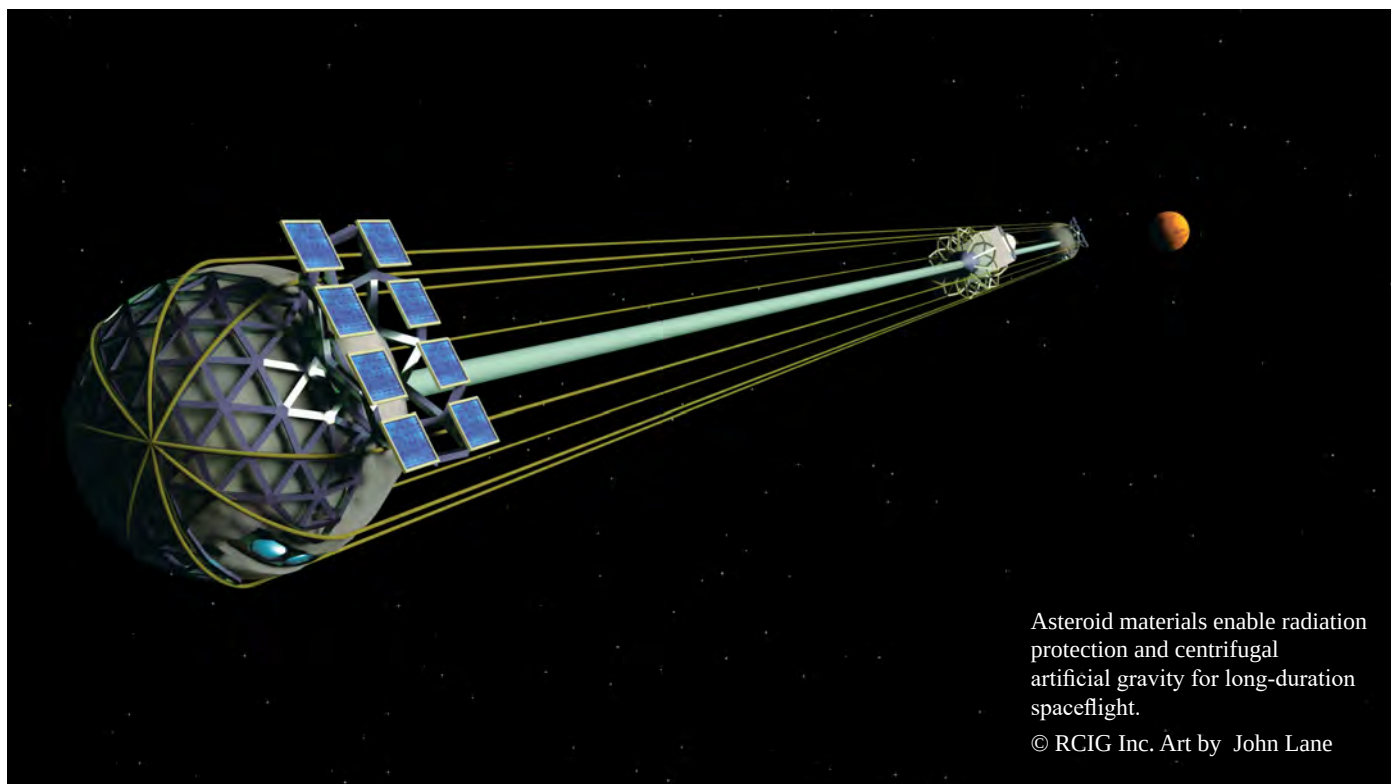
breakthrough progress. A plausible case was made for Apollo-like reassertion of US space leadership in one decade, before 2030. Leaders from government agencies, national laboratories and private space-faring industries involved in transformative technologies spoke in support. In accord with TVIW's traditional zest for promoting cross-cultural understanding of the vision of space development, several notable science fiction authors and highly innovative science promoters were invited to participate in presentations and panel discussions. The primary goal of our eponymous *Power of Synergy* is to generate a new vision and integrated plan for development and economic use of outer space within a decade. Courageous leadership with an inspired national team is the vital key. The resulting new jobs, infrastructure industries, and major fiscal growth will insure that the United States continues and expands its traditional roles of creating great innovative futures for the world. Implementation of the Apollo moonshot depended upon creation of a new Government administrative Agency. In the 1960s, the newly formed NASA unified the best elements of existing government and business functions; and it still enjoys the greatest popularity of any government agency. Recently in March 2018, NASA announced a new cooperative technology development effort with the US Department of Energy. Our TVIW symposium showed how inspired multi-agency cooperation with private industries can enable breakthrough technology and accelerate space exploration. DOE's Advanced Research Projects Agency (ARPA-E) can play a significant catalytic role. We believe that "*The Power of Synergy*" describes the vital catalytic element that must be applied. Hugely important concepts and technologies

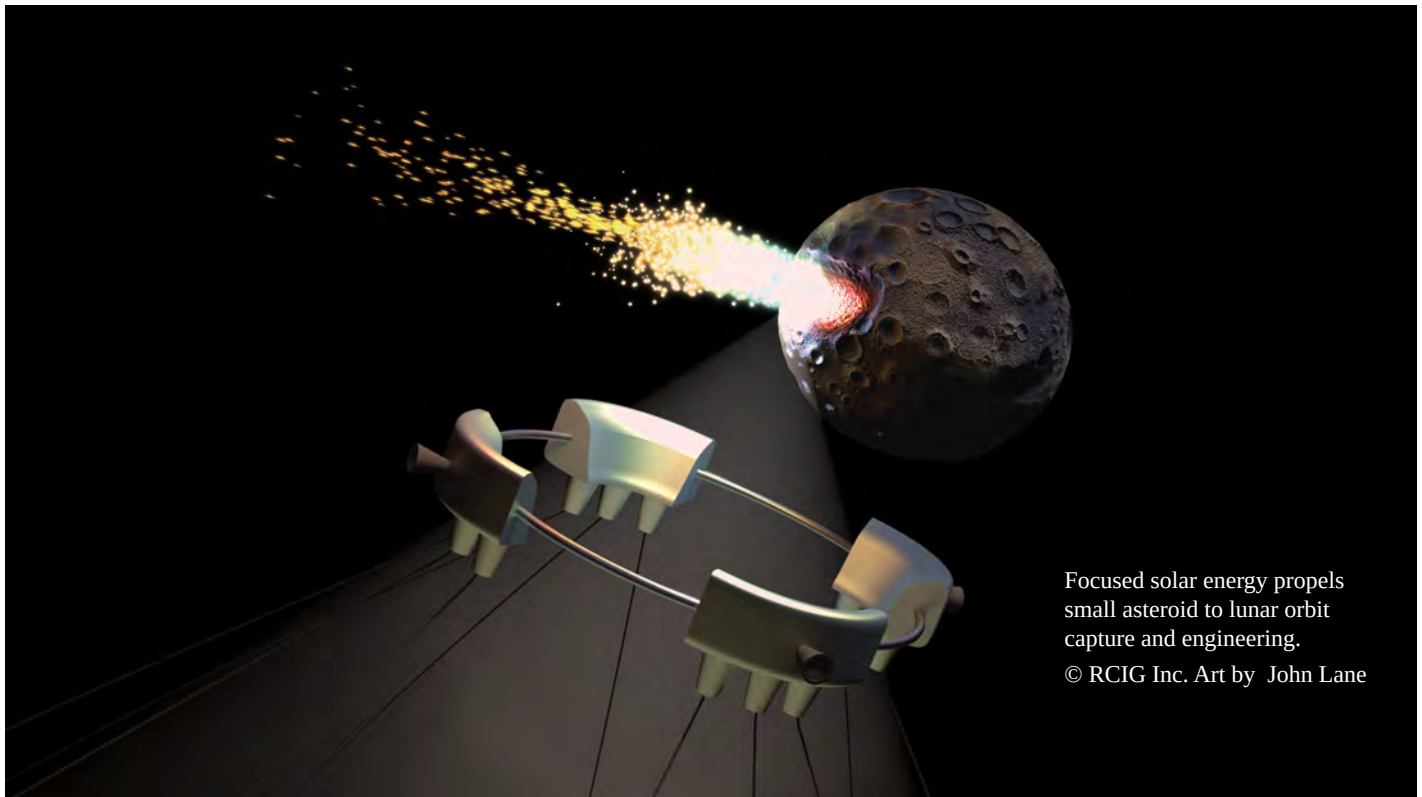
already exist that can be combined in new ways, where the sum becomes much more than the parts. Diverse presently under-exploited technologies can be marshalled together to greatly accelerate human progress in space while – serendipitously – promoting on Earth greatly enhanced national security, fiscal growth, infrastructure improvement, and human engagement. Thus the TVIW October symposium endeavored to generate a roadmap for synergy and technology superiority that will make US space development the hallmark of inspired innovative leadership. Major collaboration with private space industries is a vital fructifying principle.

Achieving success in the proposed great leap forward depends upon synergistic combinations of state-of-the-art technologies that greatly reduce fiscal costs and development times. Key examples include advanced nuclear propulsion and power generation based upon extremely well validated designs for very compact space-based reactors that can be built and fueled quickly in NASA and DOE facilities. Such reactors, fueled by Uranium 235, are completely safe to launch from the Earth before they become energized in space. Fission products and radiation safety will be easily managed in space, never contaminating surface environments. Other key technologies such as large solar concentrators, high-energy lasers, high-temperature superconductivity, and large-scale 3D printing can play decisive innovative roles. For example, capturing and industrializing

very small near-Earth asteroids can solve space radiation and zero-gravity problems while enabling construction of relatively inexpensive large human habitats in space and on the moon and Mars. Safe and affordable travel through Earth's Van Allen Belts to permanent colonies on the moon, and safe trips to Mars in sixty days rather than one year will become routine. *The fundamental requirement for large amounts of low-cost energy to accelerate fast space development can be met within a decade by exploiting technologies now completely within existing states-of-the-art.*

Described below are brief examples of seven technologies and concepts that can initiate transformative progress. Most have high Technology Readiness Levels (TRLs), not requiring decades to implement. Further, all key materials, nuclear fuels, components, and applications can be designed, produced, and industrialized in existing facilities, leading to significant local and national economic gains.





Focused solar energy propels small asteroid to lunar orbit capture and engineering.
© RCIG Inc. Art by John Lane

Proposed Transformative Technologies

1. **High Impulse Nuclear Propulsion** – A huge step forward in compact nuclear reactor design was proved by DARPA in the \$330 Million Particle-Bed Reactor Program from 1988 to 1993. It remains the most advanced candidate technology for space propulsion. Upper stage nuclear rockets (ie used only in space) can enable human trips to Mars in sixty days rather than multiple years. Nuclear propulsion is also vital for capture and engineering of small (10 meter diameter) near-Earth asteroids (NEA) that can facilitate space habitats safe from solar and cosmic radiation. Space solar power and other major industries will be rapidly enabled.
2. **Fiber Optic High Energy Lasers** – Key to efficient wireless power transmission and proven by DARPA for near-term applications, this very mature, high-efficiency technology can lead directly to megawatt-class power beaming capabilities for space power and propulsion. Laser light sails are a fundamentally crucial application extending to interplanetary and interstellar propulsion.
3. **High Temperature Superconductors** – This HTSC technology will radically transform all types of electrical applications when fully exploited. It has been developed for thirty years, and is ready for many game-changing implementations. An example is Magnetically Inflated Cable (MIC) technology that can enable very large, low weight and rigid space structures for solar concentrators. Megawatts of 4000 degree solar energy at the focus can implement fast capture of 10-meter diameter near-Earth asteroids to lunar orbits, where they can be robotically engineered to solve radiation shielding and artificial gravity problems for human travel. – Also HTSC Maglev propulsion has many vital applications for space launch and centrifugal artificial gravity.
4. **Large Scale 3D Printing** – Oak Ridge National Laboratory and its innovative manufacturing spin-offs are world leaders in this vital new technology. There are direct links to in-space manufacturing possibilities using readily available regolith materials on the moon and asteroids.
5. **Solar Power Satellites** – Formerly regarded as “pie in the sky,” space solar power with microwave or laser power beaming to the Earth, moon, or planets is now a real possibility. Persuasive concepts already exist for in-space production and deployment of all of the components. Combining the above notions of small asteroid capture for raw materials with robotic machines for ever-expanding production capabilities, concepts are viable for beaming efficient, totally pollution-free solar energy to Earth, widely-deployed space industries, and to the Moon and Mars.

6. Self-Replicating Von Neumann Machines – This concept will be a vital component to expedite robotic space habitat engineering and large-scale production capabilities on the moon, Mars, and asteroids. Hierarchical Von Neumann machines are an important next-generation spin-off. Very small machines can build ever-larger machines using ambient materials and solar energy. Ever larger and more fiscally powerful space industries will result.

7. Lightweight Large Aperture Optics -- MIC technology (see 3 above) leads directly to the possibility of building enormous optical telescopes in space at orders much lower cost than present ground-based technology. Kilometer diameter interferometer arrays will enable imaging and diagnostics of earth-like planets around nearby stars. The search for Extraterrestrial Intelligence (SETI) will be greatly augmented. Importantly, the science of cosmology will be massively advanced toward ultimate understanding of the origin and destiny of our universe.

