TENNESSEE VALLEY INTERSTELLAR WORKSHOP

Proceedings of TVIW 2016
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TVIW 2016

DAVID E. FIELDS AND ABBY SHERRIFF

PUBLICATIONS COMMITTEE

Proceedings of the 2016 TVIW

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Papers and Posters

Welcome from the Board President and Meeting Chair

Dear Colleagues,

It is with great pleasure that I welcome all of you to the Fourth Symposium of the Tennessee Valley Interstellar Workshop (TVIW) under the Chairmanship of Les Johnson and for the first time in Chattanooga, Tennessee, using the theme, From Iron Horse to Worldship: Becoming an Interstellar Civilization. In particular, I would like thank the Board of Directors, the Organizing Committee, the Program Committee, our Sponsors, and all those who have volunteered their time and effort before, during, and after the Symposium to make the event happen.

As to the Symposium itself, we anticipate 19 talks on everything from human colonization to miniature probes at relativistic speeds; Seminars on Terraforming, Space Conflict, Advanced Propulsion, and Geoengineering; Working Tracks on Life Systems Engineering for Worldship, Homo Stellaris, Space Solar Power, and Space Mining; Kaffeeklatches and Posters on subjects of current interest. In addition, there will be a reception, meals, a Hospitality Suite, and a Public Outreach event.

Sincerely yours,

John F. Preston,

President, TVIW Inc.

Welcome to the 4th Symposium of the Tennessee Valley Interstellar Workshop in historic Chattanooga, Tennessee. In keeping with the TVIW's founding goal of engaging the engineering and science expertise along the Tennessee River valley, we chose Chattanooga for this year's venue because of its vibrant embrace of the future via it being America's first 10-gigabit-per-second internet connected city and a hub for the Tennessee Valley Authority (TVA) – a hugely successful, long-term investment begun in the 1930’s to provide reliable electrical power for what was then an underdeveloped region. It is THIS kind of forward thinking that will enable the interstellar future we all seek.

Get ready to have your paradigms challenged, your minds expanded and your friendship and collaborative circles enlarged as the Symposium proceeds. We have a most-excellent slate of plenary lectures scheduled, including our opening Keynote address, "Cutting the Umbilical Cord to Earth," from Dr. John Lewis, and 18 additional original talks on interstellar-related topics such as life sciences, space science and propulsion, and new approaches to SETI. We have high expectations of our four Working Tracks and new-this-year Kaffeeklatsches.

TVIW isn't just about programming. We're having our traditional Sunday night reception, Monday night banquet, Tuesday night Public Outreach Event (with several notable science fiction authors participating), and, of course, our famous Hospitality Suite where you can relax and imbibe your favorite beverage on your own personal schedule.

Be sure to explore our venue, the historic Chattanooga Choo-Choo Hotel and help us fulfill the theme of this year's Symposium, "From Iron Horse to Worldship: Becoming an Interstellar Civilization."

Les Johnson

Chair, TVIW 2016 Symposium

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 TVIW thanks all presenters and contributors for their participation and cooperation.

Contributions from the Authors

Cutting the Umbilical Cord to Earth

John Lewis

The author did not choose to provide an extended abstract of his presentation.

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Propulsion Technology Assessment: Science and Enabling Technologies to Explore the Interstellar Medium

Ben Beers

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Propulsion Technology Assessment: Science & Enabling Technologies to Explore the Interstellar Medium

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INTRODUCTION

Leveraging the success of the Voyager Interstellar Mission (VIM), the Keck Institute for

Space Studies (KISS) at the California Institute of Technology is studying *Science and Enabling Technologies to Explore Interstellar Medium* and is extending the planning for a potential mission to go there known as the *Interstellar Probe*. Table 1 highlights the mission's goals.

Table 1. Comparison of overarching goals for the Interstellar Probe mission.[3]

Goals	Voyager (VIM)	Interstellar Probe
1. Get there sooner	100 AU in 29 years	100+ AU in 10 years
2. Travel Faster	Approx. 3.6 AU/year	18-36 AU/year
3. Survive longer	Approx. 43 years	50-100 years

The role of the NASA Marshall Space Flight Center's (MSFC) Advanced Concepts Office (ACO) was to conduct a trade study comparing known or near term low-thrust Advanced Propulsion Stage (APS) candidates while determining which Space Launch System (SLS) vehicle configuration could deliver sufficient characteristic energy (C_3) to the spacecraft. The candidates considered included a Magnetically Shielded Miniature (MaSMi) Hall thruster (Fig. 1), a solar sail (Fig. 2) and an electric sail (E-Sail) (Fig. 3). Several trajectories options were also studied.

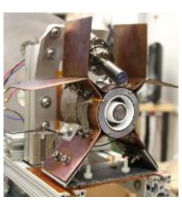

Figure 1. MaSMi Hall thruster system. *(Credit: UCLA)*

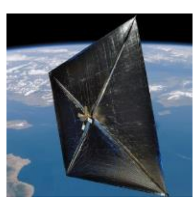

Figure 2. NanoSail-D solar sail. *(Credit: NASA Science News)*

Figure 3. Electric sail (E-Sail) system. *(Credit: Szames)*

SUMMARY

The KISS at Caltech concluded its second (of two) workshops in mid-January 2015 in order to formalize an approach for progressing the proposed *Interstellar Probe* mission into the next development phase. Table 2 outlines the study's Ground Rules and Assumptions (GR&A).

Table 2. Ground rules and assumptions for this study.

Item	Description	Notes
Mission Performance	100+ AU in 10 years	
Launch Window	2025 – 2035	
Launch Vehicle	SLS Block 1B + EUS + 8.4 m PLF	
Spacecraft Mass	380 kg (838 lb_m)	Excludes low-thrust APS
Spacecraft Heat Shield Mass†	300 kg (661 lb_m)	Scaled from Solar Probe Plus mission
Spacecraft Power	450 W	

Unlike the VIM, this mission's proposed timeline would allow for more of those involved to one day see the fruits of their labor. Because the launch vehicle industry's launch windows tend to be fluidic in nature, the window was shifted so that 2025 would be the earliest possible launch year. An SLS Block 1B vehicle architecture was assumed except with an 8.4 m (27.6 ft) Payload Fairing (PLF) instead of the 5.0 m (16.4 ft) PLF as this was the only Block 1B architecture C_3 curve available. [1] The total spacecraft mass was assumed to be 380 kg (838 lb_m), which included all components except for the onboard low-thrust APS. It was also assumed that 450 W of power would be available onboard the spacecraft and supplied by an Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) [2] as this technology was considered to be potentially available within the project development timeline given a push to develop it.

A protective heat shield would be attached to the spacecraft and its propulsive stages, especially for an impulsive Oberth maneuver at a distance of 11 solar radii or 0.05 AU from the sun. Its mass was derived by scaling the heat shield being designed for NASA's Solar Probe Plus mission by the Johns Hopkins University (JHU) Applied Physics Laboratory (APL). [3]

Table 3. Solar sail propulsion system GR&A.

Item	Description		Notes
Reflectivity	0.91		
Minimum Thickness	2.0 µm		
Maximum Size (per side)	200 m (656 ft)		
Sail Material	CP1		
Aerial Density *	3 g/m^2	10 g/m^2	Current technology is 25 g/m^2
Characteristic Acceleration	0.426 mm/s^2	0.664 mm/s^2	
System Mass	120 kg (265 lb_m)	400 kg (882 lb_m)	

Table 4. Electric Sail (E-Sail) propulsion system GR&A.

Item	Description
System Mass	120 kg (265 lb_m)

Wire Material (Density)	Aluminum (2,800 kg/m^3)	
Wire Diameter (Gauge)	0.127 mm (36 gauge)	
Characteristic Acceleration	1 mm/s^2	2 mm/s^2
Tether Quantity	10	20
Individual Tether Length	20 km (12.4 mi)	20 km (12.4 mi)

Two trajectory profiles were considered: 1) escape trajectory using a Jupiter Gravity Assist (JGA) (*E-Ju*) and 2) escape trajectory first performing a JGA maneuver followed by a sun dive via an impulsive Oberth maneuver and optional Saturn gravity assist maneuver (*E-Ju-Su-Sa*).

The first trajectory profile option relies more heavily on the C_3 capability of SLS. At departure, the SLS and an additional SRM kick stage put the spacecraft on an Earth-escape trajectory. Approaching Jupiter, the spacecraft performs a JGA with a minimum flyby distance of 4.89 Jupiter radii. Once outside Earth's sphere of influence, the spacecraft deploys and activates its low-thrust APS. Either the MaSMi Hall thruster is operated until the assumed 50,000-hour lifetime expires, the solar sail is jettisoned prior to the JGA, or the E-Sail operates until reaching a point of diminishing return, which is estimated at about 20 AU.
The second trajectory option also begins with an Earth-departure kick performed by the SLS and an additional SRM kick stage. The spacecraft performs a Jupiter flyby to reduce its heliocentric speed such that the resulting perihelion occurs at 11 solar radii. At perihelion, an SRM kick stage performs the final impulsive maneuver. Afterward, the heat shield and SRM are jettisoned and the low-thrust APS is initiated at 0.5 AU. The low-thrust APS options operate similar to the first trajectory option. At Saturn, a final gravity assist is performed.

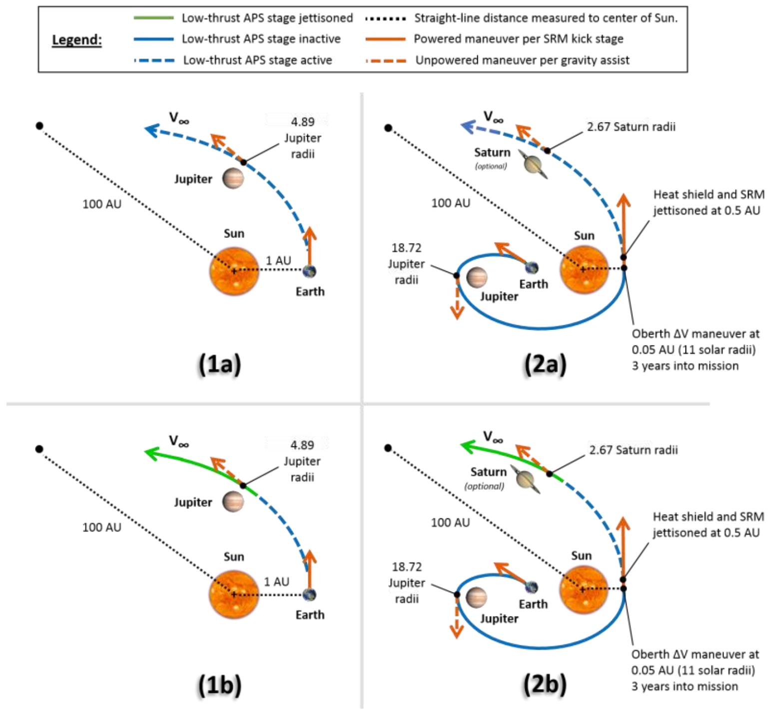

Figure 5. Mission trajectory profile options considered: a) trajectories apply to MaSMi Hall thruster and E-Sail systems and b) trajectories apply to solar sail system.