Realization of even a fraction of these technologies and concepts by 2030 will open limitless horizons for human enterprise and accomplishment in space. *This promising outcome depends upon rapid exploitation of transformative technologies focused on human development of outer-space resources, actually having near-term propitious consequences for worldwide stabilization.* Naysayers contend that no significant fraction of the population will leave the Earth, so that claims that this is an important effort are specious. However, the history of the growth of the US refutes this contention by analogy. The percentage of the US population that left the comforts of the East Coast was very small; but the effects of having an open frontier were practically, psychologically and culturally very significant. The open frontier provided vast new resources and opportunities. Historians cite the open frontier as a major factor in US cultural development as an adventurous, individualistic, creative society. Opening space for full-scale development will provide the same advantages for our future.



Dr John D G Rather
Credit: Dr Rather

About the Author

Dr John D G Rather, General Chair of the Power of Synergy Symposium, is known internationally as a scientific innovator and creator of major technology programs. His experience in business and government spans defense, space, medical, and industrial communities. Dr Rather worked in physics and space research at Oak Ridge National Lab, Lawrence Livermore National Lab and the National Radio Astronomy Observatory before moving into private business and US government senior appointments. As VP of an aerospace company, he created StarLab, which with co-contractors became the largest R&D program of the Strategic Defense Initiative. In 1990, Dr Rather was recruited to NASA HQ so as to accelerate space systems development. In 1992, he served as Chairman of the NASA/DOE study of asteroid impact prevention mandated by the US House of Representatives. Asteroid 7290 is named Johnrather in his honor. For more than twenty years he was also a contributor at the DLA and the CIA. Dr Rather moved back to Oak Ridge, Tennessee in 2006 and founded RCIG Inc and Sisyphus Energy Inc to create and develop focused revolutionary technology breakthroughs.

Interstellar News

John I Davies with the latest interstellar-related news

Andreas Hein and Dan Fries Invited to MIT Beyond the Cradle event

Andreas Hein and Dan Fries of the i4is Technical Committee have been invited to the third annual MIT Beyond the Cradle conference, representing i4is. Here's the MIT announcement -

MIT Media Lab Beyond the Cradle: Envisioning a New Space Age, March 14, 2019

With humanity at the cusp of interplanetary civilization, we are actively building the technologies, tools, and human experiences of our sci-fi space future. Join us, in the 50th anniversary year of the Apollo Moon landing, for a creative spin with the scientists, engineers, artists, and designers revolutionizing our next half-century of moonshots and starshots.

On March 14, 2019 we'll hear from NASA scientists and Hollywood storytellers, from "New Space" industry vanguards leading space tourism and lunar settlement, and from engineers of the intrepid probe missions now far beyond our planet neighborhood. Come to meet the astronauts and innovation engineers at space agencies around our home world, and the authors and artists seeding our imagination of other worlds!

Attendance at this private event is by invitation only, but the full program will be publicly livestreamed. More at - www.media.mit.edu/events/beyond-the-cradle-2019

Kelvin Long interviewed for Universe Today

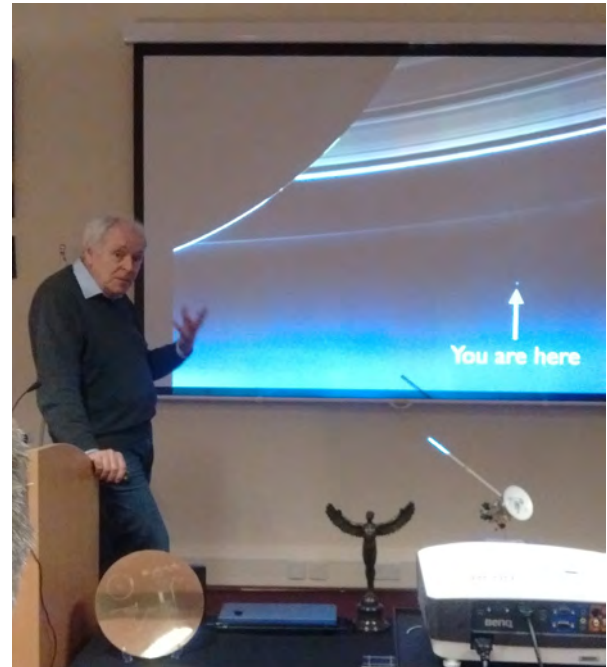
Kelvin F Long, co-founder and past President of i4is was recently interviewed for Universe Today (www.universetoday.com). He spoke about What Would be the Benefits of an Interstellar Probe? (www.universetoday.com/141295/what-would-be-the-benefits-of-an-interstellar-probe) concentrating on the science to be derived from such a mission.

Professor Carl Murray at the Mill 30 Nov

Professor Carl Murray, Queen Mary & Westfield College, University of London was invited to the i4is HQ, The Mill, by his former student, i4is cofounder Kelvin Long. He kindly agreed to give a public lecture, Cassini at Saturn: the End of an Era. Professor Murray worked on the Cassini mission to Saturn for more than 20 years.

Cassini was a collaboration between NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI). The mission ended on 15

Prof Murray shows our Pale Blue Dot as imaged from Cassini
Credit: Rob Swinney



September 2017 when the spacecraft plunged into the planet's atmosphere following a number of passes through the rings. The mission launched in 1997 as part of the NASA/ESA/ASI Cassini-Huygens mission and entered Saturn orbit in 2004. Professor Murray highlighted some of the discoveries made by Cassini in its 13-year tour including observations of giant storms on Saturn, changing weather and surface features on Saturn's largest moon Titan, the discovery of plumes of ice particles emanating from a source of liquid water beneath the moon Enceladus, as well as the discovery of several new moons. The presence of a spacecraft in orbit for more than a decade gave scientists the opportunity to study how the system changed over time.

i4is at ISU again - The ChipSats elective.

i4is is planning to deliver an elective course module for the Masters programme at the International Space University (ISU) in Strasbourg - 29 April - 10 May, in collaboration with Breakthrough Initiatives. This is the first comprehensive course on ChipSat development. ChipSats are a new class of spacecraft of the size of a credit card or smaller. Regular Principium readers will already be aware of the relevant work of Breakthrough Starshot and i4is Projects Dragonfly, Andromeda and Glowworm.

Acta Astronautica - Project Lyra paper published

The paper, Project Lyra: Sending a spacecraft to 1I/'Oumuamua (former A/2017 U1), the interstellar asteroid, first appeared in 2017, a few weeks after the discovery of Oumuamua. The version in Acta Astronautica - www.sciencedirect.com/science/article/pii/S0094576518317004 - is revised by the i4is technical team, Andreas M Hein, Nikolaos Perakis, T Marshall Eubanks, Adam Hibberd, Adam Cowl, Kieran Hayward, Robert G Kennedy III and Richard Osborne. An open publication version of the paper is available at www.researchgate.net/publication/328342348_Project_Lyra_Sending_a_Spacecraft_to_1I'Oumuamua_former_A2017_U1_the_Interstellar_Asteroid.

David Hardy at the Mill 14 December 2018

i4is welcomed David Hardy to The Mill on 14 December 2018. David has been producing astronomical art since 1952, he has illustrated dozens of books – some of them co-written with Patrick Moore, and some written by himself. His work has also been included in international exhibitions. This talk, illustrated mainly with his own art but with examples of the work of earlier artists, showed how space art has developed over the years, and how our increasing knowledge about space as a result of robotic and manned exploration has been reflected in the work of artists.

You will find his prophetic image of Ultima Thule on our front cover this time and his art has enhanced Principium from the beginning.



David Hardy at The Mill with fearsome Klingon weapon
Credit: Kelvin F Long

Acta Astronautica - Project Dragonfly Sail to the stars

The team led by Cranfield University, UK, finalists in the i4is Project Dragonfly competition, published in Acta Astronautica last month (January 2019 - [https://www.sciencedirect.com/science/article/pii/S0094576517319136](http://www.sciencedirect.com/science/article/pii/S0094576517319136)). Their paper, *Project Dragonfly Sail to the stars*, addresses the Dragonfly objectives of the feasibility of an interstellar mission to reach the Alpha Centauri star system delivering scientific data, using current and near-future technology. The authors are Tobias Häfner, Université Paul Sabatier Toulouse, and from Cranfield University, Manisha Kushwaha, Onur Celik and Filippo Bellizzi. An open publication version of their paper is available at - www.researchgate.net/publication/317491721_Dragonfly_Sail_to_the_Stars - and Matt Williams, Universe Today, gives an account of the work at - phys.org/news/2018-12-laser-powered-probe-alpha-centauri.html - *Exactly how we would send our first laser-powered probe to Alpha Centauri*.

The Mystery of 'Oumuamua, Kings Place, London, January 27th 2019

The Orchestra of the Age of Enlightenment (www.oae.co.uk) presents a regular series of concerts and talks titled *Bach, The Universe and Everything*. This union of Snow's "two cultures" presents Bach cantatas and the work of his approximate contemporaries alongside talks by scientists and science journalists on current topics in astronomy (www.kingsplace.co.uk/whats-on/bach-the-universe-and-everything).

This one, The Mystery of 'Oumuamua, naturally attracted my special attention. The programme note by John Holmes, Director of Marketing for the OAE, said -

Speculation about 'Oumuamua's makeup and origin was frantic and imaginative. It doesn't go away, as Harvard professor Avi Loeb has made the news this month with his continued speculation that it might have been sent by aliens. Today's guest, Professor Alan Fitzsimmons doesn't agree.

The principal work, Cantata: Jesu, nun sei gepreiset mir, ('Jesus, now be praised') BWV 41, immediately preceded the talk by Professor Alan Fitzsimmons of Queens University, Belfast (star.pst.qub.ac.uk/~af/Alan_Fitzsimmons/About_Me.html). I cannot recall hearing it before but, as often with Bach's choral works, what hit me was the thrill of the trumpets, the beautiful precision of voice and instruments and the barely suppressed ecstasy of the whole damn thing!

Professor Fitzsimmons began in the New Year of 1725, for which Bach wrote this piece, 100 years after the invention of the telescope and 45 years after the publication of Newton's Principia. At that time 'Oumuamua would have been inbound, just below Vega in the sky (though well beyond the range of any telescope, now or then). 292 years later his colleagues at the Pan-STARRS telescope at Haleakala Observatory, Hawaii, hunting for asteroids and comets, found a streak amongst all the dots and, having confirmed that it was a hyperbolic object, announced it to the world. Professor Fitzsimmons gave an entertaining and witty summary of what is definitely known about 'Oumuamua. As a key researcher associated with a number of observatories he gave his opinion that the anomalous outbound acceleration of 'Oumuamua was the result of the sublimation of ice under solar radiation. He did not mention Avi Loeb's conjecture (summarised in *NEWS FEATURE - What is Oumuamua? The Loeb/Bialy Conjecture and i4is Project Lyra* in Principium 23, November 2018). This was an entertaining and very clear exposition of 'Oumuamua but it left no mystery in the minds of its general audience, as I confirmed in a conversation with old friends who I met as we left. Beautiful music, rather disappointing science from my personal point of view.

The OAE presenter told us to look out for the podcast - recent ones, both speech and music, can be found at - open.spotify.com/search/results/bach [the universe and everything](#).



Credit: Orchestra of the Age of Enlightenment

Artificial Intelligence for Interstellar Travel

P23 readers will recall news of *Artificial Intelligence for Interstellar Travel* by Andreas Hein and Stephen Baxter (arxiv.org/pdf/1811.06526.pdf). Our good friend Paul Gilster has featured this major work in his *Centauri Dreams*, titled *Artificial Intelligence and the Starship* (www.centauri-dreams.org/2019/01/28/artificial-intelligence-and-the-starship/).

Astronomy Now magazine says "Become a member of an interstellar community"

Keith Cooper is editor of the prominent UK magazine, *Astronomy Now* (astronomynow.com), which has wide circulation amongst amateur astronomers. He has featured i4is Membership in the February issue - see below.

Keith is a long term supporter of i4is and, of course, the BIS. He was editor of Principium in its early days and did much to set our style. We thank him and Astronomy Now for featuring us so prominently. More about membership at i4is.org/membership and at the beginning of this issue of Principium.

SOCIETY NEWS: GRASSROOTS ASTRONOMY

Become a member of an interstellar community

Are your sights set on the stars? If so, you can take one step closer to them by becoming a member of the Initiative for Interstellar Studies (i4is). Founded in 2012, i4is advocates research and development in technologies for interstellar travel, much in the same vein as the Breakthrough Starshot project, which intends to launch craft towards alpha Centauri late this century with 'lightsails' driven by powerful laser beams from Earth. One of i4is' key research areas is Project Dragonfly, which is developing lightsail technology that could one day be used by Breakthrough Starshot. The organisation has its headquarters in a refurbished industrial mill in Charfield, South Gloucestershire, and luminaries such as Apollo 15 astronaut Al Worden, the Breakthrough Initiatives' Pete Worden, and Cassini mission scientist Professor Carl Murray have all presented public talks at the venue.

Now i4is intends to take the next step towards building an active community of interstellar enthusiasts by introducing a membership scheme. For £50 per annum (£40 for members of the British Interplanetary Society, and £10 for OAPs and students/under-16s) members will get exclusive access to online material, including videos and articles, and free or discounted pricing for selected i4is publications, merchandise and events. "We have achieved much in i4is' short history, and we have ambitious plans for the future of interstellar exploration," says the organisation's Executive Director Dr Andreas Hein. "But those plans require resources – of people, time and money. If you are enthusiastic about our mission, please join us. Together, we can plot a route to a future amongst the stars – and start to take the first practical steps on that long journey."

▼ Apollo 15 astronaut Al Worden speaking at i4is' Bone Mill headquarters. Image: i4is.