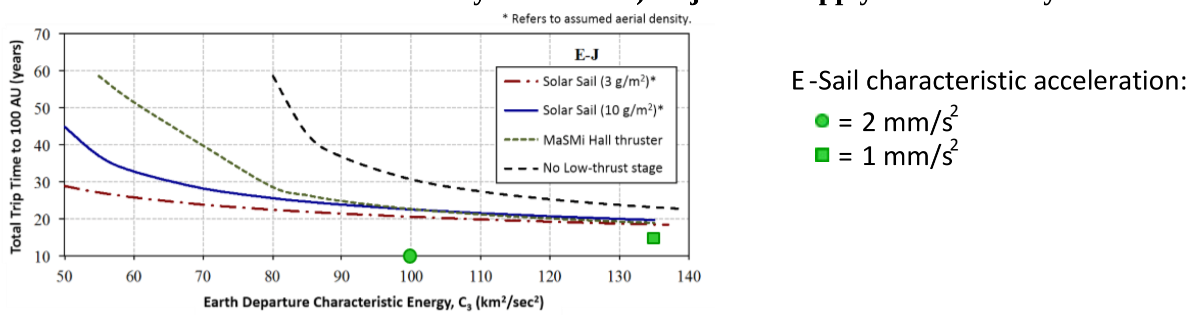

Figure 6. Low-thrust APS analysis for *E-Ju* trajectory profile.

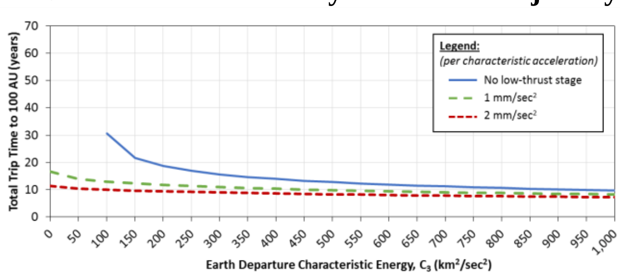

Figure 7. E-Sail propulsion system analysis for *E-Ju* trajectory profile.

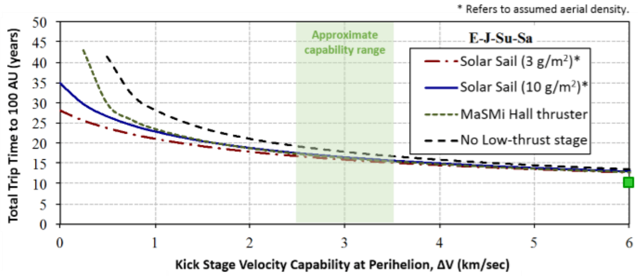

Figure 8. Kick stage analysis for *E-Ju-Su-Sa* trajectory profile.

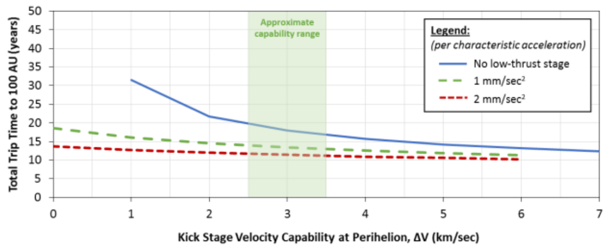

Figure 9. Kick stage analysis for *E-Ju-Su-Sa* trajectory profile (E-Sail only).

An assessment was conducted to determine payload fit within an SLS Block 1B 8.4m (27.6 ft) PLF. The spacecraft was assumed to be volumetrically similar to VIM in a stowed configuration. Two SRM kick stages were located below each low-thrust APS stage. The total payload mass includes: spacecraft bus, low-thrust APS, heat shield and SRM kick stages.

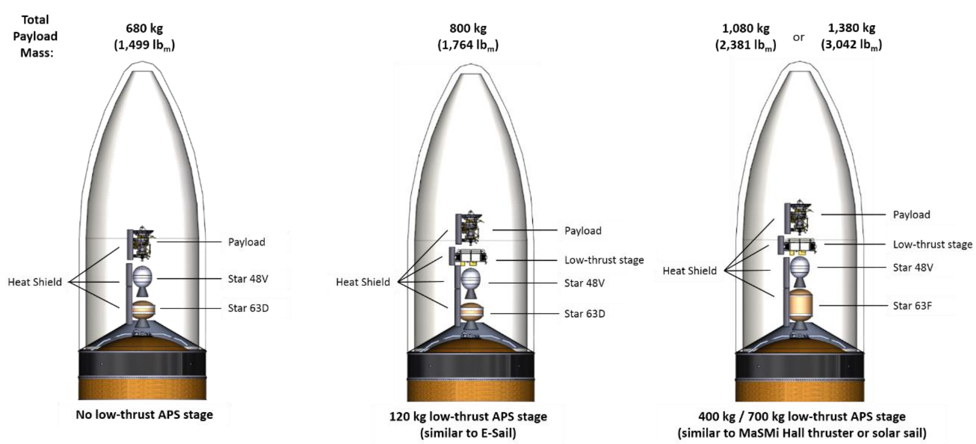

Figure 9. Approximate payload envelope inside SLS 8.4 m (27.6 ft) PLF using VIM stowed configuration.

Results show that, compared to the VIM, all low-thrust APS technologies for either trajectory option provide substantial total trip time improvements ranging anywhere from 11 to 19 years, an E-Sail yielding the lowest total trip time of 11 years for the *E-Ju-Su-Sa* trajectory option. Compared to the MaSMi hall thruster and solar sail propulsion systems, having no low-thrust APS stage actually achieves almost the same total trip time especially for perihelion kick stage velocities (ΔV) greater than 4 km/s (13,123 ft/s).

ACKNOWLEDGEMENTS

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Advanced Ion Propulsion Systems for Interstellar Precursor Probes

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Advanced Ion Propulsion Systems for

Interstellar Precursor Probes

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Introduction

Since more than 30 years, the space community proposes an interstellar heliopause probe to investigate the outer regions of the heliosphere and the very local interstellar medium (LISM). Voyager 1 is the first human-made object to venture into interstellar space; it crossed the heliopause, the boundary separating solar and galactic plasmas, in August 2012 at 120 AU from the Sun, 35 years after the launch from Cape Canaveral in 1977. However, today its measurement capabilities are very limited, and in 5-10 years the on-board power will be too low for the probe to operate any scientific instrument further; at that time Voyager 1 will be still at less than 150 AU. The minimum required distance to reach the unperturbed "virgin" interstellar medium is expected to be at least 200 AU. A trip time of 25-30 years, within the professional lifetime of a scientist or engineer, is the target mission duration for a real LISM probe equipped with modern scientific instruments.

Few existing propulsion technologies can be extended in order to enable this challenging mission. Electric propulsion (EP) is one of them, probably the most promising one together with the various space sail concepts (solar, laser, microwave, magnetic, electric). In order to reduce the propellant mass and consequently the spacecraft mass to reasonable values keeping the travel time down to a scientist career lifetime, the specific impulse must be higher than 5,000 seconds even for a scientific mission to 200 AU, just outside the solar system heliosphere.

This paper shows that a 200AU Solar Electric Propulsion (SEP) probe with a burnout speed of 10 AU/year (3 times Voyager 1´s speed) can be assembled and launched in less than 10 years. The development of advanced ion thrusters with ultra-high specific impulses (up to 50,000s) could enable the most challenging interstellar precursor missions up to the Oort Cloud.

1. Electric Propulsion Historical Background

Electric propulsion is a technology which allows for much higher exhaust velocities than conventional chemical propulsion, resulting in a major reduction of the propellant mass for a certain space mission. This leads either to a significant decrease of the launch mass of a spacecraft or to larger payloads. In general, electric propulsion comprises all types of propulsion in which a certain amount of propellant is ionized and then accelerated by electric or magnetic fields, or both. It was first conceived more than 100 years ago by the American physicist Robert H. Goddard (1882-1945), who as early as 1906 addressed the problem of producing "reaction with electrons moving with the velocity of light" and wrote down his thoughts on this problem in his notebook [1]. He was considering electrons and not ions because the concept of the ion, as an atomic-sized particle possessing a net positive charge, had not yet been fully established at that time. His visionary ideas culminated in a US Patent ("Method and means for producing electrified jets of gas", No. 1,163,037, filed in 1917) which represents the world's first documented electrostatic ion accelerator intended for propulsion.

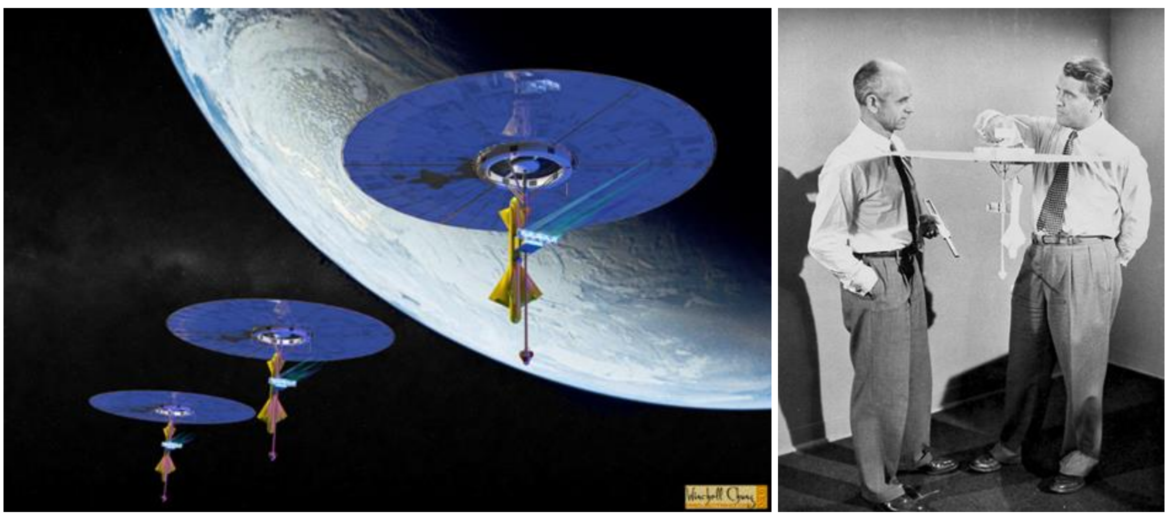
Almost at the same time on the other side of the world Konstantin Eduardovitch Tsiolkovsky (1857-1935), a self-taught Russian school teacher of Kaluga, Russia, published his first statement on the possibilities of electric propulsion: "*It is possible that in time we may use electricity to produce a large velocity for the particles ejected from a rocket device*" in 1911 [2].

The third space travel visionary that independently developed the idea of electric propulsion was Hermann Oberth. Born in Romania, he studied physics in Germany and, in 1929, he published the all-time astronautics classic "Wege zur Raumschiffahrt" (Ways to Spaceflight). The whole last chapter, "Das elektrische Raumschiff" (the Electric Spaceship), was about electric propulsion, predicting its future role in propelling spaceships to distant targets. This book was like a bible for an entire generation of space enthusiasts, among which there was a brilliant student of Oberth, Wernher von Braun. When von Braun was brought to the United States as part of Operation Paperclip in order to continue the work on the V-2 rocket at Fort Bliss, Texas, he asked his assistant Ernst Stuhlinger to review Oberth´s research on electric propulsion: "*Professor Oberth has been right with so many of his early proposals; I wouldn't be a bit surprised if we flew to Mars electrically*" [3].