Image credit: Astronomy Now

astronomynow.com • February 2019 117

Interstellar in JBIS

The Journal of the British Interplanetary Society has recently published multiple papers on interstellar topics-

JBIS Vol 71 No 4 April 2018 Tennessee Valley Interstellar Workshop

From the JBIS Introduction "Held 40 years after the launch of Voyager 1, the October 2017 meeting of the Tennessee Valley Interstellar Workshop (TVIW), with its theme of "Step by Step: Building a Ladder to the Stars", emphasized the small steps that will one day pave the way for monumental interstellar missions."

INTRODUCTION, Tracie Prater and Les Johnson

PULSED MAGNETIC NOZZLE for Fusion Propulsion, Jason Cassibry et al

FISSION FRAGMENT ROCKET: Fuel Production and Structural Considerations, Pauli Erik Laine

FLYING ON A RAINBOW A Solar-Driven Diffractive Sailcraft, Grover A Swartzlander, Jr.

EVALUATION OF THE HAZARD OF DUST IMPACTS on Interstellar Spacecraft, Richard A London & James T Early

A SCIENCE-DRIVEN MISSION CONCEPT to an Exoplanet, Stacy Weinstein-Weiss et al

CONTACT WITH ALIEN BIOMES: Possible Biochemical Incompatibilities, Kenneth Roy & Catherine Smith

Publication Date: 23 November 2018

JBIS Vol 71 No 6 June 2018 The Origin of the Fermi Paradox

THE ORIGIN OF THE "FERMI PARADOX", Anthony R Martin

FERMI AND LOTKA: the Long Odds of Survival in a Dangerous Universe, Kent A Peacock

SCENARIO BLOCK DIAGRAM ANALYSIS of the Galactic Evolution of Life, Stephen Ashworth

EXTREMOPHILES: The Resilience of Life under "Adverse" Conditions, Robert O J Weinzierl

LIFE BEFORE FERMI – Back to the Solar System, David L Clements

ALIEN AIRCRAFT: Have they been observed on Earth?, Alan Bond

Publication Date: 6 December 2018

JBIS Vol 71 No 8 August 2018 Foundations of Interstellar Studies NY

Foundations of Interstellar Studies NY Issue - papers from the i4is conference at City University of New York in July 2017 (as reported in Principium 18, August 2017)

FIRST STOP ON THE INTERSTELLAR JOURNEY The Solar Gravity Lens Focus, Louis Friedman & Slava G Turyshev

EXPERIMENTAL SIMULATION OF DUST IMPACTS at Starflight Velocities, Andrew J Higgins

PLASMA DYNAMICS in Firefly's Z-pinch Fusion Engine, Robert M Freeland II

GRAM-SCALE NANO-SPACECRAFT Entry into Star Systems, Albert Allen Jackson IV

THE FUSION FUEL RESOURCE BASE of our Solar System, A J Kennedy

TESTS OF FUNDAMENTAL PHYSICS in Interstellar Flight, Roman Ya Kezerashvili

Publication Date: 3 January 2019

JBIS vol 71 No 10 October 2018

DIRECT MULTIPixel IMAGING OF AN EXO-EARTH with a Solar Gravitational Lens Telescope, Slava G Turyshev

A TELESCOPE AT THE SOLAR GRAVITATIONAL LENS: Problems and Solutions, Geoffrey A Landis

ET PROBES, NODES, AND LANDBASES: a Proposed Galactic Communications Architecture and Implied Search Strategies, John Gertz

NUMERICAL CONSTRAINTS ON THE SIZE OF GENERATION SHIPS from total energy expenditure on board, annual food production and spacefarming techniques, Frédéric Marin, Camille Beluffi, Rhys Taylor & Loïc Grau

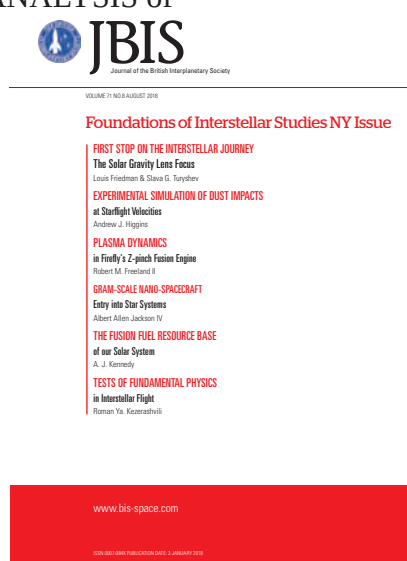
EFFECTS OF ENHANCED GRAPHENE REFLECTION on the Performance of Sun-launched Interstellar Arks, Gregory L Matloff
Publication Date: 17 January 2019

Front cover of the JBIS *Foundations of Interstellar Studies NY* Issue

To join The British Interplanetary Society and receive JBIS go to -

www.bis-space.com/eshop/products-page/memberships/bis-new-membership-2016/

Members of the British Interplanetary Society receive a 20% discount on membership of i4is - i4is.org/membership



News Feature:

Oumuamua, Project Lyra and Interstellar Objects

John I Davies & Adam Hibberd

Oumuamua and its possible successor interstellar visitors will continue to be the subject of study by the i4is Project Lyra team. The central objective of i4is is, of course, to pave the way for our species to reach the stars but visitors from beyond the solar system will help us to understand what lies beyond our system and may even help us to get there.

Elsewhere in this issue you will find a brief review of a classical music concert and lecture "The Mystery of Oumuamua" and a major feature by Marshall Eubanks "What is Oumuamua? Oddities and how a Mission could resolve them". Here we review the major developments since our last issue.

Project Lyra publication

The original Project Lyra paper was published by i4is within a few weeks of the discovery of Oumuamua (arxiv.org/abs/1711.03155). In January 2019 a revised version appeared in the peer-reviewed journal, Acta Astronautica (www.sciencedirect.com/science/article/pii/S0094576518317004). It's worth quoting the last sentence of the abstract "It is concluded that although reaching the object is challenging, there seem to be feasible options based on current and near-term technology." Here's just one of the diagrams from the Acta Astronautica paper (right).

Example from the Acta Astronautica paper. Encounter velocities with respect to mission duration and launch date. Showing how early launch dates reduce the $v_{\infty,2}$, effectively the encounter velocity, and thus the velocity of flyby or the velocity to be lost to achieve a landing or orbit.

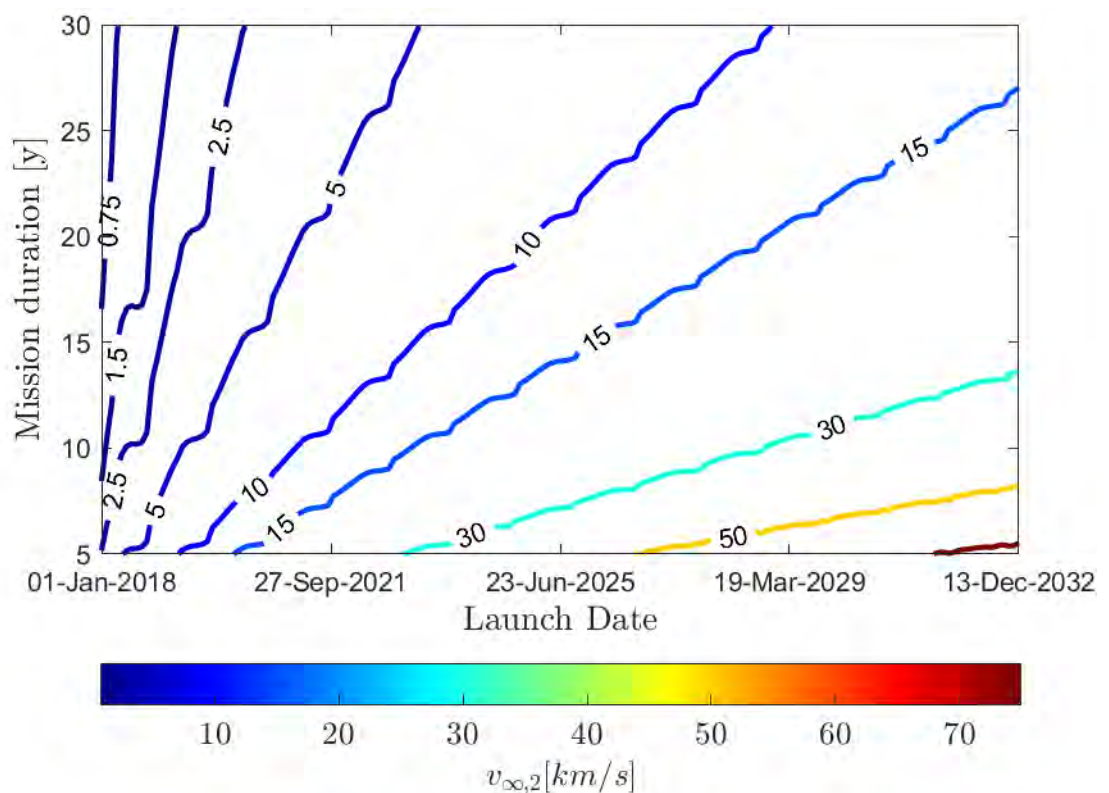
Credit: i4is Project Lyra team

In particular, a large conventional launcher such as the SpaceX Falcon Heavy, and a spacecraft using "slingshot" manoeuvres around the Sun and Jupiter, could reach Oumuamua within a few years of launch. There's a lot more detail, of course, and you can see an open publication of the paper at arxiv.org/ftp/arxiv/papers/1711/1711.03155.pdf.

Further speculations, hypotheses and results about Oumuamua

Professor Abraham (Avi) Loeb has featured heavily in the debate about the nature of Oumuamua. See News Feature - What is Oumuamua? in Principium 23 for an introduction to this area. His (and colleagues) conjecture remains controversial. Notably the Pan-STARRS researcher Professor Alan Fitzsimmons of Queens University, Belfast, believes that ice sublimation is the cause of the anomalous acceleration (as reported in our News item The Mystery of 'Oumuamua, Kings Place, London, January 27th 2019.). Keep up with Avi Loeb's thinking via his blog in Scientific American - www.scientificamerican.com/author/abraham-loeb.

Others are still less than certain, for example,



Trilling et al in the The Astronomical Journal, V156, #6, November 2018, Spitzer Observations of Interstellar Object 1I/'Oumuamua, analysed images to determine outgassing influences on the non-gravitational accelerations observed and concluded finally that "Our results extend the mystery of 'Oumuamua's origin and evolution." and sadly "...it is likely that we will never know the true nature of this interstellar interloper" (arxiv.org/pdf/1811.08072.pdf). Happily the latter may not be so, if the Lyra results are taken and implemented!

Finding the next Interstellar Object

If interstellar objects are common, and remember we have only found one so far, then we need a way of spotting them as early as possible in their dive towards the Sun. The best instrument for this purpose in the near future is probably the Large Synoptic Survey Telescope (LSST, www.lsst.org), likely to see "first light" next year with full capability a year or two later. This is a wide-field survey instrument covering 3 degrees of sky (about 40 full moons) in each image. LSST will image the entire visible sky every few nights so anything which moves within those few nights will, in principle, be easy to detect. The Pan-STARRS telescope, which first found Oumuamua, will continue to be useful and software/hardware for processing the images from these instruments will improve our ability to spot movement. LSST is at 30 degrees south while Pan-STARRS is at 20 degrees north so between them the majority of the sky will be covered.

Once a moving object is found and its trajectory found to be hyperbolic (from outside the solar system) then instruments with a narrower field of view (FOV) will come into play. This includes that old war horse, the Hubble, and of course the James Webb telescope (JWST), when it finally launches. JWST, being at a Lagrange point, can "sit and stare" at things. However even this monster will have difficulty imaging Oumuamua since it will be about magnitude 34 next year.

And terrestrial telescopes with a narrow FOV are coming along in some numbers. But to get to this object and find out its nature in detail we will need mission capability. Work by i4is Project Lyra and elsewhere come next...

Project Lyra current and future work - and other mission planning

The Lyra team is in intense discussion and study of both Oumuamua missions and planning for any future interstellar visitors. And i4is is by no means alone in this. Here is a sample of what is happening.

Lyra team thinking includes the use of multiple slingshot manoeuvres both to achieve the velocity (ΔV) and trajectory to intercept Oumuamua and similar objects. Oumuamua did not arrive in the same plane as the Solar System (the ecliptic) and is not departing in that plane either. Other visitors are likely to come from any direction so any probe trajectory needs to be "bent" out of our plane to match it. Such plane changes are of course, ΔV s, just like any linear acceleration or deceleration. ΔV is not free, it has to be "bought" by rocketry, momentum exchange with massive objects like the Sun or Jupiter or a push by external sources like lasers or the Sun.

Oumuamua missions may have launch dates as late as 2032 with intercepts in the 2050s (Sadly your humble editor will reach his century in 2046 so is unlikely to be around to join in the fun!)

Adam Hibberd joined the Project Lyra team after the first publication of their paper. He had performed his own investigations into missions to Oumuamua in 2017. When he became aware of Project Lyra he approached the team with his results and contributed substantially to the version of the paper in Acta Astronautica. He had independently developed a MATLAB programme to analyse various missions to Oumuamua and similar objects. This software, Optimum Interplanetary Trajectory Software (OITS), continues to assist the team in mission planning.

For various reasons, viable missions to Oumuamua generally have Jupiter as the last solar system port of call before flying out of the ecliptic plane towards Oumuamua. However, Jupiter must be located at a certain point in its orbit for a conducive alignment to occur and this has a period of around 12 years (approximately the duration of Jupiter's orbit around the Sun). Thus for example, missions from Earth to Jupiter to Oumuamua (E-J-O) have favourable launch years: 2019, 2031, 2043, 2055 and so on. Because Oumuamua is receding from us, as the launch year is delayed the mission durations are correspondingly increased. Assuming E-J-O, a launch in 2031 and setting a mission duration of 20 years, achieves ΔV s down to levels of around 26 km/s. This is still too high a value

despite an ETA of 2051! However if this 26 km/s could be reduced by say a half by exploiting some combination of planetary gravitational assists then we would possibly have a practical proposition in terms of a spacecraft mission arriving in 2051. This would necessarily be accompanied by an advance in the launch date giving less time to prepare for a mission.

One possible mission that cuts the total delta-V down by 10 km/s is the one pictured below.

It has a launch in 2023 and flies underneath the ecliptic plane. After an Earth launch, there is initially a return trip to Earth and then on to Jupiter, followed by a high inclination orbit to a Deep Space Manoeuvre (DSM) at a Jupiter distance away from the sun. A return to Jupiter sets up the favourable conditions for a trajectory to Oumuamua. Are there any mission scenarios that can improve on this solution? The hunt is on!

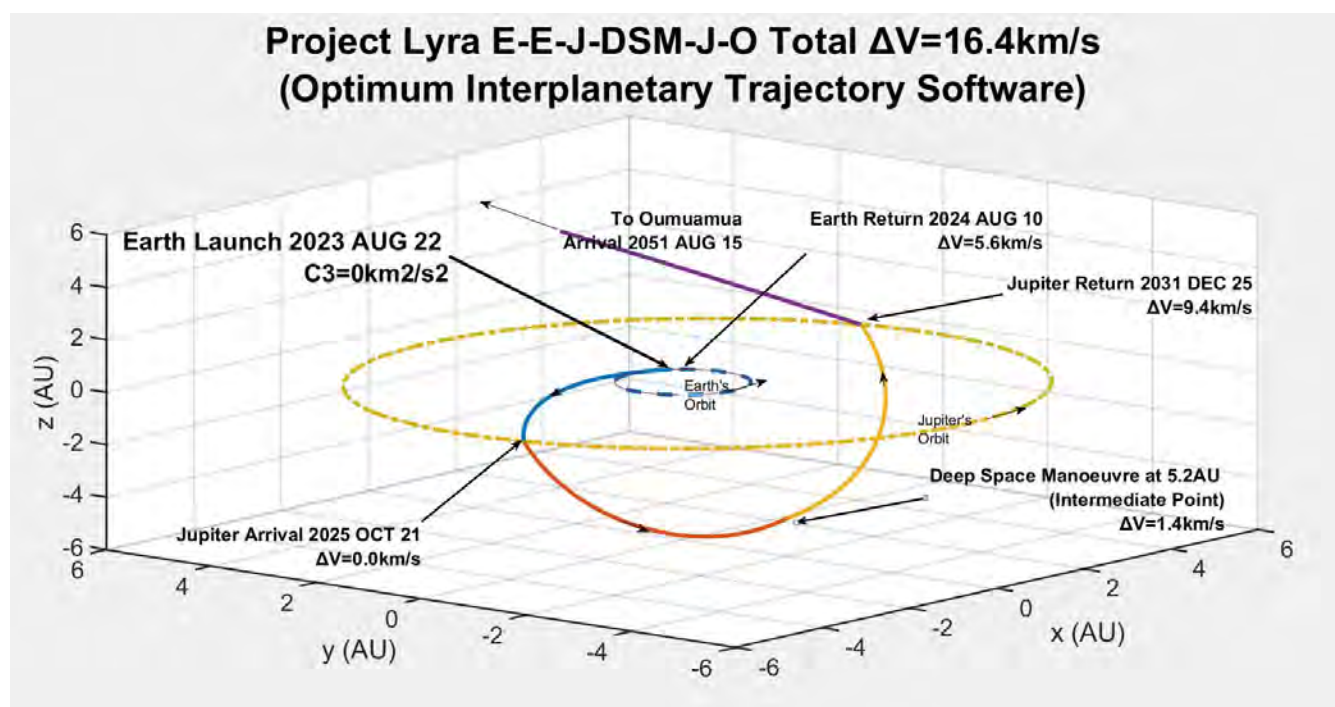
Ideas for interception of future interstellar objects include preparations to launch rockets, like the Falcon Heavy, but these are expensive to keep on standby and difficult to plan for. They are not

Spitfires sitting at Biggin Hill waiting for radar detection of incoming bombers from across the Channel, thankfully!

A promising idea is ESA's Comet Interceptor which will launch in 2028 to the L2 Lagrange point ready to launch a sub-spacecraft towards an incoming object - www.cometinterceptor.space/mission.html

'Comet Interceptor would be launched with the ESA ARIEL spacecraft in 2028, and delivered to the Sun-Earth Lagrange Point L2. It will be a multi-element spacecraft comprising a primary platform which also acts as the communications hub, and sub-spacecraft, allowing multi-point observations around the target. All spacecraft would be solar powered. The spacecraft will remain connected to each other at L2, where they will reside until directed to their target. The mission cruise phase will last months to years.'

The Comet Interceptor Mission Proposal Lead, Professor Geraint Jones, gives his Inaugural Lecture - *All Comets Great and Small* - at University College London on 11 February. We'll be reporting on this in the next issue.



Project Lyra: E-E-J-DSM-J-O Total delta-V=16.4 km/s (Solved by Adam Hibberd's Optimum Interplanetary Trajectory Software).

About the Authors

John Davies is a retired software engineer and mobile telecom consultant. In his early career he was briefly part of the UK space sector where he worked on ground checkout for the Bluestreak vehicle and contributed to an early study for the Hubble telescope. He has a first degree in Electronics from the University of Liverpool and a Masters in Computer Science from the University of Manchester.

Adam Hibberd is a freelance Software Engineer and Musician/Composer. He has worked for Marconi Communications and EASAMS, where he was a Guidance Specialist working on Ariane 4 Flight Software and Testing. He has a Bachelor's Degree in Physics and Mathematics from Keele University.

Territory in Outer Space

Max Daniels

The political and legal issues of exploration and settlement in space have arisen already in our home system but will inevitably extend to interstellar when this is achieved. Here Max Daniels presents the current "state of the art" with a focus on how the concept of territory may be understood in these contexts. Max recently completed an MA in Geopolitics, Territory and Security at King's College London, concentrating on the political framework of private-sector activities in outer space.

Outer space is widely considered as odd, distinct and different from terrestrial pastures. It has long been the backdrop and subject of science fiction that portray strange and – in multiple senses – alien worlds. This is not only because it lies outside of the land that is the site of most permanent human habitation, but because it extends outside and above the oceans and airspace. The harshness, remoteness and inhospitable nature of outer space make it seem an 'other' space, away from the land most humans call home.

Despite this, outer space has also been the focus of significant geopolitical tension. This concerns not only the 'Space race' of the Cold War era, but also recent announcements of new military branches, notably including the US military's 'space force'¹. Space, then, has long been viewed in the political and scientific worlds as an asset, something to be explored and studied, or, with the advent of the Cold War in the 20th century, a new strategic domain.

Far less thought has been given to how space itself – that is, the vast emptiness itself and all the celestial bodies it contains – can be understood politically, and how it may become a governable space. We must consider how outer space can be framed as **territory**.

Territory in space?

Humanity's presence in space is not new. Yuri Gagarin first left Earth's atmosphere in 1961, and since 1998 humans have had a permanent presence in outer space on the International Space Station (despite the threats of 'privatisation' by the Trump Administration). So why consider human territory in outer space now?

There is a rapidly growing private-sector space industry that is changing the dynamics of who is planning to visit space, and the subsequent political-economic implications. SpaceX announced in 2017 they would send the first craft to 'colonise' Mars in

2022, followed by crewed missions in 2024². Other firms led by wealthy individuals are also making progress, including Blue Origin, Boeing, Bigelow and Virgin Galactic³. This has received much media attention, with the BBC⁴ and The Economist⁵ both announcing a 'new space race'. As will be discussed, the legal frameworks of outer space are also uncertain.

Space exploration has, on the whole, been conducted by wealthy states with a high degree of scientific excellence – the US, those in Europe, Japan, China. This concentration of power demands scrutiny, writers have argued⁶, but the encroachment and ever-deeper involvement of the private sector means this should include those firms and corporations with their own immense technological systems.

What is territory?

We begin with a discussion of territory. In geography and political science, territory has often been considered the political bounding of space – that is, land and the oceans – directed by powerful groups such as kingdoms, states and empires. Over time, this describes the gradual enclosure of the world's habitable space such that the end-result is today's system of nation-states whose territory is separated by national boundaries. This analysis is broadly accurate for the make-up of today's political environment – but only on a descriptive level. It fails to recognise how and why this happens.

Geographers and historians sought to rectify this, with notable interventions in the 20th century. Jean Gottmann suggested territory serves a range of functions: providing an area of sovereign rule (the UK as sovereign from other European countries), of resources (minerals, agricultural and the like) and for defence (where borders prevent encroachment by potential enemies)⁷. Robert Sack defines territory as a practice of, "strategy for access and control,"



Blue Origin's New Shepard rocket. The private sector is engaging more closely not only in launches but also on exploration.

Source: Blue Origin;
<https://www.nasa.gov/press-release/nasa-announces-new-partnerships-to-develop-space-exploration-technologies>

where people seek control over migration, financial flows, or aircraft passage⁸. He argued that as it applies to pretty much anything crossing a border, the political power involved – determining who can migrate into a country – is not about the place in question but about the migrants themselves.

Instead, it is argued here that (political) power and place cannot be separated, and this relationship is crucial in determining why and how territory has formed. We need a conceptual history of territory to inform how territory is understood and practised today. This is beyond the scope of this article, but it is useful to consider territory as a technique of government: something governments do to secure the spatial extent of their control⁹. This is important as this concept of territory will be applied in the context of contemporary space exploration.

Outer space as territorial space

We can examine how people have thought about outer space. Early human societies and civilisations were aware of and used the cosmos as a source of divinity, often conflating the sun to the head of the realm (as with the Pharaoh in ancient Egypt). The idea of the abstract hierarchy of the cosmos – stretching from the Earth to the Heavens above – would influence social orders in the West through feudalism to the early capitalism of the Renaissance¹⁰.

Outer space was considered a space ‘out there’, influencing society here on Earth. Some individuals and governments have capitalised on this, making use of space to project their power and to create wealth. Such ‘elites’ include the space agencies of powerful countries, as well as firms. This is seen

in NASA’s enduring cultural legacy of the Apollo missions, and contemporary efforts at outer-space tourism, mining and private-led exploration.

These firms often use the frontier in their imagery: recalling ‘undiscovered’ lands, the spirit of European colonialism, as well as the Arctic, Antarctica and the oceans as uninhabited places ripe for exploration – and for the extraction of their resources. These last three have, indeed, had direct legal implications and relations with outer space: Antarctica for the Moon’s research bases, permitted within the outer-space treaty system; the deep seabed for the possibility of intergovernmental management of resource extraction and the common heritage principle, proposed in the Moon Agreement; and the ocean for the rights of flagged vessels¹¹. This last analogy is enshrined in Art. 8 of the 1967 Outer Space Treaty: where states, “on whose registry an object is launched into outer space is carried shall retain jurisdiction and control over such object, and any personnel thereof, while in outer space”¹².

To focus on one of these analogies, the oceans are not simply a site where economic and political activity has extended from the land. Rather, because of its very different materiality – being made of water, not solid landmass – it has required different types of activities and, crucially, regulations, where flagged vessels can sail freely across the high seas and can capture moving shoals of fish, sometimes in need of a licence. Outer space, likewise, features a range of actors – national governments, international bodies such as the UN Committee for the Peaceful Use of Outer Space (COPUOS) and private firms – all of whom are coming together

to form new regulations. Outer space will not simply follow any other model in both the activities taking place and the regulations that will govern them; it is forging a new, innovative route, based on new applications of territory as a concept. These innovations have spurred recent attempts to construct international laws about how countries should conduct themselves in space.

(Inter)national law of space

The territory of outer space is regulated by internationally agreed laws. Prior to the 1950s there was no specific agreements relating to space on the international stage; the 1957 launch of the Sputnik satellite spurred attempts to codify its legal status, particularly in the period 1967-82. There are five binding treaties:

- **The Outer Space Treaty** (OST, 1967): providing the first binding criteria on the political status of outer space, and the conduct of states. Space exploration, “shall be carried out for the benefit and in the interests of all countries”; all states have free and equal access to outer space; activities shall be peaceful; and states are responsible for the activities of their astronauts, whether governmental or non-governmental;
- **The Rescue Agreement**¹³ (1968): on assisting astronauts in distress;
- **The Liability Convention**¹⁴ (1972): on determining state liability for launches;
- **The Registration Convention**¹⁵ (1976): where states agree to inform each other of launches;
- **The Moon Agreement**¹⁶ (1984): determining how the Moon and other celestial bodies, and any local resources present, are the ‘Common Heritage of Mankind’.

The first four Treaties are signed by a significant number of states, with the OST ratified by 107 of the UN’s 194 member-states. It declares space as free from national appropriation, and as the ‘province of mankind’ (Art. 1), but this is a vague statement, leaving uncertain whether space should be deemed *terra nullius* (open to no states) or *terra communis* (open to every state, equally; this is what applies in Antarctica, albeit with the qualification of the Antarctic Treaty)¹⁷. It should be noted that what is ‘outer space’ has never actually been legally defined¹⁸.