Stuhlinger immersed himself in electric propulsion theory, and in 1954 he presented a paper at the 5th International Astronautical Congress in Vienna entitled, "*Possibilities of Electrical Space Ship Propulsion*", where he conceived the first Mars expedition using solar-electric propulsion [4]. The spacecraft design he proposed, which he nicknamed the "Sun Ship", had a cluster of 2000 ion thrusters using cesium or rubidium as propellant. He calculated that the total mass of the "Sun Ship" would be just 280 tons instead of the 820 tons necessary for a chemical-propulsion spaceship for the same Mars mission. In 1955 he published: "*Electrical Propulsion System for Space Ships with Nuclear Source*" in the Journal of Astronautics, where he replaced the solar-electric power system with a more advantageous nuclear reactor (Nuclear Electric Propulsion - NEP). In 1964 Stuhlinger published the first systematic analysis of electric propulsion systems: "*Ion Propulsion for Space Flight*" [3], while the physics of electric propulsion thrusters was first described comprehensively in a book by Robert Jahn in 1968 [5].

Figure 1. Left: Ernst Stuhlinger (seated, left) poses with Hermann Oberth (center) and Wernher von Braun (seated right); on the background U.S. General Holger Toftoy and Robert Lusser (image: NASA Marshall Space Flight Center). Right: Stuhlinger´s "Sun Ship"

Figure 2. **Left: Stuhlinger's proposed fleet of 10 nuclear-electric manned spacecraft for the 1957 Walt Disney television program "*Mars and Beyond*" (credit: © Winchell Chung). Right: E. Stuhlinger and W. von Braun pose with a model of the 1957 nuclear Mars spacecraft (image: NASA Marshall Space Flight Center.**



The first in-space demonstration of electric propulsion was an ion engine carried on board the SERT-1 (Space Electric Rocket Test) spacecraft, launched on 20 July 1964; however, its complexity and the long development needed to demonstrate the lifetime required by EP missions (several thousands of hours) have long delayed its use as standard propulsion system for commercial and scientific space applications.

Ion Thruster State-of-the-Art

Ion thrusters use a variety of plasma generation techniques to ionize a large fraction of the propellant. These thrusters then utilize biased grids (from a few kV to more than 10 kV) to electrostatically extract ions from the plasma and accelerate them to high velocity. Ion thrusters can provide very high specific impulses (from 2000 to over 10,000 s) compared to other electric thruster types; hence, they are the best candidate for interstellar precursor missions [6].

Table 1 shows a list of ion thrusters with their main characteristics and their technology readiness level (9 corresponds to a flight-proven technology); notice how the specific power, the electric power per thrust unit, rapidly increases with increasing I_{sp}, as clearly shown in Fig. 4. This drawback is particularly severe for interstellar precursor missions, which require very high specific impulses in order to reduce the propellant mass to acceptable values. Unfortunately, the power source mass rapidly increases with increasing I_{sp}, cancelling the advantage of a reduced amount of propellant. Hence, an advanced EP system for interstellar precursor missions needs a power source with very low specific mass α, expressed as mass per unit electrical power (<< 50 kg/kWe).

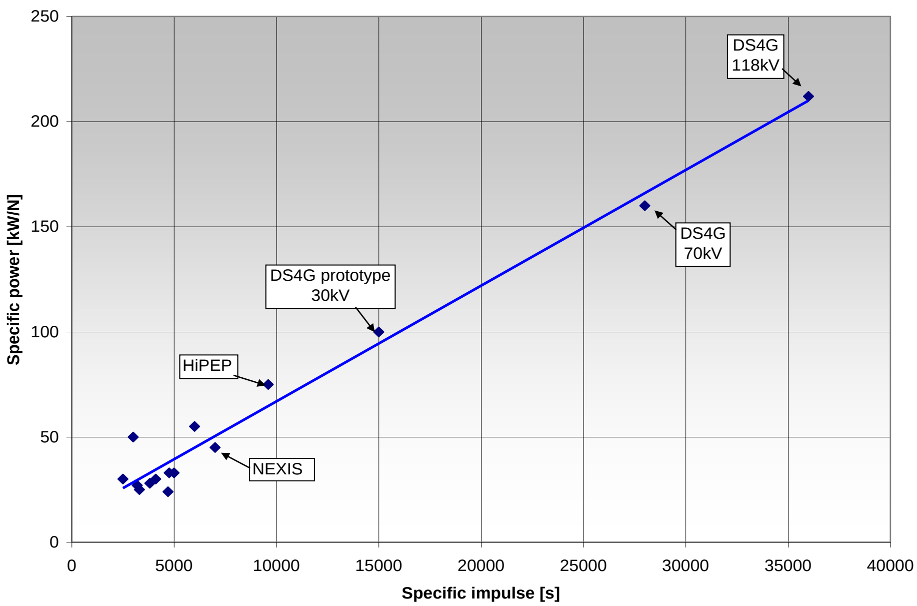
The first EP system demonstrated in space as primary propulsion is the one used by the NASA´s Deep Space 1 spacecraft, launched from Cape Canaveral on October 24, 1998; the NSTAR ion thruster, developed at NASA Glenn (see Table 1), provided a ΔV of 4.3 km/s using less than 74 kg of xenon. It thrusted for 678 days, far longer than any propulsion system had ever been operated in space. Primary power for the mission was produced by an innovative solar array technology, the Solar Concentrator Array with Refractive Linear Element Technology (SCARLET), which generated 2.5 kilowatts at 1 AU. The next NASA scientific mission to use NSTAR engines is the DAWN spacecraft; it was launched in 2007 and it is the first spacecraft to orbit 2 solar system bodies thanks to its EP system, the protoplanet Vesta and the dwarf planet Ceres. DAWN is propelled by three NSTAR ion thrusters firing one at a time. The whole spacecraft is powered by a 10 kW (at 1 AU) triple-junction gallium arsenide photovoltaic solar array. The DAWN spacecraft reached Vesta in 2011 and Ceres in 2015 with just 400 kg of Xenon, performing a total ΔV of 10 km/s, far more than any previous spacecraft has achieved with onboard propellant.

Table 1: Characteristics of ion thrusters including their Technology Readiness Level (TRL)

Engine	Specific Impulse (s)	Required Power (kW)	Thrust (mN)	Specific Power (kW/N)	Verified Lifetime	TRL	Mission
NSTAR	3300	2.3	92 max	25	30,000h (3.4 years)	9	Deep Space 1, Dawn
RIT-10 (10cm-dia)	3810	0.59	21	28	23,000h (2.6 years)	9	EURECA, ARTEMIS
RIT-22 (22cm-dia)	4760	5.8	175	33		7	IHP probe
NEXT	4100	7	236 max	30	48,000h (5.5 years)	7	NASA Flagship, New Frontiers
NEXIS (57cm-dia)	7000	20	440	45	2000h	5	JIMO (cancelled)
HiPEP	6000-9600	25-50	460-670	55-75	2000h	5	JIMO (cancelled)
DS4G (laboratory prototype, 30kV)	15000	0.61	5.4	90-110		3	
DS4G (predicted, 70kV)	28000	240	1500	160		1	400AU mission (Fearn 2008 [Error!

Figure 3. The 20-kW Nuclear Electric Xenon Ion thruster System (NEXIS) developed at NASA-JPL for the Jupiter Icy Moons Orbiter (JIMO), later cancelled (courtesy of NASA)

Figure 4. The required electric power per thrust unit rapidly increases with the specific impulse (dots are measured or predicted values from Table 1, propellant used is Xenon).

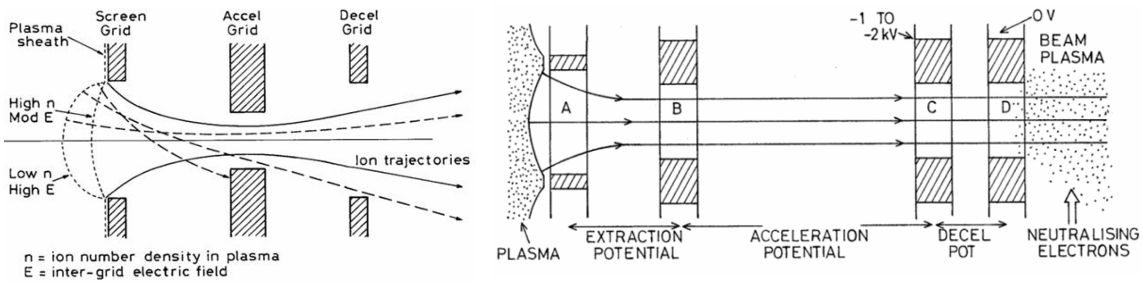


Dual-stage 4-Grid Ion Thruster

The innovative Dual-stage 4-Grid Ion Thruster has been proposed by Fearn (2000, [7, 8]) in order to extend gridded ion thruster performance to very high specific impulses, thus enabling interstellar precursor missions. Four grids are used instead of the usual three-grid arrangement in order to separate the ion extraction and acceleration processes (done simultaneously in current systems). This enables very high ion beam potentials to be put on the grids in the acceleration stage, thereby significantly increasing exhaust velocity, specific impulse, power density and thrust density. Fearn calculated that, using a beam potential of 70 kV and a propellant with a mean atomic mass of 4.5 AMU (compounds of hydrogen with carbon and nitrogen), a specific impulse as high as 150,000 s is achievable. Using Xenon (131.3 AMU), the specific impulse is almost 30,000 s, as shown in Fig. 4. Applying higher beam potentials it is possible to get even higher specific impulses with Xenon, with the drawback of higher specific power values.

In order to demonstrate the feasibility of this new thruster concept, a small experimental laboratory prototype has been designed and constructed. The experimental test campaign comprised two successful test phases which were conducted in a vacuum facility at ESTEC during November 2005 and May 2006. Total accelerating potentials of up to 30kV were demonstrated. Narrow beam divergences of the order of 2-4° were also achieved. The I_{sp} reached values as high as 14,000–15,000 s; total efficiencies of 70% and thrust over 5 mN were obtained. The specific power was between 90 and 110 W/mN. The values achieved represent an improvement by several times on the current state-of-the-art, whilst maintaining very small direct ion impingement of the beam on the grids [9].

Figure 7. Left: ion beam optics in a classical 3-grid system; acceleration voltage limited by penetration of inter-grid electric field into the plasma, which cause ion defocusing leading to grid erosion. Right: 4-grid system used in fusion reactor plasma injectors (courtesy D. Fearn, 2000)



Interstellar Precursor Missions with SEP

Loeb (2011, [10]) has proposed a combination of solar electric propulsion (SEP) with radioisotope electric propulsion (REP) in order to reach the goal of 200 AU within 25 years. The SEP stage for a heliopause probe is based on the exploitation of increased solar radiation flux and gravity by first going to the inner solar system and taking up momentum there. The German RIT-22 ion thruster has been selected for the SEP stage; six RIT-22 thrusters running at +5 kV with a specific impulse of 7377 s. The propellant storage and feed system, electronic components and thermal control parts are mounted within the bus structure. The LISM probe with the REP-stage is mounted on top of the hexagonal SEP stage (see Fig. 5).

After launch, the SEP-thrust is used to lower the perihelion by thrusting in anti-flight direction. The perihelion height is now lowered below Earth orbit but not closer than 0.7AU, thus avoiding the need for a heavy thermal shield. Close to perihelion, when the solar panels provide maximum electrical power to the propulsion system, the probe is accelerated with maximum thrust. The SEP-stage's propellant is depleted after 831 days at a Sun distance of 3.05AU, resulting in a heliocentric SEP-burnout velocity of 30.5 km/s (see Fig. 6).

The REP stage will use RIT-10 ion thrusters. Performance variations of the REP/SEP combination resulted in a preferable beam voltage of 1.5 kV and specific impulse of 3810 s. With a power of 592 W and a Xenon flow of 0.558 mg/s, the RIT-10 thruster delivers a thrust of 21 mN. Four RIT-10 engines are envisaged, running one after the other and thus, accelerating the LISM probe continuously for nearly 10 years (ΔV = 8 km/s).

Payload mass is assumed to amount to 35 kg. Eleven different scientific instruments are foreseen including a radar system and a camera to observe eventually Kuiper belt objects along the trajectory. For the power supply of the thrusters, the scientific instruments, the telemetry, and housekeeping, 4 advanced radioisotope batteries (specific mass of 8.5W/kg) would be required delivering 648 W at BOM (Beginning Of Mission) with a total mass of 76 kg. An Advanced Stirling Radioisotope Generator (ASRG) with a length of 62 cm has specifications close to the requirement.

With the described SEP+REP propulsion system and a capable launcher like the Ariane 5 ECA with a launch energy of C3 = 45.1 km^2/s^2, which corresponds to a hyperbolic excess velocity of 6.7 km/s, a flight time of 27.5 years to 200AU is achievable. Finally, making use of a Jupiter Gravity Assist (JGA) between the SEP phase and the REP phase results in a flight time of 23.7 years, with a burn-out speed of 47.4 km/s (10 AU/yr), as shown in Fig. 6.

In conclusion, SEP combined with REP enables to send a spacecraft within less than 25 years to a solar distance of 200 AU. However, in 2013 NASA decided to cancel the ASRG development program due to budget cuts; hence, it is not clear if and when a sufficiently advanced RTG will be available for this kind of mission.

With just the SEP stage, the Ariane 5 ECA launch and the Jupiter Gravity Assist, a final speed of 8.4 AU/yr (2.3 times Voyager 1´s speed) could be achieved; the SEP Probe would then reach 200 AU in 27 years, using state-of-the art technology (TRL ≥ 6). Furthermore, using a SLS launch with a four-engine Exploration Upper Stage could give more than 350 km^2/s^2, thus significantly reducing the flight time.

Figure 5. Left: SEP stage with 6 RIT22 ion thrusters, with the LISM probe on top of it. Right: the SEP stage equipped with 4 light-weight solar arrays

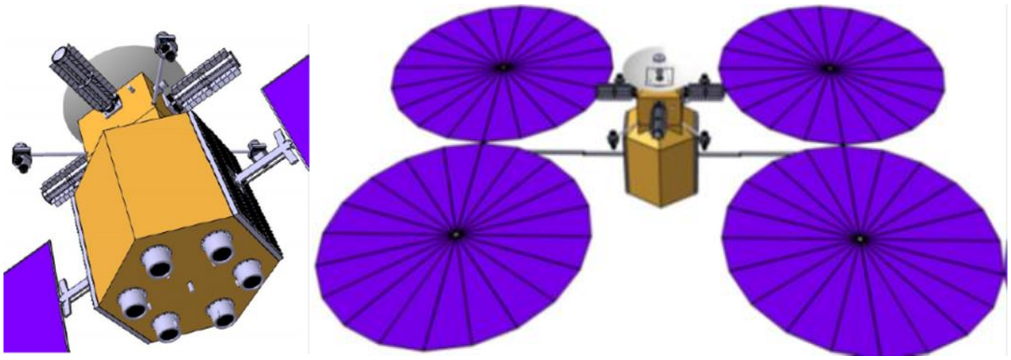
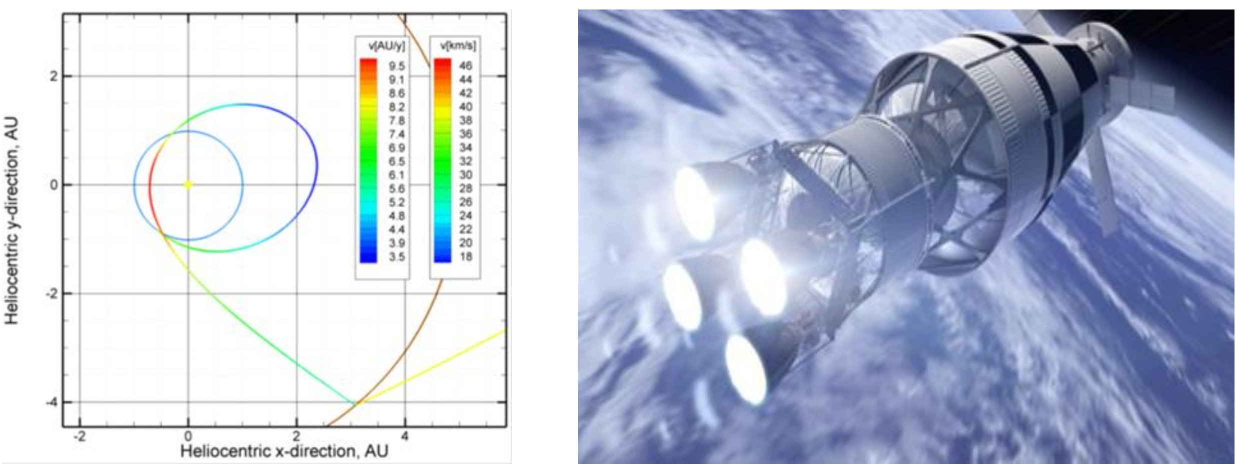


Figure 6. Left: SEP+REP transfer to 200 AU with a gravity assist at Jupiter. Right: Exploration Upper Stage for the SLS launcher



Interstellar Precursor Missions with NEP

The Thousand Astronomical Unit (TAU) mission was an interstellar precursor mission concept, studied by JPL scientists in the late 1980s, with the potential for enabling an unmanned probe to reach a distance of 1,000 astronomical units (0.016 light years) within a 50-year trip time [11]. The challenging ΔV needed (> 100 km/s) can be achieved with an advanced nuclear reactor in the 1-MWe class with a specific mass of 12.5 kg/kWe and a full-power operating (thrusting) time of 10 years. The ion thrusters required would have a specific impulse Isp of 12,500 s, a thrust of 6.8 N, an input power of 490 kW, and a burn time (per thruster) of 2 years.

As two thrusters would have to fire simultaneously to provide the total thrust of 13.6 N, and taking into account a 20% redundancy, a cluster of 12 thrusters was considered to perform the mission.

How realistic is the TAU mission?

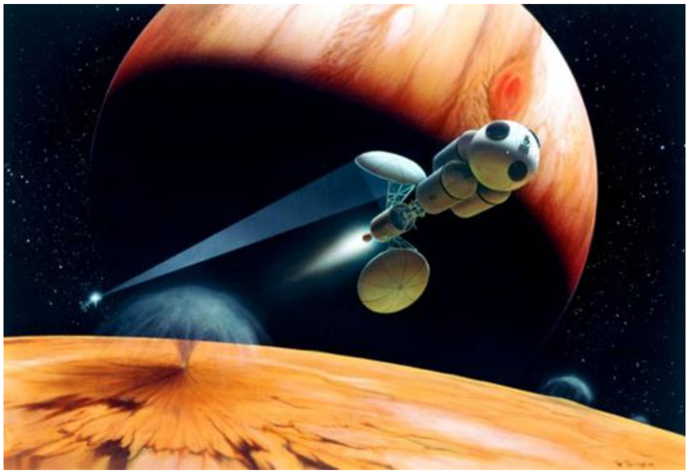
- Today a space nuclear reactor can be realized with a specific mass of 30 kg/kWe. An advanced nuclear reactor using a Brayton conversion cycle can be developed with a specific mass of 10 kg/kWe within 20 years (Berend, 2012 [12]).
- The NASA´s HiPEP ion thruster has demonstrated a specific impulse of ~ 10,000 s (TRL 5); the TAU ion thruster can be developed within the next 20 years.

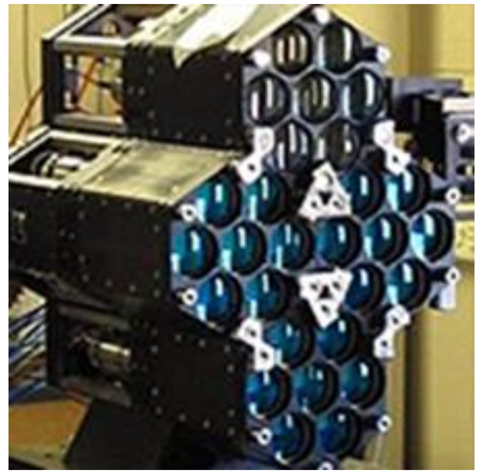
Interstellar Precursor Missions with LEP

A high-power laser beam coming from an in-space laser power transmitter is aimed at a photovoltaic (PV) collector on the target spacecraft, where it is converted to electricity for a high-power EP system (see Fig. 7, left). This type of space propulsion is called Laser-powered Electric Propulsion (LEP). The PV collector/converter on the spacecraft can be tuned to the laser wavelength, thus achieving high monochromatic conversion efficiencies, currently ~ 50% with the potential to reach 80% in the near future (Bett, 2008 [13]).

Tsiolkovsky had clearly anticipated laser-powered propulsion in this quote from 1926: "*We may have a case when, in addition to the energy of ejected material, we also have an influx of energy from the outside. This influx may be supplied from Earth during motion of the craft in the form of radiant energy of some wavelength"* [14]. As regards the in-space laser power transmitter, it is already possible to build a large array of laser emitters capable of creating a combined high power laser beam (Lubin, 2015 [15]), see also Fig. 7, right.

Figure 7. Left: a laser beam illuminates the PV collector of a high-power EP spacecraft (source: http://www.projectrho.com/public_html/rocket. Right: array of 21 laser emitters generate and steer a combined beam (Courtesy of DARPA)





Laser-Powered TAU Mission

The TAU mission can greatly profit from the LEP concept. Instead of a huge nuclear reactor with a mass of 12.5 tons (1-MWe class with a specific mass of 12.5 kg/kWe), we could have a light monochromatic PV collector with 50% efficiency and a specific mass of just 1 kg/kWe. This allows us to use a more advanced ion propulsion system based on 12 high-power ion thrusters (each 2 MW, ~50,000 s specific impulse, 6.8 N thrust) using the same thrusting strategy as for the original TAU mission (see Table 2). The much higher specific impulse allows a strong reduction in propellant mass from 40 tons to 10 tons, leading to a TAU initial mass of just 23 tons instead of 62 tons. The final burnout speed is 240 km/s (50 AU/yr), which permits to reach 1000 AU in just 25 years. This is possible assuming that the laser beam is constantly illuminating the PV collector with at least 8 MW (4 MW are needed by the two 50,000s ion thrusters firing simultaneously) during the whole thrusting time of 10 years up to a distance of 230 AU. This is a huge distance to keep a laser beam focused on the spacecraft collector; this challenging issue has been investigated by Forward and Landis [16, 17].

It is interesting to compare the laser-powered TAU mission with a pure laser sail mission, keeping the same payload mass, the same laser beam power and the same thrusting time of 10 years (see Table 2, last column). In this case we do not have any propellant mass and any power source mass, just the ultra-light laser sail. But even if we consider the laser sail mass included in the 5 tons of payload, the final speed after 10 years of 8MW laser beam pushing is just 5 km/s (1 AU/yr), thus it will take more than 1000 years to reach 1000 AU. The LEP solution is 5 times heavier than the laser sail solution, but the thrust provided by the ion thrusters is almost 300 times higher than the photonic thrust provided by the 8 MW laser beam.

This comparison shows that for interstellar precursor missions with significant payload mass (not just some grams) and moderate in-space laser beam power the LEP concept looks more interesting than the pure laser sail concept. Laser-powered Electric Propulsion can enable challenging missions like Planet 9, FOCAL, TAU, Oort Cloud.