Moreover, the OST is unclear with respect to private firms. While there are international agreements, it is up to individual states to enact these laws in their domestic legislations, and there is considerable

variation in how the laws are applied – including in the sophistication of its relevance to commercial activities. The key line is that national appropriation – that is, claiming territory – is forbidden.

In international law, private vessels moving through outer space are governed by their relevant state – much like flagged ships on the high seas. When it comes to private space stations (which are static when situated on a celestial body), it becomes more complicated. While the station itself is, again, subject to the laws of the state where it is registered, its activities are legally uncertain. Several authors argue that taking resources, as occurs in mining, is forbidden, as this would be equivalent to claiming the recovered minerals as property, which entails that firm’s government recognising such a property – which could be seen as a territorial claim in this unclaimed part of space¹⁹. This was made explicit in the Moon Agreement, which treated recovered resources as the ‘Common Heritage of Mankind’. However, even though this Agreement is officially in practice, only 11 states ever ratified it – hardly the universal recognition that would give it legitimacy.

The gridlock of the UN has led to alternative attempts at international governance. Bodies such as The Hague International Space Resources Governance Working Group²⁰ are informal gatherings of states and, crucially, non-state organisations, including the private commercial firms in such industries as tourism, mining and exploration. These can only offer suggestions and are not able to legislate, but the connections and knowledge generated may break the impasse.

Instead, national laws are providing the innovations relevant to the private sector. Ever more states are enacting domestic legislation that accounts for commercial activity, on a spectrum from the recognition of its legality to the explicit facilitation of private property rights. The United States, through its SPACE ACT (2015)²¹, allows individuals and firms to keep as property any resources gathered on celestial bodies, provided the firm and the majority of its shareholding reside in the US. Luxembourg goes further, permitting the holding of such property by any firm registered in the country through its 2017 ‘space mining’ law, even if the firm or shareholders are based outside Luxembourg²².

The problems of the private sector

With little direction at the international level and increasingly diverse domestic laws, the legality of various private-sector activities in outer space remains vague. The private sector is responding to these domestic legal changes, particularly in the United States. SpaceX plans to send cargo to Mars in 2022, followed by humans in 2024, alongside a possible lunar base featuring in-situ resource utilisation. Blue Origin is preparing its New Shepard suborbital and New Glenn orbital rockets; from then, the company would construct a lunar lander and, subsequently, a lunar base. But there are limits.

These remain in the planning stages, on the whole, and the firms have a history of overly-optimistic targets. The real push – and the real money – remain with space agencies. NASA is leading the development of the Gateway, a lunar orbital base to replace the ISS²³. The European Space Agency is pushing for a lunar base, although it is involving the private sector for the first time²⁴. Overall, the plans of both public agencies and private companies indicate separate but highly connected paths that aim for similar objectives: the exploration of ‘deep space’ and the establishment of human presence.

Territory is coming, whatever that entails

Space has long been thought about as something ‘out there’. With the advance of technologies to reach it, as a political entity – somewhere to govern – it has become ever more familiar. This has spurred attempts at governance through international law. The problem is that the UN is difficult, primarily because little can be agreed upon. This opens the door to vagueness in relation to the private sector; and that could lead to geopolitical tensions over access to space and its resources. It has, however, also presented new, informal groups of states the opportunity to discuss space’s legal system.

With the finances required, the public sector will be crucial to space exploration, and so state involvement will remain central. To understand territory, then, is to understand how we conduct ourselves in space. Territory in space needs much more thinking²⁵, and an update of our understanding of governance before a misunderstanding takes place.

This article is based on an MA dissertation for the Geopolitics, Territory, Security course at King’s College London. For a copy of the original dissertation, or for any questions, please contact the author at max.daniels@kcl.ac.uk

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ESA's designs for in-situ resource utilisation (ISRU) show how space agencies remain integral to technological development in deep space. Source: ESA;

<http://exploration.esa.int/moon/59878-workshop-towards-the-use-of-lunar-resources/>



About the Author

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News Feature: 69th International Astronautical Congress 2018 Follow-Up

Reported by Patrick J Mahon

The 69th IAC, Bremen 1-5 October, was a massive and impressive event. Out of the thousands of presentations we could only schedule coverage of papers by the i4is team & others of interstellar interest. We reported on most of these in our last issue, P23.

IN-SITU INVESTIGATION OF THE INTERSTELLAR MEDIUM

Friday 5th October		IAC reference: IAC-18.D4.4.1
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Prof. Dr Robert F Wimmer-Schweingruber University of Kiel Germany

[IAC paper: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/manuscripts/IAC-18,D4,4,1,x47057.pdf>]

[IAC presentation: not available]

[Open paper: not available]

Professor Wimmer-Schweingruber opened by asking why we needed to investigate the Local Interstellar Medium (LISM) in-situ. The answer is that astrospheres (the generalisation of our own heliosphere) are a unique phenomenon, which raise the question of how they form and function. There are three key areas to explore: (a) heliophysics: how do the Interstellar Medium (ISM) and the stellar wind interact? (b) astrophysics: how do the properties of our own ISM compare to other ISMs? (c) fundamental physics: how do the various components of the ISM (plasma, dust, gas, waves and particles) interact here?

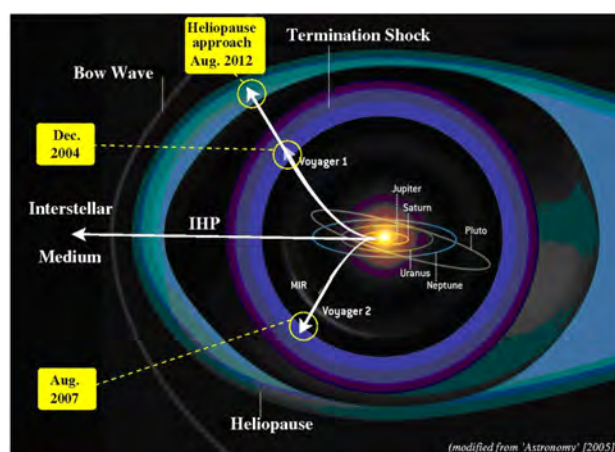
The Interstellar Boundary Explorer (IBEX) spacecraft told us that (a) is very complicated, but our knowledge of the boundary conditions (between the ISM and the stellar wind) is very limited. The IBEX 'ribbon' of Energetic Neutral Atoms (ENAs) told us that $\mathbf{B} \cdot \mathbf{r} = 0$, implying that there is no bow shock. The Cassini/INCA 'belt' of ENAs was tilted with respect to the IBEX 'ribbon', which suggested that the pressure is dominated by suprathermal particles. Also, the termination shock differed from expectations. Turning to the Very Local Interstellar Medium (VLISM), the Ulysses/GAS experiment showed that the inflow direction of the gas disagreed with the relative flow direction of the ISM.

Professor Wimmer-Schweingruber concluded by saying that to understand this complex dataset, we need to go out and perform in-situ investigations of the LISM with modern instruments, which requires a new interstellar probe. There is an urgency to the task because we ideally want the next probe in place before Voyagers 1 and 2 expire, to ensure continuity of data.

Reported by: Patrick Mahon

The positions of the Voyagers in the heliosphere. In August 2012 Voyager 2 entered a region likely to be associated with the heliopause. Neither Voyager will be able to probe the Interstellar Medium (ISM), necessitating an Interstellar Probe.

Credit: IAF/ Prof. Dr. Wimmer-Schweingruber



Near-Term Interstellar Probe: First Step

Friday 5 October		IAC reference: IAC-18,D4.4.2
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Dr Ralph L McNutt, Jr. Johns Hopkins University Applied Physics Laboratory USA

IAC paper: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/manuscripts/IAC-18,D4,4,2,x44169.pdf>

IAC presentation: not available

Open paper: not available

Dr McNutt and his collaborators proposed an interstellar mission, using current technologies, to send a probe 2000AU through the outer heliosphere and into the Very Local Interstellar Medium (VLISM). It would act as a precursor to larger future missions. This was not a new idea, but Johns Hopkins University had been tasked by NASA’s Heliophysics Division with re-examining the concept.

To do so, they asked themselves two questions: (a) Could such a mission fly before 2032? (b) Is the achievable science compelling? They propose a mission with four targets of interest: (i) the Interstellar Medium; (ii) the circumsolar dust disc; (iii) Kuiper Belt Objects; and (iv) Trans-Neptunian Objects. In designing the mission, there are multiple trade-offs to be considered, including mass, power, communications and propulsion. The end result left them with three options for the mission concept. By using the Space Launch System, followed by a solar gravity assist (flying very close to the Sun, but without burning up), the probe could potentially reach a velocity of 12 AU per year. Dr McNutt concluded by reporting that the study results would be announced at the AGU meeting in Washington in December 2018. Reported by: Patrick Mahon

Decelerating interstellar probes with magnetic sails

Friday 5 October		IAC reference: IAC-18,D4.4.3
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Prof. Claudius Gros University of Frankfurt am Main Germany

IAC paper: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/manuscripts/IAC-18,D4,4,3,x42427.pdf>

IAC presentation: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/presentations/IAC-18,D4,4,3,x42427.show.pdf>

Open paper: not available

Professor Gros described a theoretical study of a wafersat (with a mass between 1g and 1kg) attached to a 1m² solar sail and accelerated out of the solar system using a 100 GW laser. The question he considered is whether it would be possible to decelerate this probe into orbit at its destination by transferring sufficient momentum to the local Interstellar Medium through a magnetic sail. His model leads to two divergent conclusions, depending on the probe’s speed. A fast (0.1 c) spacecraft headed, for example, to Alpha Centauri, and taking roughly 40 years to travel 4 light years, cannot be slowed down by this approach. However, a slower (c/300) probe going, for example, to the TRAPPIST-1 system, and taking roughly 12,000 years to travel 40 light years, could slow down using a magsail. Such a probe could have a payload of self-replicating von Neumann machines, or perhaps a Genesis probe along the lines described in the author’s other talk at the conference in Bremen (see talk A7.1.8, summarised by John Davies in the last issue of Principium).

Reported by: Patrick Mahon

Performance characteristics of magnetic sails
Credit: IAF/ Prof. Claudius Gros

effective reflectivity area

critical current

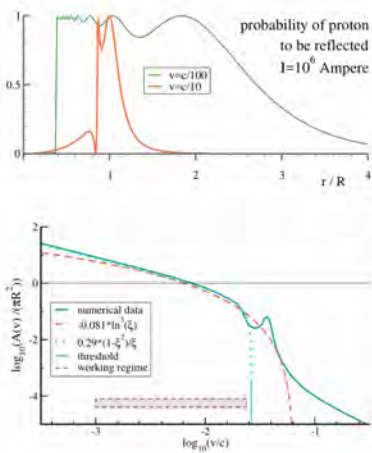
Larmor radius ≈ diameter

• $I \approx \frac{v}{c} \cdot 2.5 \cdot 10^6$ Ampere

analytical approximation

$$A(v) \sim -\ln^3(\xi) \\ \sim (1 - \xi^2)/\xi$$

$$\xi = vI_c/(cI)$$



Characterization of a Non-Stationary Spherical Inflated Light Sail for Ultra-Fast Interstellar Travel by Using Commercial 3D Codes

Friday 5 October		IAC reference: IAC-18.D4.4.5
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Mr. Dario Riccobono Politecnico di Torino Italy

IAC paper: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/manuscripts/IAC-18,D4,4,5,x43399.pdf>

IAC presentation: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/presentations/IAC-18,D4,4,5,x43399.show.ppt>

Open paper: https://www.researchgate.net/publication/328028194_Characterization_of_a_Non-Stationary_Spherical_Inflated_Light_Sail_for_Ultra-Fast_Interstellar_Travel_by_Using_Commercial_3D_Codes

The paper was presented by Mr Riccobono’s supervisor, Professor Giancarlo Genta. The project was designed to feed in to the Breakthrough Starshot programme, and addressed the question: can commercial 3D codes be used to simulate a typical Starshot mission, to avoid the considerable time and effort that would be required to develop the code from scratch? Now, one of the key physical challenges for a laser sail-powered probe is to achieve stability with respect to the laser beam. This can be achieved actively or passively, and it is known that flat or conical sails are unstable without active control, whereas a spherical sail can be stabilised passively. They therefore modelled a spherical sail. This had previously been done in 2D but the results were of limited value.

In the present project, they modelled in 3D, using the commercially available Altair Hyperworks suite, a spherical lightsail constructed from carbon nanotubes. Given limitations on available computer time, they did not simulate the entire mission, but just the most challenging phase: the initial rapid acceleration. However, the first set of results were disappointing, as the inflated light sail blew up! Analysis showed that this was due to the pressurised gas inside the sail. However, if the gas pressure were reduced, the sail material would get wrinkled, making the sail progressively less stable and more ineffective. However, when they modelled a sail with *no* internal gas pressure, it survived the acceleration phase. Their conclusion, somewhat counterintuitively, was therefore that the sail should not be inflated until *after* the acceleration phase.