Table 2. Original TAU mission compared to an advanced TAU concept based on Laser-powered Electric Propulsion

	TAU (1987)	Laser-powered TAU	Laser Sail TAU
Ion propulsion system dry mass	4160 kg	4160 kg	-
Propellant (xenon)	40,000 kg	10,000 kg	-
Nuclear fission reactor	12,500 kg (12.5kg/kWe)		-
PV collector/converter		4,000 kg (1 kg/kWe)	-
Payload	5,000 kg	5000 kg	5000 kg
TAU initial mass	**61,660 kg**	**23,170 kg**	5000 kg
Ion thruster specific impulse	12,500 s	50,000 s	-
Ion thruster specific power	73 kW/N	294 kW/N	-
Total power (2 engines)	1 MW	4 MW	8 MW
Total thrust (2 engines)	13.6 N	13.6 N	0.05 N
Burn time	10 yrs	10 yrs	10 yrs
Burnout speed	112 km/s (23.5 AU/yr)	240 km/s (50 AU/yr)	5 km/s (1 AU/yr)
Time to 200 AU	15 yrs	9 yrs	
Time to 500 AU	27 yrs	15 yrs	
Time to 1000 AU	50 yrs	**25 yrs**	**1000 yrs**
Time to 10000 AU	430 yrs	200 yrs	

SUMMARY

Electric Propulsion is a major candidate for the propulsion system of near-term interstellar precursor missions:

- The present EP performance level can enable a 200AU mission to the undisturbed interstellar medium with a trip time of < 30 years

- Advanced EP concepts (DS4G, Isp = 50,000 s) can be powered by a medium-size space laser array (8 MW) enabling a 1000AU mission with a trip time of just 25 years
- The laser-powered EP concept has the potential of significantly reducing the development time of the most visionary missions like Planet 9, FOCAL, TAU, Oort Cloud.

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Where No Planetary Protection Policy Has Gone Before

James Schwartz

Where No Planetary Protection Policy Has Gone Before

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Introduction

One of the most compelling reasons for exploring our solar system is the possibility that in doing so we might discover new forms of life. Although few still hold out hope for the discovery of large, complex life forms, nevertheless many anticipate the discovery of microbial life, perhaps in the Martian subsurface, the subsurface oceans of Europa or Enceladus, or in the hydrocarbon lakes of Titan. Planetary protection policies have been devised in order to protect the scientific viability of the search for life in these, and other, locations in the solar system. Among the many questions raised by planetary protection policies is whether microbial extraterrestrial life would fall under the scope of moral consideration. A common perspective here is that such life would have a special moral status and that it would be worth protecting for its own sake.[1][2][3] Some have even gone so far as to suggest that extraterrestrial microbes should be protected even if this requires prohibiting any scientific study of this life.[4] Consequently, it has been argued that the mere *potential* for an environment to harbor extraterrestrial life (or traces of past life) constitutes an ethically compelling reason for implementing planetary protection policies in order to protect that environment from biological and organic-chemical contamination.

But what about space environments that we do not at all suspect of harboring life or traces of past life? Are these environments, by contrast, *mere* instruments for satisfying our desires, whatever those may be? Or are there nonetheless ethical reasons for maintaining that lifeless space environments might sometimes be worthy of protection? And what should we say about these issues as we entertain the possibility of exploration beyond our solar system? Should a concern for planetary protection place any constraints on the kinds of interstellar expeditions that we might one day mount? Or will such exploration likely take place for purposes that moot any desire on our part to protect other solar systems?

I suggest that mainstream thinking about planetary protection is dangerously jaundiced in that it gives the appearance that *ethical* considerations are exhausted by a duty to protect *living organisms*. This rather narrow conception of planetary protection ethics ignores a crucial possibility: That we have an ethical duty to scientifically study the solar system, and that satisfying this duty requires protecting opportunities for satisfying scientific curiosity *regardless* of whether that curiosity is *biological* in nature. If we recognize this broader ethical duty to conduct science in the solar system, then we have coherent grounds for broadening the scope of *ethically motivated* protection to include at least some lifeless environments. In other words, there is a *life-bias* in planetary protection ethics, and I think that it is one that we can and should overcome.

I entertain the question as to whether we should take the life-bias with us as we venture beyond the solar system. After all, how we decide to conceive of planetary protection ethics---e.g., with our without a bias toward life---has consequences for the planning of interstellar exploration missions. I argue that early missions to other solar systems---exploratory probes and human precursor missions---would benefit from a non-life-biased approach that, as a rule, aims to preserve as many sites of scientific interest as possible in the target system.

Overview of discussion

According to the most recent articulation of COSPAR's Planetary Protection Policies, the underlying justification for planetary protection is that ``[t]he conduct of scientific investigations of possible extraterrestrial life forms, precursors, and remnants must not be jeopardized.''[5] Historically, COSPAR had not viewed the pursuit of this goal as containing an ethical component, and has only in the last two decades fostered serious discussion about supplementing planetary protection policies with ethical considerations. This is already telling evidence of the existence of the life-bias, in that the desire to protect ``scientific investigations of possible extraterrestrial life forms'' was not (and generally still is not) seen in and of itself as an ethical consideration. Rather, the perspective that appears to have gained the most adherents is one according to which planetary protection is only genuinely *ethically* motivated when it is pursued for the sake of extraterrestrial life. Or, in other words, planetary protection only becomes ethical when protection policies are supplemented with an ethical position under which extraterrestrial life forms---including microbial life forms---are recognized as intrinsically valuable. Evidence for this bias is drawn from [1], and [6]-[9].

[10] and [11] provide a clue for overcoming the life-bias, which is, roughly, to resist compartmentalizing environments primarily as either ``lifeless'' or ``life-bearing'', which diverts our focus away from the positive features of these environments and thus negatively affects our ethical evaluation of these environments. To do this, of course, we must expand our perspective well beyond that afforded by astrobiology. For instance, in the case of Mars, we should investigate the planet through the lenses of other scientific perspectives, and through the eyes of artists, writers, musicians, etc. It would be astigmatic to fail to acknowledge that Mars might be worth protecting even if only for its value to geologists (and, no doubt, for its value to a sundry of other scientists whose interest in Mars is not determined by the magnitude of its bioload). Crucially, these

kinds of considerations might never occur to us if, under the spell of the life-bias, we deny the relevance to planetary protection of disciplines other than astrobiology.

To draw out such protections as *ethically* motivated, I build on an idea developed in [12]-[14]---that one of our ethical obligations is to acquire scientific knowledge about the universe. The duty to acquire scientific knowledge competes alongside other duties associated with space exploration, e.g., to use space resources to improve the material well-being of humanity; to colonize space to improve the chances of long-term species survival, etc. There is of course debate about the comparative strength and present importance of each of these duties, and I have argued in the above references that we can at present effectively satisfy only the duty to acquire knowledge. Two points are relevant to this assessment:

1. Scientific examination is very often benign when compared to resource extraction and human habitation as far as contamination is concerned. Thus, effective science may only be possible *in advance* of more disruptive uses of space environments. If there is no pressing or immediate need to consume the resources of a given space environment, there is little to be lost---and much knowledge to be gained---by preserving that environment for scientific study.

2. Activities such as space mining and colonization cannot be undertaken prudently in ignorance of the chemistry, geology, climate, etc., of space environments. The suitability and, very likely, the profitability of such activities are likely to depend on prior scientific study of the environments in question. Thus, preserving space environments for scientific study can help to enable and to streamline later development of those environments, in the event such development is deemed desirable.

Rushing to develop space resources will not help solve major social, economic, and environmental problems any more quickly. But it will harm a myriad of opportunities for scientific study, the generation of new knowledge, and the progress of science. There is little harm, then, and much to gain, by expanding the scope of planetary protection (and its ethics) to incorporate protecting opportunities for scientific study more broadly, which implicates devising protection policies for space environments that are not of interest in the search for life.

Interstellar travel may not be hopelessly distant in the future, especially given the large, recent investment in the Breakthrough Starshot initiative, which hopes to use laser propulsion to accelerate very small, ``wafer'' satellites to relativistic speeds. Thus is not entirely foolish to initiate conversation about planetary protection for interstellar travel.

It would be the height of foolhardiness to attempt to colonize another solar system without extensive prior study of that system, e.g., without knowing anything about either the number and orbital characteristics of its planets, the stability of the climates of its Earth-like planets (if it has any), the local radiation environment, or a sundry of other details about the system which might affect its ability to support a substantial human presence. Thus, if there is no immediate need to colonization other solar systems, then there is ample time during which we can engage in extended ``exploratory'' phases for each target system. Indeed, I would argue that it is ethically obligatory to engage in extensive exploration in advance of colonization so that colonists are not sent on one-way trips to systems that cannot easily support human life.

It is during such exploratory phases that planetary protection will be most appropriate and important. A previously unexplored solar system would be for scientists, to borrow from Sagan, a treasure beyond assessing. The opportunity to study this system in its pristine state should not be spoiled by unnecessary or poorly justified contamination or disruption for much the same reasons as local opportunities for scientific study should not be spoiled by over-hasty contamination. Thus a similar, non-life-biased ethical justification can be given for both local solar system and extrasolar planetary protection: That we have an ethical duty to engage in the scientific study of the universe and that such study requires at least some planetary protection measures, wherever in the universe we happen to be.

Thus, a failure of the interstellar community (and of the space advocacy community more generally) to disabuse itself of the life bias may do harm to the cause of interstellar exploration. Alienating or ostracizing those with non-life-biased perspectives threatens to attenuate critical thought about rationales and goals associated with interstellar travel---an endeavor that very much relies for its success on the critical evaluation of new ideas. In my view, the interstellar community appears open primarily to new *technological* ideas but not as much open to new *ethical* ideas. This lacunae is disquieting precisely because there is no sharp division between science, technology, and ethics. What we learn while doing science influences what technologies we develop and what we place value upon. But what we place value upon also influences what we decide to study and what technologies we develop. The contemplation of an undertaking as grand as interstellar exploration simply *cannot* be conducted without awareness of the broader social and ethical context in which such exploration will occur. As the late Molly Macauley recognized in the case of solar system exploration [15], interstellar science and interstellar exploration goals, and thus, rationales for protection, are interdependent and fluid. We do not know when interstellar travel will be realized, nor for what purposes it will be conducted. It would be myopic to claim that we no longer need to subject reasons for interstellar travel to critical scrutiny, or that other compelling reasons, possibly contrary to those presently accepted, will not arise. Which is all to say that discussion of interstellar planetary protection should not be dismissed out of hand.

Our best means of determining what is of interest, and hence, what might be worth protecting in a system will be by visiting that system for the first time. Thus, in order to minimize the chances of a mission harmfully contaminating or disrupting a site of potential importance, ``first visits'' should be conducted with the utmost precaution.

What this will mean in practice will depend upon our technological capabilities. If human missions can eventually be conducted with contamination risks rivaling those of robotic missions, then perhaps robotic precursor missions will in future become unnecessary. And if, for instance, joint human/robot missions allow for sites to be remotely explored via local, in-orbit human operators, then perhaps protection protocols will not look significantly different from those required in our solar system. However, if, as is most likely, early interstellar missions will be purely robotic, then additional concerns will arise.

Even if probes reach modest percentages of c, interstellar missions will take a considerable amount of time (at a minimum, on the order of decades for the fastest missions to the closest stars). This requires fully autonomous interstellar probes, which will risk malfunctioning in critical ways. If, for instance, there is a hardware failure, the probe could pose a contamination hazard should it end up on a collision course with some body in the target system. Additionally, the probe's software may become corrupt, or it may prove insufficiently intelligent for conducting effective exploration. For instance, if the software is not able to make reliable and autonomous decisions about what items are of scientific interest---i.e., if the software cannot mimic the deliberations of the scientific community---then it will not provide future explorers with adequate information about what is of scientific interest in the system. Thus, ensuring spacecraft sterilization and reliability of hardware may prove inadequate as protection measures, if the spacecraft is not controlled by sufficiently intelligent software. It is therefore conceivable that protection policies might prohibit all interstellar exploration until such time as we can provide probes with sufficiently advanced artificial intelligences.