Spherical Inflated Light Sail
Credit IAF/Dario Riccobono



Reported by: Patrick Mahon

Project Glowworm: Testing Laser Sail Propulsion in LEO

Friday 5 October		IAC reference: IAC-18,D4.4.6
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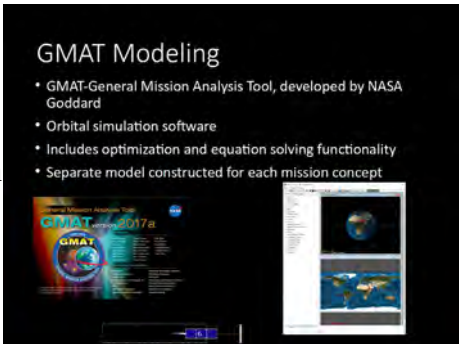
Mr. Zachary Burkhardt International Space University (ISU) USA

IAC paper: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/manuscripts/IAC-18,D4,4,6,x47477.pdf>

IAC presentation: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/presentations/IAC-18,D4,4,6,x47477.show.pptx>

Open paper: See **LEAD FEATURE** in this issue of Principium and references

Zachary Burkhardt’s ISU project, supervised by Chris Welch at ISU and Nikolaos Perakis at i4is, was inspired by i4is’s Project Glowworm, which aims to be the first demonstration of a laser sail in space. Glowworm will deploy a chipsat attached to a sail from a cubesat, and use a laser onboard the cubesat to push the sail, increasing the semi-major axis of the chipsat’s orbit by 10 km. This project focused on simulating two different ways to achieve this: (a) the ‘chaser’ concept, where the cubesat uses an onboard electric propulsion system to maintain its position relative to the laser sail; and (b) the ‘passive’ concept, where the cubesat stays in its original orbit and fires the laser whenever the laser sail passes nearby. Both approaches were simulated using NASA Goddard’s General Mission Analysis Tool (GMAT) software.



The simulation results showed that the chaser concept met the design brief, increasing the semi-major axis by over 10 km in a design with a realistic sail mass and laser power. For the passive concept, however, the force of atmospheric drag at the target altitude (800km) is larger than the infrequent thrust from the laser, and the objective cannot be achieved. However, if moved to a much higher orbit with lower drag, it was found to take over five years to achieve the project objective. The passive concept was therefore judged impractical, and the chaser concept was selected for further design work. [Editor’s note: see Zachary Burkhardt’s LEAD FEATURE in this issue of Principium for more information on this project.]

Reported by: Patrick Mahon

Using Graphene Interstellar Solar Photon Sails: Sensitivity Studies for Pico-Probes and Arks

Friday 5 October		IAC reference: IAC-18,D4.4.7
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Prof. Gregory Matloff, New York City College of Technology USA
 IAC paper: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/manuscripts/IAC-18,D4,4,7,x41903.pdf>
 IAC presentation: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/presentations/IAC-18,D4,4,7,x41903.show.pptx>

Open paper: not available

Professor Matloff explained that he had developed a linear BASIC program (on an iPad) to perform sensitivity studies for two distinct types of solar sail mission to Alpha Centauri using graphene for the sail material: (a) a small, unmanned, Starwisp-type probe; and (b) a much larger, manned, interstellar ark. Having checked that the program gave results that matched previous analytical work by the author, he then ran the program multiple times for both missions to simulate different perihelion distances and to investigate the impact of changes in the reflectance of the sail. For the starwisp probe, travel times to Alpha Centauri, using realistic parameters, varied between 440 and 72 years, although the latter case involved a peak acceleration at perihelion of over 11,000 g! In the case of a manned interstellar ark, where peak acceleration had to be limited to 3 g due to human physiology, the trip duration for an ark carrying 100 passengers would be around 1,640 years.

Reported by: Patrick Mahon

Case Study of an Interstellar Mission to Tau Ceti: Unmanned Interstellar Probe Using Gas Core Nuclear Reactors with Early 21st Century Technology

Friday 5 October		IAC reference: IAC-18,D4.4.8
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Dr. Ugur Guven, UN Center for Space Science and Space Technology Education in Asia and Pacific (CSSTEAP) USA
 IAC paper: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/manuscripts/IAC-18,D4,4,8,x43448.pdf>
 IAC presentation: <https://iafastro.directory/iac/proceedings/IAC-18/IAC-18/D4/4/presentations/IAC-18,D4,4,8,x43448.show.pptx>

Open paper: not available

The paper was presented by Dr Guven’s student and co-author, Mr Anand Kumar Singh, who explained that they had explored an unmanned mission to Tau Ceti, 12 light years from Earth. A key element of the study was the use of a gas core nuclear reactor for the propulsion system, providing constant, high specific impulse acceleration in the early phase of the mission to take the spacecraft to semi-relativistic velocities, where time dilation would start to affect the mission duration. They had calculated the mission duration for accelerations of 1 g or 2 g, reaching terminal velocities of 1, 5, 10, 20 or 30% of the speed of light. A mission at 30% would take less than 40 years to reach Tau Ceti, with time dilation leading to a 1.8 year difference between the mission duration seen from Earth versus ship time. [Editor’s note: it is unclear from the paper what the mass ratio of such a spacecraft would be, a question raised by Professor Matloff at the talk.]

Reported by: Patrick Mahon

Project Daedalus – A Beginners' Guide

Patrick J. Mahon

Project Daedalus was the first serious attempt to design a spacecraft intended to travel to another star. Under the auspices of the British Interplanetary Society, a group of engineers spent five years in the mid-1970s investigating the feasibility of sending a probe to Barnard's Star, six light years away. Forty years on, many interested in interstellar travel may have heard of Daedalus but know little about it. Here Principium Deputy Editor Patrick Mahon gives us an introduction to the project and the spacecraft design which was the result.

1. INTRODUCTION

I imagine that many Principium readers will already be familiar with Project Daedalus, the first fully-developed design for an interstellar spacecraft. However, if you haven't heard of it, or aren't as familiar with it as you'd like to be, this article will fill you in on the basic details.

1.1. Is interstellar travel even possible?

This is the question that led the British Interplanetary Society to set up Project Daedalus. The project started in 1973, in the immediate post-Apollo period which, in retrospect, proved a high-water mark for excitement about manned space travel. Many space enthusiasts were confidently predicting a permanent Moon base, and a first mission to Mars, within a decade or so. These looked like a natural evolution from the Space Race of the 1960s. For those with larger and more revolutionary horizons, buoyed by the expansion in science fiction as a genre, the prospect of interstellar, rather than simply interplanetary, travel beckoned.

However, there was a problem. The Drake Equation, developed by radio astronomer Dr Frank Drake in 1961, provides a way to estimate the number of intelligent civilisations in our own galaxy. Plugging a plausible dataset into the equation leads to the conclusion that there should be lots of them. But as the famous physicist Enrico Fermi concluded a decade earlier, in the paradox that now bears his name, if that's true, where are they all?

One potential solution to Fermi's Paradox is that interstellar travel is impossible. Project Daedalus was initiated to investigate that possibility. The final project report, published in 1978 [1], clearly indicated that interstellar travel appeared to be possible, thus removing one potential explanation

for the Fermi Paradox and enabling the idea of interstellar travel to move from the realm of science fiction into that of scientific and engineering possibility.

1.2. Project Daedalus in Principium

Project Daedalus has appeared several times before in the pages of this magazine [2]. There was a brief introduction to the starship in issue 1, while issues 8, 13 and 14 included articles on Terry Regan's amazingly impressive project to scratch build a detailed scale replica of the design – now on permanent display at the London HQ of the British Interplanetary Society.

In this article I want to outline the project for those not familiar with it, in the hope that this may encourage interested readers to find out more – about Project Daedalus, and about its successors, such as Project Icarus – for themselves.

2. OBJECTIVES OF PROJECT DAEDALUS

The primary objective of Project Daedalus was to act as a feasibility study for a simple interstellar mission, using only present-day technology or reasonable extrapolations thereof. Given the technological limitations, compared to the scale of the challenge, and given also the wish that the mission should be completed within the professional lifetime of most of the scientists and engineers working on it, the aim was to send an unmanned probe on a flyby mission to a nearby star, reaching its target within 50 years of launch.

A subsidiary, but important, objective of the project was to expose the project participants to aspects of spacecraft design and engineering which they would not otherwise have encountered, thus creating a group of starship engineers with a practical understanding of the many challenges to achieving interstellar flight.

3. TARGET SELECTION

The first question that needed to be answered, before detailed design work could commence, was where the spacecraft would be sent. Since Daedalus was a proof of concept study of a problem where the biggest issue was the almost unimaginable distances involved, one might imagine that the answer to this question would be ‘the nearest star system’ – that is, Alpha (and Proxima) Centauri, some 4.3 light years away.

However, it was clear from the start that implementing Project Daedalus would, in reality, require huge amounts of investment. This would not be forthcoming unless there was seen to be an appropriate return on that investment, for example in terms of scientific discoveries. Therefore, an early focus of the project was to rank thirteen of the nearest stars or star systems, all within twelve light years of Earth, in relation to three broad areas of scientific interest:

- Stellar evolution and astrophysics;
- Likelihood of any exoplanets orbiting the star;
- Astrobiological interest – might the system harbour life of any kind?

Interestingly, the ranking that resulted put the Alpha Centauri system very clearly at the top, with Barnard’s Star, 61 Cygni, Epsilon Eridani and Tau Ceti coming a somewhat distant second to fifth, but all with very similar rankings to each other.

The project team eventually chose Barnard’s Star, 5.9 light years away, as the target, principally because it was at the time thought to harbour exoplanets, unlike the only nearer system (Alpha/Proxima Centauri), which was not.

4. MISSION PROFILE

So, having decided on the mission objectives and target, the next step was to produce a basic outline of a mission that could achieve them. This was refined several times during the project. For example, the starship was originally designed as a single stage vehicle, but when it became clear that such a design could not satisfy the mission constraints, it was redesigned as a two-stage rocket. The final result is set out below.

4.1. Mission and vehicle profile

The basic details of the Daedalus mission and vehicle are as follows:

- Mission type: undecelerated fly-by of target star
- Mission target: Barnard’s Star, 5.9 light years distant
- Mission duration: around 50 years
- Vehicle velocity: 12.2% of the speed of light
- Vehicle type: Two-stage nuclear fusion rocket
- Vehicle length: 190 metres
- Vehicle mass: 53,000 tonnes (approximately)
- Propellant mass: 50,000 tonnes (46 kt in 1st stage, 4 kt in 2nd stage)
- Structure mass: 2,220 tonnes (1,690 t in 1st stage, 530 t in 2nd stage)
- Payload mass: 450 tonnes
- Propulsion: Inertial confinement fusion, utilising Deuterium and Helium-3

4.2. Project timeline

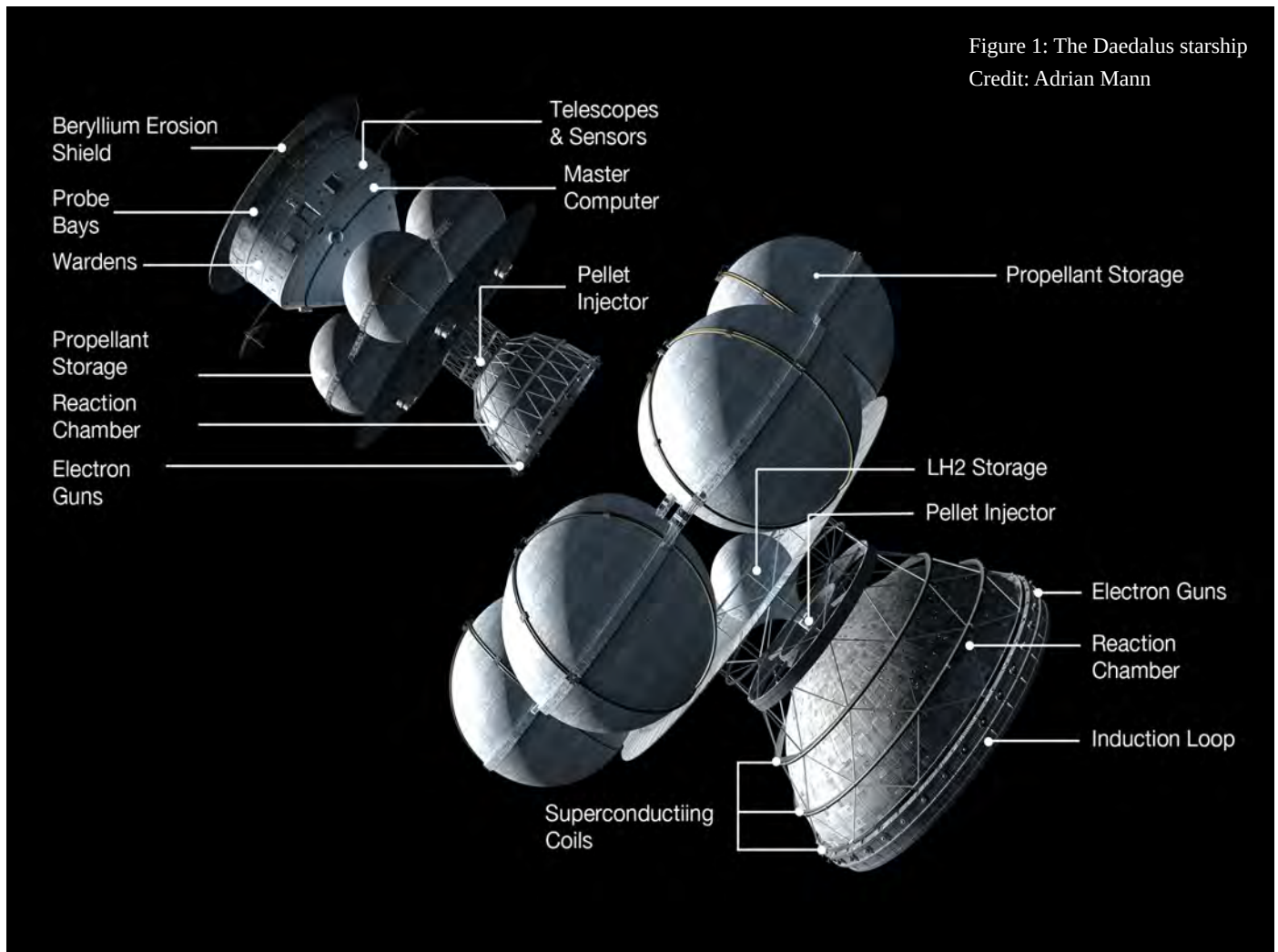
The indicative timeline for the project is as follows:

- Year 0: Launch from Jovian orbit and initiate fusion engine
- Year 0: First stage engine burns for 2.05 years, then is discarded
- Year 2.05: Second stage engine burns for 1.76 years
- Year 3.81: Shut-off engine, with final cruise velocity of 12.2% c
- Year 3.81: Cruise for around 45 years
- Year 50: Arrive at Barnard’s Star, 5.9 light years away
- Year 50: Fly-by of Barnard’s Star system, lasting about 100 hours
- Year 50: Communicate science results back to Earth

5. THE SPACECRAFT

This section will briefly describe each of the key subsystems that enable the Daedalus spacecraft to fulfil its mission objectives. To do so, it needs to be able to function successfully (structure, power), operate autonomously (computers and self-repair), get to the target system (propulsion and navigation), undertake scientific measurements on the way and at the target (payload) and return its results to humanity (communications).