A concern for protection also rules out various mission profiles that would, by their nature, lead to the contamination or destruction of significant parts of target systems, including:

- ``Life-seeding'' missions in which genetic material and incubators are sent to a target system with the intention of preparing that system for human settlement.
- Exploration via von Neumann machines which replicate themselves indiscriminately from the materials of target systems, possibly as a precursor to human settlement.
- Any other mission that would require extensive, indiscriminate in-situ resource use.

It is difficult to envision a situation in which our survival so urgently depends on interstellar colonization that we cannot preserve candidate systems for prior scientific study. That is not to say that, technology permitting, we do not have an ethical obligation to attempt the colonization of other solar systems. It is only to say that, in all likelihood, the satisfaction of our duty to engage in the scientific study of the universe is compatible with our long-term survival obligations. The burden is on those who would argue that we do not have time for preserving other systems for scientific study in advance of large-scale human settlement.

SUMMARY

There are ethical reasons for expanding the scope of planetary protection to include sources of scientific curiosity generally---and not just sites of interest in the search for life. However, the recognition of these reasons as ethical requires mitigating the life bias in thought about planetary protection; policy discussions should therefore actively solicit perspectives both from both extrabiological *and* extrascientific perspectives. Awareness and appreciation for extraterrestrial environments will not come solely through the communication of wider scientific interests, but also through more characteristically cultural means, much as, for instance, the work of natural historians and landscape painters helped to foster an appreciation for the American wilderness. The value of these non-biological and non-technological perspectives should not be ignored as we proceed with more ambitious forms of solar system, and ultimately, interstellar exploration.

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Concerning America's Far Future in Deep Space

Steven L. Kwast

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The author has not submitted an extended abstract.

A Lunar Settlement: Prototype for Eventual Interstellar Colonization

Ken Roy

A Lunar Settlement: Prototype for Eventual Interstellar Settlements

Kenneth Roy

Note: This talk is based on a paper published in the Journal of the British Interplanetary Society, Vol 68 no 9/10 dated September/October 2015 titled, "Safe Comfortable Habitats on the Moon, Mars and Mercury Using Soil Vitrification" by Richard J. Soilleux and Kenneth Roy.

Abstract: It is unlikely that we will identify living worlds around distant stars that are ready to receive and support a Human colony without considerable terraforming efforts. Even if we could, there are very real ethical issues with even trying to install a human colony on an existing living world. Terraforming a sterile planet may be the best alternative. But terraforming planets can take many centuries or even millennia. In the meantime, a Human colony will need a semi-permanent settlement where they can survive and from which they can explore the new solar system and from which they can conduct a terraforming effort. Earth's moon is a logical place to begin to learn how to establish bases and eventually long-term settlements. This paper presents one approach to establishing a lunar base using soil vitrification that can also be expanded to become a long-term settlement that addresses many issues with humans living on a low gravity, airless world.

The idea of melting in-situ lunar regolith to create underground verified structures has been developed previously ("The In-situ Construction, From Vitrified Lunar Regolith, of Large Structures Including Habitats in Artificial Lava Caves" by Richard Soilleux and David Osborne published in the same JBIS edition as listed above.) Knowing how to construct such a settlement will go a long way to assuring the success of future interstellar colonization and exploration efforts. Using this technique, the possibility of establishing long term bases/settlements on the Moon, Mars, Mercury, or on any other rocky body becomes a real possibility. There are two basic obstacles to such settlements: gravity and radiation, and a possible solution to both problems are offered utilizing subsurface structures fabricated using vitrification of the local soil. Such structures could house large settlements of humans in comfort and safety in conditions similar to those envisioned with space based habitats. These settlements would have access to all the material and energy resources available to the planet or moon on which they are constructed. Such settlements offer protection to their inhabitants from radiation events or asteroid strikes that could destroy an Earth-based civilization.

Power Beaming Leakage Radiation as a SETI Observable

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Power Beaming Leakage Radiation as a SETI Observable

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Discussions of SETI at this and previous TVIW meetings have focused on searching for intentional Beacons from ETI. We advocate that the most observable leakage radiation from an advanced civilization may well be from the use of power beaming to transfer energy and accelerate spacecraft. Applications suggested for power beaming involve Earth-to-space applications such as launching spacecraft to orbit, raising satellites to a higher orbit, interplanetary concepts involving space-to-space transfers of cargo or passengers, beam-driven launch to the outer solar system, interstellar precursors and ultimately starships. We quantify the various classes of power beaming applications/missions, estimate the principal observable parameters and discuss the implications of observability of ETI power beaming leakage and our own future emissions. By observing leakage from power beams we may well find a message embedded on the beam. Recent observations of the anomalous star KIC 8462852 by the Allen Telescope Array (ATA) set some limits on extraterrestrial power beaming in that system. We show that most power beaming applications commensurate with those suggested for our solar system would be detectable if using the frequency range monitored by the ATA, and so the lack of detection is a meaningful, if modest, constraint on ET power beaming in that system: Most applications would be seen, but are not seen. Until more extensive observations are made, the limited observation time and frequency coverage are not sufficiently broad in frequency and duration to produce firm conclusions.

Human Health in Space: What's Being Done? What Needs To Be Done?

Robert E. Hampson

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The author has not submitted an extended abstract.

An Adaptive Framework for Permanent Human Space Settlement

Cameron Smith

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"The Great Affair is to Move": Evaluating Human Cultural Adaptive Suitability and Readiness for Interstellar Voyaging

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Abstract

Permanent human space settlement will be an adaptive endeavor on the order of the transition of Earth life from aquatic to terrestrial. To give this endeavor a better chance of success I advocate a genuinely evolutionary and adaptive approach, in which lessons from the study of evolution on Earth are used to guide overarching and specific aspects of planning human space settlement. Among many lines of research required to implement this approach is to identify humanity's adaptive tools and capacities and to evaluate their suitability and readiness for multigenerational interstellar voyaging. In a preview of research in progress I introduce humanity's chief adaptive tools and outline how they may be evaluated for their (a) suitability and (b) readiness for multigenerational interstellar voyaging.

1. Introduction

Robert Louis Stevenson (1850-1894) wrote that "For my part, I travel not to go anywhere, but to go. I travel for travel's sake. The great affair is to move…" (Stevenson 1910). For whatever motivations, the last decade has seen a resurgence of interest in and serious research on the possibility of a "great affair" indeed, that of interstellar voyaging by our species, partly a reaction to and in tandem with advances in theoretical propulsion physics (Long 2011), the discovery that many of our galaxy's stars host planetary systems (Heng 2013) and astrobiology's strong suggestion that the conditions for Earth-type life are more common in our galaxy than previously thought (Irwin et al 2014). In the research community considering interstellar voyaging (currently including Icarus Interstellar, the Initiative for Interstellar Studies, the Tau Zero Foundation, the 100-Year Starship Study and other) it is commonly accepted that such a project is perhaps a century or more away, as noted in the founding statements of the research group Icarus Interstellar. This mature approach proposes to build nothing at present but to build quality reference studies that address both the engineering and the life sciences involved.

In prior publications I have suggested that the life science be guided by evolutionary principles because permanent human space settlement will be multigenerational and an evolutionary, adaptive endeavor in magnitude comparable with the transition of Earth life from entirely aquatic to include terrestrial life (Smith 2016). To apply lessons from Earth evolution to shaping this human *extraterrestrial adaptation* (Smith and Davies 2006) requires a survey of the adaptive tools and capacities of humanity—as it has adapted to myriad Earth environments over the past 50,000 years—as these will be the evolutionary tools used to succeed in space settlement. In this Extended Abstract I describe important issues in considering cultural adaptation as a factor in permanent human space settlement.

2. Cultural Universals and The Adaptive Suite of Modern *Homo sapiens*

Life forms endure changes in their selective environments (those pressures effecting their likelihood of survival and having offspring) by the processes of individual *acclimatization* (a reversible phenomenon of individual behavior and/or physiology) and population *adaptation* (a genetically-encoded adjustment) (Moran 1979). Here we are interested in adaptive features used in the long-term evolution of humanity, as suitable for consideration in multigenerational worldship studies. Over the 2+ million years of evolution of the genus *Homo* many adaptive tools have evolved, both biological and cultural. Grossly, in the *terrestrial adaptation* (*c.*5mya) early hominins became bipedal, a biological adaptation that opened up new ecological niches for previously tree-bound ancestors of our genus, in the *technological adaptation* (c.2+mya) our genus became dependent on technology (largely early stone tools) to survive, beginning a long-term trend of decoupling behavior from anatomy, in the *cognitive adaptation (c.*c.1.5mya to c.100,000 ya) both biology and culture reconditioned the way our minds process information, resulting in such adaptive features as grammatically-complex language and symbolism and in the *domestication adaptation* (c.10,000 ya) humanity took direct genetic control of other species (domesticates), ultimately supporting large populations, urbanism and the disengagement of most people from food production leading to the specialization of action that underwrites state or civilization structures (for a review see Smith and Davies 2012).

Through the course of these adaptations, biocultural evolution has served to safeguard living and expected future humans, their resources, their domesticates (after about 10,000 years ago) and--racheting up complexity--even the cultural institutions (e.g. religious and political) that promote such welfare (this has not always worked, and cultural maladaptation is discussed in Edgerton 1992). This has resulted in a number of *human universals*, domains of experience related to survival that are addressed by each human culture; various authors (from the fields of anthropology and human behavioral ecology) recognize either >100 or roughly a dozen of these depending on classification issues, but they are well-established (Brown 1991, Brown, et al 2011, Ember and Ember 2009). While each culture differs somewhat in its adaptations in the various domains of these human universals, each culture must address them as they are required for safeguarding human cultures over multigenerational time (note that social viability can be as important as biological viability, so domains addressing such intangibles as *Styles of Bodily Decoration* are far from negligible). In this way, human universals are served or safeguarded by human behavioral flexibility in addressing them. Table 1 introduces just ten of these human universals as examples of the kinds of universals that must be addressed by worldship theorists (I will expand discussion of human universals in respect to interstellar voyaging in forthcoming work), with evidence of flexibility in these universals indicating a particular *human adaptive feature* (biological adaptive features will be addressed elsewhere).

Table 1. Ten Human Universals Requiring Adaptive Adjustment in Each Culture.

Cultural Universal Domain	Concept	Evidence of Adaptive Flexibility
Language	Specific spoken and gestural (bodily) systems of communication, including vocabularies and grammars.	Some languages assign gender to nouns, while others do not; today nine major language families and over 6,000 languages.
Ethics & Group Decision-Making	Concepts of group right and wrong, justice, and fairness.	Some cultures execute murderers, while others do not; ethical systems quite fluid and may be conditioned by political, religious, economic and other factors. Political systems range from despotic monarchy to representative democracy; all deal with *leadership selection*, *regulation of social behavior*, *conflict resolution* and *neighbor relations.*
Social Roles	Rights and responsibilities differ by categories such as age (child, adult), gender (man, woman), and status (peasant, King).	Cultures differ in the ages at which people take on certain rights and responsibilities, and specifically what those rights and responsibilities are. Different conceptions of life stages e.g. *infancy*, *childhood*, *adolescence*, *adulthood*.
The Supernatural	Concepts regarding a universe considered fundamentally different from daily experience.	Different cultures worship different gods, goddesses, and other supernatural entities; religious types include *shamanic* (lacking supreme deity or formal priests), *communal* (more formalized ritual), *olympian* (complex supernature accessed largely by religious specialists) and *ecclesiastic* (monotheistic with large body of religious functionaries).
Styles of Bodily Decoration	Human identity is often communicated by bodily decoration, either directly on the body or with clothing.	Some cultures heavily tattoo the body while others communicate identity more with clothing styles; all communicate visually.
Family Structure	Concepts of kinship or relations between kin, and associated ideas such as inheritance	Some cultures are *polygynous* (males have several wives), and some are *polyandrous* (females have several husbands); all family systems manage *coresidence*, *economic cooperation*, *management of reproduction* and *management of property*.

Cultural Universal Domain	Concept	Evidence of Adaptive Flexibility
Sexual Behavior	Regulation of sexual behavior, including incest rules.	Cultures differ in the age at which sexual activity is permitted.
Food Preferences	Concepts of what are appropriate food and drink in certain situations.	Some cultures eat certain animals while others consider them unfit to eat; many taste preferences are influenced by social norms.
Aesthetics	Concepts of ideals, beauty, and their opposites.	Some cultures value visual arts more than song, and vice versa.
Ultimate Sacred Postulates	Central, unquestionable concepts about the nature of reality.	Some cultures consider time to be cyclic while others consider it linear.

To adjust human biology and behavior to accommodate these universal requirements, humanity became both biologically and culturally very plastic, successfully settling myriad diverse environments globally, including the high Tibetan and Andean plateaus and Arctic, Australasian and Saharan environments with ambient conditions that would kill the human body quickly if it were not furnished with appropriate survival technologies, both material and social (extended mating networks are one social adaptation that provides access to distant resources, for example). In the past 6,000 years of states and civilizations, behavior became even more plastic and social relations more extended and complex. Above I have suggested one way to confront this complexity and structure our thinking for worldship research.

In the current research effort, as worldships are designed and we ‘design’ or propose the cultural features of such craft we must also ask whether a given course of action or use of a human adaptive tool—the adjustment of a human universal to prospective worldship conditions—would be beneficial to adapting to worldship conditions. Currently such questions are effectively innumerable, but, again to narrow the field we may begin by addressing *how* to evaluate alternative adaptive courses of action for worldship conditions, introduced below.

3. From Observation to Evaluation of the Adaptive Suite of Modern *Homo sapiens*

How do we evaluate the theoretical deployment of any of humanity's adaptive features for the project of human space settlement, specifically on interstellar voyaging timescales of some centuries, but less than a millenium? We may begin by evaluating two properties of these adaptive tools and features, as outlined below.

3.1. Evaluating Adaptive Feature Suitability for Interstellar Voyaging

The *suitability* of a human adaptive feature for the conditions of worldship voyaging may be evaluated by answering the following questions.

First, *does the adaptive feature promote and preserve the cultural values we wish to preserve on the worldship*? This of course depends on what cultural values we wish to promote, which often leads to a significant departure from research as individual researchers try to justify their ideals of cultural norms for humanity. In this example let us be guided by the ideals of the United Nations' Universal Declaration of Human Rights (United Nations 2016), a rather widely-recognized statement of Western Civilization's most morally-accepted minimal code of conduct. Other researchers may (and certainly will) propose other moral codes, but let us imagine that in this case we propose *despotic monarchy* as a mode of governance addressing the human universal of *Ethics & Group Decision-Making*, one that might well work to govern some tens of thousands of people for some centuries—it has in fact been predominant in the human experience of civilization. In this case, the political arrangement would be rejected as morally unjust by our guiding document (in this case the UN Declaration of Human Rights) and so it would be rejected as unsuitable for our reference study.

Second, *does the adaptive feature promote and preserve multigenerational resource sustainability*? This is a requirement of the closed ecosystem of any worldship in the current thoughtscape. If the resource ethics employed by an adaptive feature were similar to that of current first-world civilization—which is in the second human generation of widespread recycling but remains rather wasteful—then it would be rejected from the worldship reference study and thoughtscape.

Third, *does the adaptive feature promote and preserve the individual and population health*? These health levels are required to sustain the population in various modes; in my research the age- and sex-structured population (the overall demography) must be maintained for several centuries , but less than a millenium, and arrive at a destination exoplanet in sufficient numbers and genetic health to itself serve as a stock, founding population (e.g. see Smith 2014). Any adaptive feature that does not support this goal, such as a population ethic that values exponentially-growing populations (a current feature of many Earth populations) would be rejected.

Other human universals should be either supported by or at least not transgressed by the proposed adaptive feature, tool, or behavior. My current research effort underway is to expand the understanding of both Human Universals and Adaptive Features to improve worldship theory.

3.2. Evaluating Adaptive Feature Readiness for Interstellar Voyaging

Adaptive features identified in the course above as suitable for the worldship experience must also be evaluated for their capacity for adaptation, which we may call *readiness* (in a way somewhat analogous to considering Technology Readiness Levels (NASA 2012)). In evolutionary studies the adaptive range of a given life form—or its capacity to adjust internal relations to external relations—is referred to as the *reaction norm* (Gotthard and Nylin 1995); note that no similar term is in wide use regarding cultural adaptation. Although current reaction norm refers studies focus on individual capacities for short-term acclimatization, in this study we may heuristically expand the concept to include multigenerational cultural adaptation and from this perspective evaluate at least three questions.

First, *does the adaptive feature currently have sufficient reaction norm to adjust to the worldship experience*? This requires outlining the worldship experience, which includes specifying the thoughtscape in terms of population, demographic structure, resources, expected duration and so on. With these outlined we may research whether the human adaptive feature has a history of adapting to similar perturbations from Earth-normal experience (the useful concept of *resilience* refers to a life form's capacity to return to equillibrium after such perturbation; see (ref)). As an example, we might inquire whether first-world populations might become accustomed to a worldship in which people lived in barracks rather than houses; while humanity certainly can adjust to nearly anything over long time, this would be found to be unlikely reasonably within humanity's reaction norm regarding family structure as families typically live together and somewhat apart from other families for many reasons, and because interstellar voyages would be multigenerational family structures would have to be viable and barracks quarters for the starship population rejected.

Second, *if the adaptive feature does not possess the required reaction norm (as identified above), does it have the capacity to be modified for the new experiences of the specified worldship conditions*? This evaluation would require informed speculation, as do many issues in worldship (and other) research.

Third, *is there a reasonable timescale available for an adaptive tool or feature to be adjusted to worldship conditions* ? If the reaction norm must be expanded substantially to accommodate the worldship experience, multiple generations may be required. Depending on the thoughtscape for worldship technology, development and construction, such a period might be too great, in which the adaptive feature or tool would be considered unworkable for the reference study. For example, it is normally the second generation of immigrants to a new home region who become operationally assimilated there, and similar conditions can be imagined regarding the 'boarding' of a worldship—indeed it has been proposed that worldships be inhabited for some generations before they are launched to an interstellar destination, an idea with several benefits.

3.3. Evaluating Adaptive Features: the Time Dimension

Both biology (Smith 2011) and culture evolve (Whiten et al 2011), so multigenerational voyaging necessarily involves change. A 400-year voyage to an exoplanet would compose 12, 33-year biological generations and might be attended by as much cultural change as distances modern people from, say, Elizabethans of 400 years ago, whose dialect was so different that today we require special training to understand it. We needn't simply guess at how such change would play out and how it might be of interest to worldship designers as both history and anthropology have some understanding of trends of long-term change in human culture. We can productively consider the interests of at least three 'ages' in such a 400-year voyage, for example, envisioning that the generations first leaving Earth (Departure Age) would have cultural ties to Earth and its concerns, the generations on the way to a destination to lose Earth ties and yet have no ties to the exoplanet destination (the Space Age) and the arriving generations to once-again consider the issues of planets (Arrival Age) and how to explore them after centuries of an enclosed life. These are important issues that can, again, help to shape our thinking when we consider the tremendously complex project of worldship design.

4. Concluding Comments

To build productive worldship theory and reccomendations, formalized models of the worldship and its culture must be developed. The biocultural domains of such models can be based on evolutionary and anthropological understanding of universal human requirements (biological and cultural) and adaptive features. Ultimately a decision tree shaped by these variables would allow scholarly, informed screening of various social, economic, demographic and other proposed courses of action, systematically specifying the shape or character of a given proposed worldship culture. Many may be proposed for the benefit of future planners, who will make the final decisions. The value of our contributions in this field will be founded on their fidelity regarding human biocultural dynamics to date, which itself rests on thorough anthropological research tailored to worldship theory.

The research recommendations presented above may sound like the simple application of common sense, but note that (a) 'common sense' changes through time (e.g. there was little suburban recycling in the USA before the late 1970's, whereas today—just a generation later—recycling is 'common sense') and (b) serious worldship research should begin to explicitly name these recommendations, justify them with referenced scholarship and provide positive, actionable statements that allow them to be encoded in the culture of serious worldship research.

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Proton Beam Reduction - Primary Extraction from Generic Asteroid Material

Eric Hughes

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The author has not submitted an extended abstract.

SETI, Interstellar Diffusion and Stability Equilibrium Hypothesis in Galactic Civilizations

Kelvin Long

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The author has not submitted an extended abstract.

Electric Sail Propulsion to Enable Quick Heliopause and Beyond Scientific Missions of Discovery

Bruce Wiegmann

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The author has not submitted an extended abstract.

Progress in Fusion Propulsion Research at the University of Alabama in Huntsville

Jason Cassibry

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Progress in Fusion Propulsion Research at the University of Alabama in Huntsville

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Introduction

The objectives of University of Alabama in Huntsville (UAH) Fusion Propulsion Research Facility (FPRF) are to 1) Train the students and scientists that can develop fusion propulsion systems for human flight to the planets and 2) Develop the technologies, materials and plasma sciences for reliable fusion propulsion for human piloted space flight within the next half century. We are pursuing this research because of the potential for low yield pulsed nuclear reactors to reach 1-10 kW/kg specific power and ~30,000 s specific impulse, which enables rapid interplanetary space travel.

Both fission and fusion systems release 10^{14} J per kg of propellant, over a million times higher than chemical reactions[1]. Nuclear thermal propulsion[2] uses heat transfer from the reactor to the propellant, and thermal limitations prevent specific impulses above 10^3 s. Many important missions are enabled by NTP, including piloted trips to Mars; but beyond Mars the trip times become too long. Nuclear Gas Core Rockets[3], [4] may reach high thrusts (10's of kN) and high exhaust velocities (20-50 km/s), but containment of uranium plasma at critical mass presents numerous engineering challenges. Nuclear pulse propulsion (e.g. Orion [5]) detonates low yield (0.1 kiloton) nuclear devices near a pusher plate and achieves exhaust velocities of 25 to 1500 km/s with a thrust-to-weight ratio of 4. An outgrowth of this is the potential of smaller yield fission/fusion hybrid targets[6], such as the PUFF concept[7]. International treaties prohibit atmospheric testing, and there are formidable political hurdles to pursuing such an approach. Nuclear electric propulsion (NEP) converts thermal energy into electricity via a thermodynamic cycle, often either a Brayton cycle[8] or Stirling engine, and the electricity is used to run ion thrusters or other electric propulsion

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systems. NEP is hampered by the heavy radiators needed due to the ~30% efficiency of thermodynamic cycles, limiting specific power to perhaps 10 to 100 W/kg. Direct drive fusion propulsion, where the burning plasma is mixed with a propellant and exhausted, can potentially achieve specific impulses ranging from 10^4 to 10^6 seconds and thrusts in the 10 kN to 100 kN range. The primary challenge with fusion, which cannot be overstated, is that no working fusion reactor has ever been developed, in spite of billions of dollars and decades of time invested in doing so. It is our belief that fusion, because of its potential for superior performance, should be part of an overall strategy lead by the use of NTP, in which more advanced fission and fusion propulsion systems leverage the simpler, more near term systems. Because of the long lead time in developing fusion systems, UAH believes the time is now for working on fusion propulsion.