Figure 1: The Daedalus starship
Credit: Adrian Mann



An impression of the vehicle, produced by a great friend of both i4is and BIS, the interstellar artist Adrian Mann, is shown in Figure 1, to indicate the location of each of the major subsystems.

5.1. Structure

The Daedalus starship comprises two stages. The larger first stage consists of six spherical tanks holding 46,000 tonnes of propellant, mated to the first stage fusion engine. The smaller second stage comprises four propellant tanks, a second fusion engine, the payload, computer system and at the front a Beryllium shield to protect the vehicle from erosion by space debris. These various sub-structures are made from a selection of metal alloys, each chosen to match their particular material properties to their function on the vehicle.

Figure 1 shows the spacecraft as it is at the beginning of the mission. Once the first stage's fuel is exhausted, just over two years into the flight, the entire first stage is discarded, and the second stage continues the journey towards Barnard's Star on its own.

5.2. Power

During the initial acceleration phase, power is tapped from whichever fusion engine is operational, using an induction loop. When this is insufficient, auxiliary power is provided by two nuclear fission reactors (one on each stage). The second stage fission reactor will also provide all the power once all the propellant has been exhausted.

5.3. Computers and self-repair

Project Daedalus requires a spacecraft which can operate reliably for half a century, and which can make crucial decisions autonomously, given that for most of the mission, the round-trip travel time for any communication to and back from Earth will be measured in years. It is therefore vitally important that the computer system is up to the task, and that the spacecraft is capable of repairing any faults which occur.

Inevitably, the computer architecture for the Daedalus spacecraft is based on the state of computing technology in the mid-1970s, when it was designed, and so looks relatively primitive from the perspective of 2019. However, the project team put forward a sensible outline design focused on the

functions that would be required of the hardware and software onboard a starship that was required to function autonomously for a period of fifty years.

The ability of machines to repair themselves is not available today, let alone in the 1970s. However, the project team developed a feasible outline of the sorts of capabilities that would be necessary, and packaged these in a pair of autonomous robotic ‘Wardens’ not completely dissimilar from Huey, Dewie and Louie, the drones depicted in the 1972 science fiction film ‘Silent Running’ (although they don’t walk, since zero-g applies, other than during the acceleration phases).

5.4. Propulsion

As already described, the spacecraft is a two-stage fusion rocket, with each stage containing an engine powered by nuclear fusion between Deuterium and Helium-3. These propellants were chosen because they do not produce lots of neutrons in the fusion products. Uncharged particles cannot be focused, and high velocity neutrons would weaken structures they encountered as they exited the engine. Instead, the products are charged particles which can be focused electrically through the engine bell, enabling maximal translation of the fusion energy into forward thrust.

The fusion reaction is produced using Inertial Confinement Fusion (ICF), a method which focuses powerful lasers or electron beams onto a small pellet of the fusion fuel, heating and compressing it to create temperatures and pressures at the centre of the pellet sufficiently high to initiate nuclear fusion. This process is repeated 250 times each second, providing a Specific Impulse of approximately one million seconds, equivalent to a velocity of 10 million metres per second for the exhaust plume (roughly 3% of light speed). (Specific Impulse is the measure of the efficiency of a rocket. Typical numbers for chemical rockets are hundreds of seconds, and even ion thrusters, which are much more efficient, are only in the thousands.)

5.5. Navigation

A key challenge for Project Daedalus is the need for the navigation system to be extremely accurate, very sensitive and able to function autonomously, not only to ensure that the spacecraft gets to the Barnard’s Star system itself, but also so that the onboard probes can be sent to any planets that are detected.

From this perspective, the mission has several discrete phases: the acceleration from the solar system, the cruise phase, a mid-course correction

and, later on, identifying any planets in the Barnard’s Star system, enabling cross-range manoeuvres so that the probes can be sent to their targets, final navigation through the system, and then the post-encounter phase. Each of these has its own navigation challenges.

Thankfully, forty years on we now have much better data on stellar positions, and we have proved our ability to guide spacecraft successfully to faint objects at the edge of our own solar system, as recently demonstrated by the rendezvous of the New Horizons probe with the Ultima Thule asteroid in the Kuiper Belt [3].

However, the different scale of the challenges involved in navigating the New Horizons probe to an asteroid in the Kuiper Belt, some 40 AU from Earth, where the one-way communications delay is around 12 hours, compared to sending Daedalus to Barnard’s Star 6 light years away, where the one-way communications delay is 6 years, should not be underestimated. Nonetheless, the project team concluded that the navigation challenges should be soluble in time, given a feasible rate of technological development.

5.6. Payload

There is, of course, very little point in sending a spacecraft some six light years from home unless it can do something useful when it gets there. The Daedalus spacecraft includes 450 tonnes of payload, intended to achieve a number of discrete scientific objectives across three distinct topics, as follows:

- Fundamental physics – Very Long Baseline Interferometry and Astrometry;
- Astrophysics – measuring the properties of the target star and the Local Interstellar Medium; and
- Exoplanet studies – investigating the nature of any exoplanets in the system.

Some of these experiments are performed by instruments onboard the spacecraft, principally optical and radio telescopes. Others are undertaken by over twenty free-flying probes which are launched from Daedalus at different points in time, to perform imaging and spectroscopy on the star, any gas giants in the system, any terrestrial planets in the system, and on the interstellar medium that surrounds the star and its planets.

5.7. Communications

There are four distinct phases to the mission from a communications perspective: acceleration, cruise, encounter and post-encounter. During the acceleration phase, when the spacecraft is still relatively close to the Earth, communications

would be via a near-infrared (NIR) laser system. This would avoid interference from the high energy fusion engine plume. However, once the second stage fusion engine is turned off, communications during the remaining phases will be accomplished by pointing the paraboloid engine bell precisely at Earth and using it as a high gain antenna to broadcast radio signals back to Mission Control. There would be brief disruptions to communications when the engine was used again for manoeuvring purposes during the encounter with Barnard's Star, but the data would be saved for later transmission.

6. CONCLUSION

The primary objective of Project Daedalus, as set out above, was to act as a feasibility study for a simple interstellar mission. A few details of the mission architecture set out in the final report do require capabilities significantly beyond a simple extrapolation of the state of technology in the mid-1970s – most notably, the need for a solar system-wide economy to enable the mining of Helium-3 from the atmosphere of Jupiter. Even so, the project showed that most aspects of an interstellar mission to Barnard's Star were indeed feasible. Some forty years later, the project papers continue to reward close study by those who wish to reach for the stars, in fact as well as fiction.

If you would like to know more about interstellar spacecraft design, you may wish to read my review paper about the Firefly Icarus spacecraft published in Principium 22 last August [4]. I would further encourage you to follow up the references (particularly [1]), read relevant books (eg [5, 6]) and consider attending one of i4is's Starship Engineer courses (see [7] for details).

ACKNOWLEDGEMENTS

I would like to put on record my admiration for, and gratitude to, Alan Bond, Tony Martin and the whole of the Project Daedalus team, whose dedication and hard work over a period of years demonstrated convincingly that interstellar travel is feasible, and converted the topic from an aspect of science fiction into a question of science and engineering.

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The Daedalus starship compared with the Saturn 5 launcher
Credit: Adrian Mann

Amerigo: Brief Overview of a 1000 AU probe study

Jamie Bockett

The i4is Starship Engineer Summer School took place from 15th to 19th August 2018 at i4is HQ, The Mill, in Gloucestershire, UK. The core part of the course was a team project intended to analyse a substantial problem in interstellar probe design. Here one of the team describes how this project has progressed towards a published paper.

Introduction

In August 2018, The Initiative for Interstellar Studies launched its first residential education course, with a focus on interstellar exploration – The Starship Engineer Summer School. Out of this course has come a paper on which the course participants (myself included) are currently working; this is currently titled: *Amerigo: A 1,000 AU Interstellar Precursor Mission Study from the i4is Starship Engineer Summer School Class of 2018**. Due to the unfinished nature of the paper, I aim to give an overview of the paper in its current state – please remember that aspects of the paper may be changed before completion.

Firstly, I would like to present the main focuses of the study, more specifically, the questions to be addressed by the flight of Amerigo as stated in the paper: “What is the nature of the nearby pristine interstellar medium? How do the Sun and galaxy affect the dynamics of the heliosphere? What is the structure of the heliosphere? How did matter in the Solar System and interstellar medium originate and evolve? Is there life or intelligence outside of our Solar System?” These are very different from the final refined mission objectives and instead aim to explore the large range of topics that could be studied by Amerigo. These questions embody the nature of the study, namely, to examine multiple issues across multiple areas of space science.

Whilst conducting preliminary research for the paper, the team found recent research into a mission from the Johns Hopkins University Applied Physics Laboratory (APL) being completed for NASA’s Heliophysics Division, which is similar to Amerigo. As a small group with relative inexperience compared to large bodies such as NASA and the APL, the team members were inspired to find confirmation that interstellar probes are already a substantial field of study.

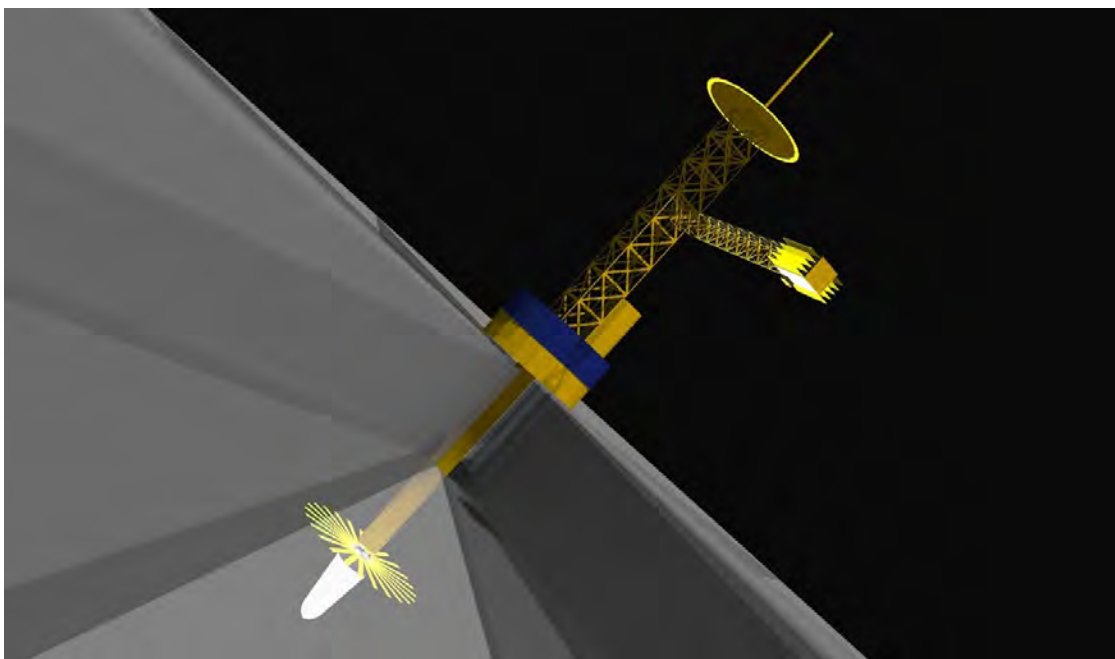


Illustration of spacecraft structure
Credit: Amerigo paper

* N.B. All quotes come directly from the Amerigo Paper.

Overview of the Structure of the Craft

Amerigo will use a solar sail as its main source of propulsion; this was inspired by the success of previous space-tested solar sails such as from IKAROS and LightSail; unlike these two sails, the sail used for the Amerigo probe would be much larger, roughly 1.5 km in diameter. This sail will be unfurled, after the probe has performed a gravity assist around the Sun, at the probe's perihelion for increased solar pressure then later jettisoned as the solar pressure falls to a minimum, achieving a maximum velocity of approximately 224 km/s (at this speed it would take less than 10 days to reach Mars from the Sun). The craft will weigh 315 kg in total (a limit of 500 kg was set for the team) and will be powered using a 238 Pu radioisotope generator with an initial power level of 200 W, falling to 35 W during the journey to 1000 AU. The cost of the mission is estimated at approximately \$800 million minimum. This comparatively low figure has been achieved largely due to the current growth in the space sector leading to large decreases in factors such as launch costs (typically missions to the outer solar system have cost several billions

of dollars). A significant factor in the cost is, of course, the mass of the probe; the team expects that, given the rate of recent advancements in the miniaturisation of technologies, the probe's mass will be reduced, reducing costs of aspects such as launch and propulsion.

The probe will "establish reliable, accurate and fast communication" using infrared laser transmitted from and received by an orbital relay station. Optical communication was chosen since much higher data transfer rates could be achieved than in more common solutions, like radio wave communications. Given the vast distance over which Amerigo is proposed to travel, choosing an optical method also seems more viable due to optical communications maintaining signal strength well over great distances. The team also found that NASA plans to launch an infrared Laser Communications Relay Demonstration this year, promising, "a low-cost [...] solution the size 'of a loaf of bread', capable of 200 Gigabits per second". Such a demonstration will help to bolster the feasibility of the use of laser communications for the mission.

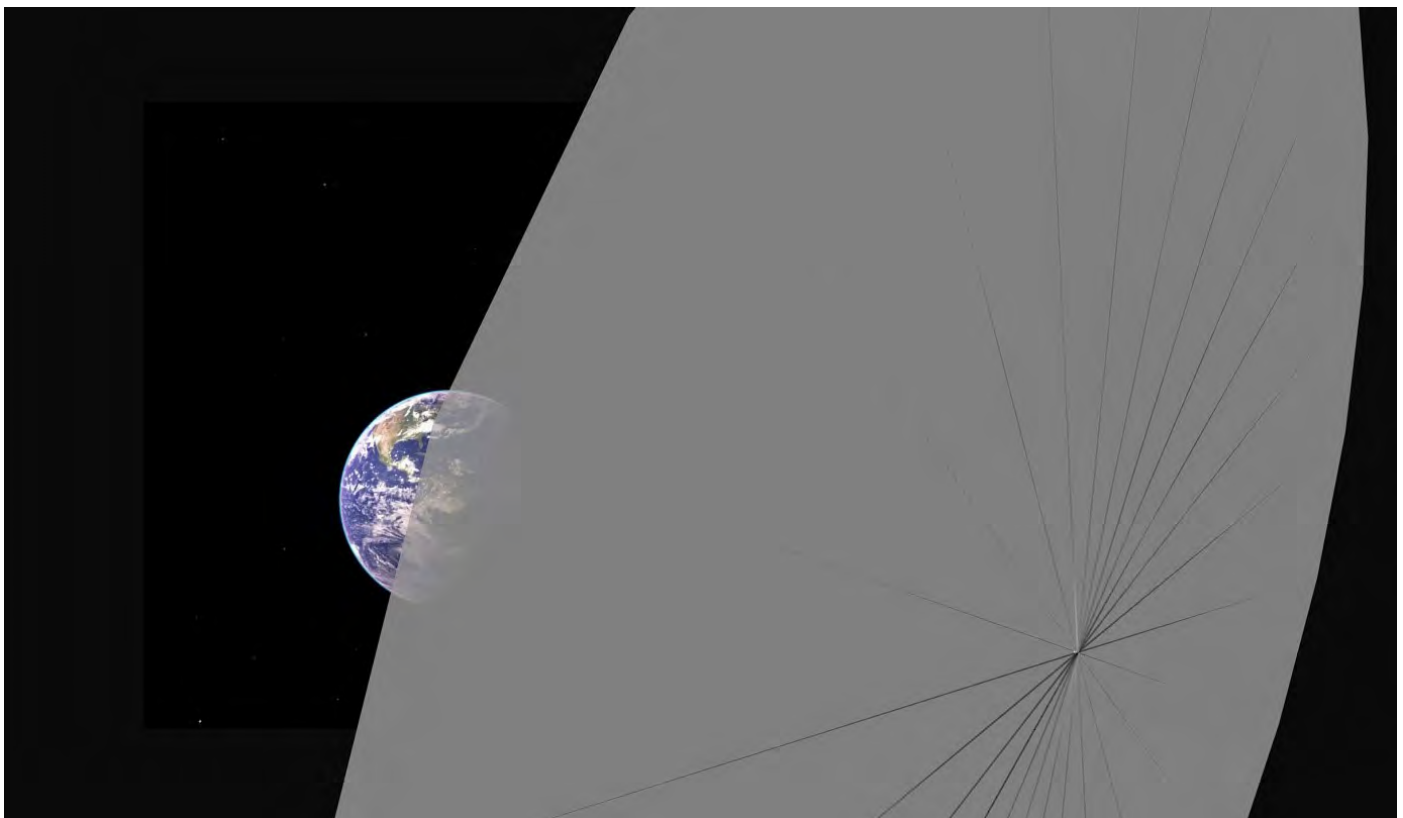


Illustration of unfolded Solar Sail
Credit: Amerigo paper

Objectives for the Mission

The team was given some main objectives for the mission, these are:

- Primary Objectives:
 - o To study the solar heliosphere.
 - o To study the Kuiper Belt.
 - o To perform a fly-past of an as-of-yet unstudied dwarf or minor planet.
 - o To progress the search for a planet in the Outer Solar System (currently dubbed 'Planet 9' or 'Planet X').
- Secondary Objectives:
 - o 2 tasks focussed on SETI (The Search for Extra-Terrestrial Intelligence).

The manner in which these objectives would be carried out was left to be decided by the team.

To decide on how to fulfil the objective of a planetary fly-past, the team researched planetary bodies that would be of particular interest due to abnormalities or incongruences with the rest of the Solar System. Eventually, the dwarf planet Sedna was selected. There is little known about Sedna, making it all the more intriguing; it has a diameter of roughly 1000 km; it is in a highly eccentric orbit beyond the Kuiper belt; it has an orbital period of around 11,400 years; an aphelion of 937 AU and a perihelion of 76 AU (meaning that it moves in and out of the heliosphere). The team believes that the prospect of a Sedna fly-past is a, “unique and remarkable science opportunity”, because it offers the chance to *'kill 2 birds with one stone'* – both the objectives of studying the heliosphere (due to Sedna's 'trans-heliospheric' movements) and performing a fly-past could be achieved. Furthermore, there is the possibility that some research into the formation of the early Solar System could be conducted from Sedna due to its, “fossil-history”, and previous reports of methane, water and nitrogen ices on the surface could be confirmed. Studying Sedna in this way would also likely allow for an accurate picture to be drawn of the composition of the surface of the dwarf planet, likely giving suggestions as to why it is one of the reddest objects in the Solar System. The team was very surprised to find out that Sedna's perihelion is relatively soon – 2076*. Given the long orbital period of about 11,400 years, the perihelion presents itself as being a rare opportunity with great

scientific gain that will become more difficult to carry out in later years.

Developing the idea of a Sedna fly-past, led to the team producing a plan for “a piggy-back low-mass sub-probe to enter orbit around [Sedna] and also release a small lander/impactor to take a closer look”. These would be released together from the parent craft before reaching Sedna and would decelerate, allowing them to begin orbiting Sedna. The lander/impactor would then be deployed to the surface and the orbiter would act as a communications link between Earth, the parent craft and the lander/impactor whilst both it and the lander/impactor carry out research. An added benefit of using a sub-probe is that it allows for methods of deceleration of interstellar probes to be tested; the team is currently looking into the best method for decelerating the sub-probe, the current suggestions include the use of laser, electric or magnetic sails. The team expects some form of artificial intelligence (AI) to be used for decisions that need to be made in ‘real-time’ or that cannot be made from the Earth; for example, to decide upon a suitable landing location for the lander/impactor and to allow the parent craft to avoid high-speed collisions with objects encountered in transit to 1000 AU.

With regards to studying the heliosphere and the nature of the Interstellar Medium (ISM), the probe uses instrumentation similar to that used on the Osiris-REX mission. The team suggests that the probe would be able to investigate which gases and particles are present in the ISM, along with extreme-energy space particles, in the ISM. Research into the ISM from Amerigo would aim to inform future interstellar missions about the effects of the properties of the ISM on craft and possibly even aid research into the precautions needed for humans to travel through the ISM. The mission also seeks to form a better image of the heliosphere: how the solar wind and ISM affect the size and shape of the heliosphere; where the heliosphere begins and ends; what the conditions are at the front and back edges of the heliosphere and how the environment changes at the Plasma Bow Shock.

For the secondary objectives, SETI, the team decided these would focus on Proxima Centauri to confirm or deny the existence of further exoplanets in its vicinity, which would allow for further

* This is more than 50 years hence and the Amerigo study is therefore likely to be superseded many times. However we believe it is important to choose a real target in an advance-planning study such as Amerigo.

research to be done into signs of intelligent life in the star system. The team also concluded that the probe would be able to ‘target’ stellar systems thought to contain exoplanets and search for signs of intelligent life through multiple techniques, including the use of telescopes, spectral analysis and radio and laser beam detectors (the team theorised that the probe being in deep space would allow a more pure radio quiet allowing for signals to be detected more easily).

Conclusion

This ambitious study promises, “significant scientific returns in a fairly short space of time”, such as the first use of solar sails to accelerate a craft to speeds necessary for interstellar travel and a visit to a unique, unexplored dwarf planet. As is mentioned in the paper, the study (so far) has taken a short amount of time and so, to best use this time and to reduce complexity, the team maintained that, “the idea was not to ‘re-invent the wheel’ where existing technology or experience could be used to good effect.”. It must also be noted that i4is is known for its speciality of, “rapid mission scoping”; this small team has taken this to heart and so has managed to produce this study despite the small amount of time given.

To conclude, I would like to quote the paper’s ‘conclusions’ section: “The team are under no

illusions that the majority of designs of this nature fail to see starlight! We enjoyed putting together a mission profile which we did not think we would be capable of at the beginning of the Starship Engineering Summer School. However, thanks to our instructors, we have exceeded our own expectations and we hope that even if the proposal as a whole is not taken up, there will be some ideas or concepts within it, which may form the basis of new thinking, and possibly contribute towards a mission which is eventually funded, built and flown.”

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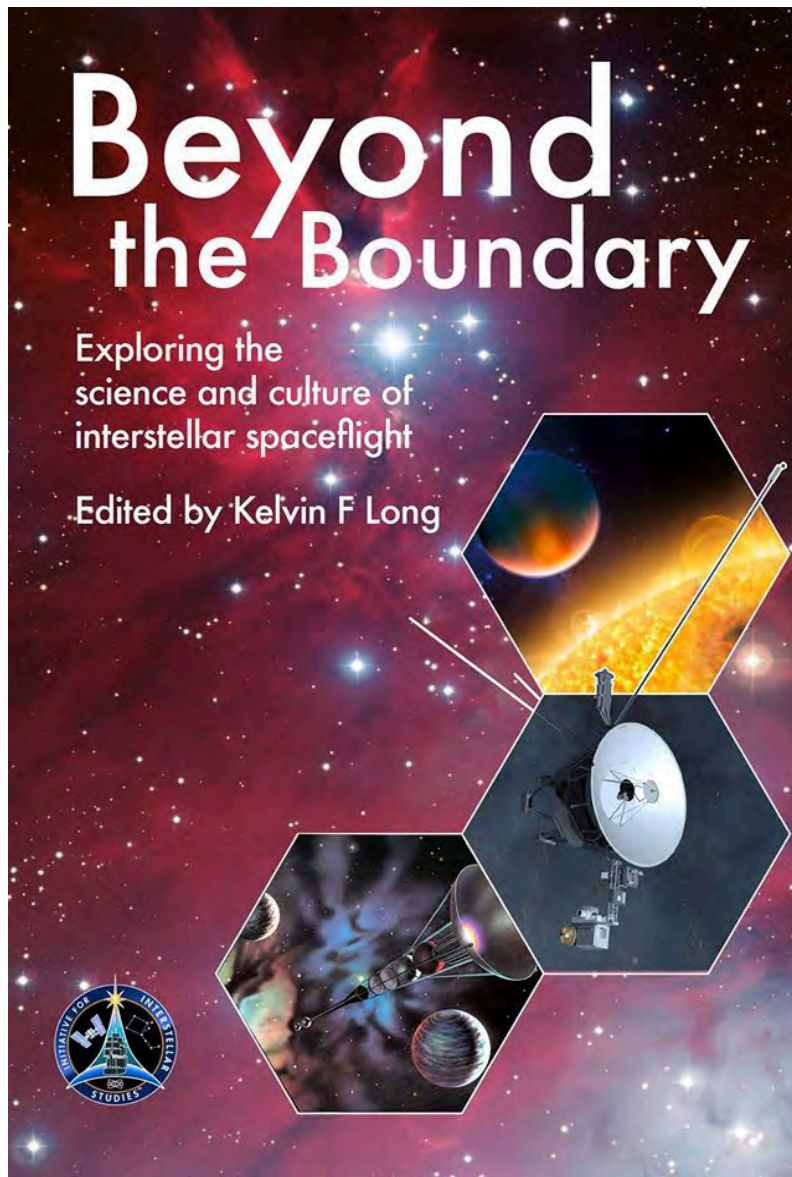
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A US Navy Lockheed Orion flying over the Italian Naval Academy sailing ship Amerigo Vespucci in 1976.
Credit: Wikimedia Commons / U.S. Navy National Museum of Naval Aviation / PH1 R.W. Beno, U.S. Navy

The probe design concept was titled Amerigo, after the Italian explorer, financier, navigator and cartographer Amerigo Vespucci (1454-1512), from whom the name ‘The America’s’, in reference to the New World of exploration, derives.

We hope that an Amerigo probe and its sail may be as beautiful as the eponymous sailing vessel here - and as technologically advanced as the aircraft above it was in its time,



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

Vision

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

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

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Back cover: BIS Daedalus
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