Charger 1 Pulsed Power Facility and Fusion propulsion Mission Performance

This effort initiated with the receipt of the 3 terawatt (TW), DECADE Module 2 from the Defense Threat Reduction Agency in May of 2012 which we have renamed Charger 1 (Figure 1). The machine is the last existing prototype developed as part of a $65M program to develop the next generation of pulsed power for reaching high energy states. The FPRF team has reassembled Charger 1 and is repurposing it for fusion propulsion research at the UAH Aerophysics Research Laboratory. UAH is working with NASA MSFC, The Boeing Company, L3 Communications, Oak Ridge National Laboratories, and Y-12 National Security Complex in this effort. The state of Alabama has also provided a significant innovation award to help with infrastructure. The total collective investment made by these entities towards the goal of reaching initial operating capability is approximately $2.0M. These investments have allowed us to make extensive repairs to various subsystems, install the capacitor bank, develop a custom control and data acquisition system, and design the first experiments. Additionally, Y-12 has explored and confirmed the ability to make lithium deuteride wire targets for our upcoming experiments, Figure 2.

Figure 2. Charger 1 pulsed power machine in the Aerophysics Research Laboratory at the University of Alabama in Huntsville.

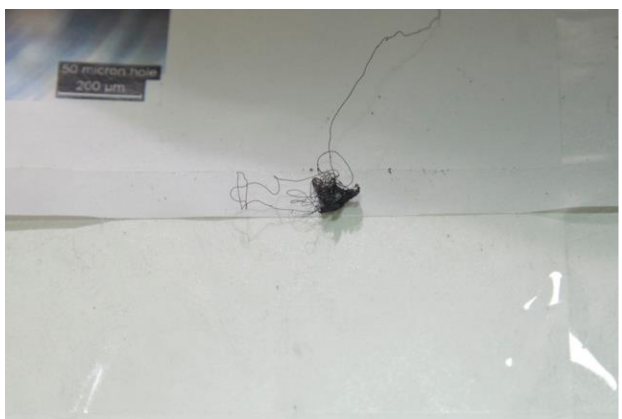


Figure 3. 50 µm diameter ^{6}Li wires made at the Y-12 National Security Complex..

The Charger-1 oil system and water deionization system are identified in the layout below in Figure 3. Shell Diala AX oil is needed for the Charger-1 in order to insulate the capacitors and other components in the Marx tank, as well as the A-K (anode/cathode) gap of the high voltage tube at the front of the Output Line. The Oil Purification subsystem consists of installed storage and transfer components, a recirculation and filtration skid, and the associated plumbing and controls. The oil was delivered at the end of November, 2015. The deionizing water system will be used in the Transfer Capacitor (TC) and Output Line (OL). Evoqua Water Technologies delivered and assembled the water system during the spring and early summer of 2016

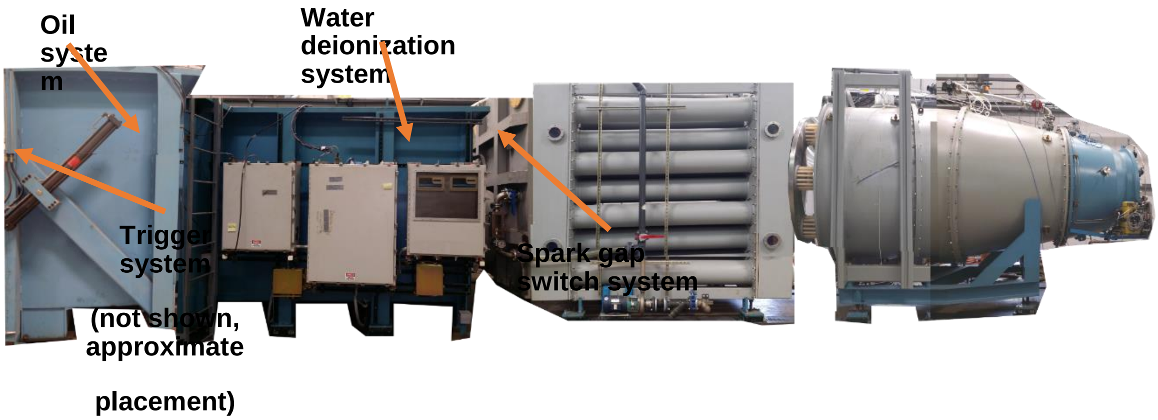


Figure 4. Charger-1 Subsystem Layout

The front end of the machine (far right in Figure 3) is the output line. A bell-shaped magneto-insulated transmission line (MITL) is connected in series with the output line to get the current concentrated in a small coaxial line of ~2 cm in diameter. The design for the MITL includes slits machined into the surface to prevent azimuthal current flow, Figure 4. The curves are calculated to achieve constant impedance along the length of the MITL, where Z = 10 Ω and the effective impedance = 6 Ω due to the electron cloud which forms above the surface of the electrodes during the operation. Experimental loads are connected in series with the MITL and are housed inside the vacuum chamber.

Figure 5 .UAH 3D MITL Assembly 10 ohm with Injector, mated to a vacuum chamber.

To motivate the work towards bringing Charger 1 to initial operating capability in order to conduct advanced propulsion experiments, we conducted and present below some patched conic trajectories for single stage round trip missions from Earth to destinations including Mars, outer gas giant planets, Kuiper belt objects, Oort cloud, nearest star, and a radius of 12 parsecs which includes the nearest ~550 stars. The study is summarized in Table 1 to include the initial mass in low earth orbit, specific impulse, specific power, and total trip time in years. Of interest was that a near term fusion propulsion vehicle can reach as far as Eris and return within the span of a typical career, 44 years. More ambitious missions such a gravitational lensing beyond 550 AU, interstellar precursor, and interstellar missions, require significant advancements and may require generations to complete.

Table 2. Summary of destinations investigated using a patched conic analysis. The same vehicle can be used throughout the solar system out to Neptune and possibly the inner Kuiper belt, but specific power and Isp need to dramatically increase as distances exceed 10^3 AU.

Destination	Vehicle mass (metric tons)	Isp (s)	α (kw/kg)	Trip time (years)
Mars	1620	3.0×10^4	1	0.3
Jupiter	1620	3.0×10^4	1	2
Saturn	1620	3.0×10^4	1	4
Uranus	1620	3.0×10^4	1	8
Neptune	1620	3.0×10^4	1	17
Eris	1620	3.0×10^4	1	44

Destination	Vehicle mass (metric tons)	Isp (s)	α (kw/kg)	Trip time (years)
10^3 AU	2615	2.0×10^5	1	60
3×10^5 AU	4.72×10^5	2.0×10^6	10	80
2.5×10^6 AU	4.72×10^5	2.0×10^6	10	260

The orbits of the inner planets in February of 2016 along with a notional outgoing and return hyperbolic trajectory are shown in Figure 5. The trip time reported in Table 1 only includes the flight time and not the duration. For this trajectory the journey to and from Mars only takes a total of 4 months.

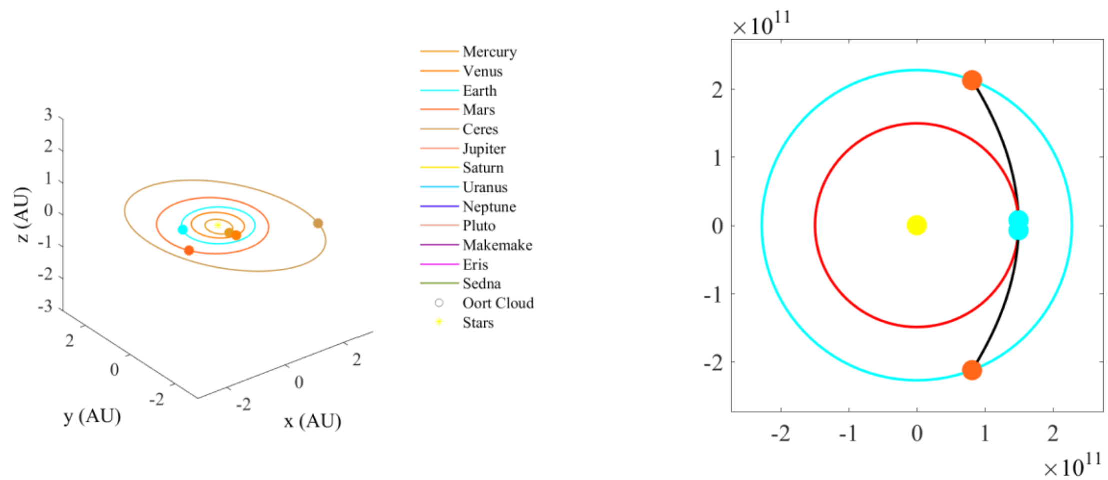
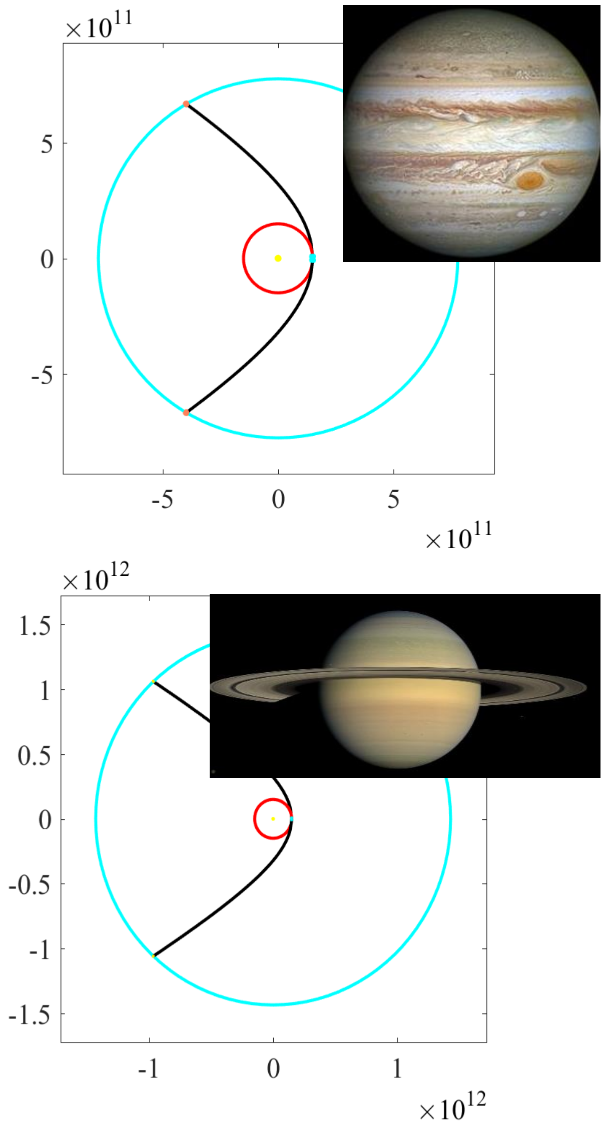


Figure 6. Patched conic trajectory to and from Mars.

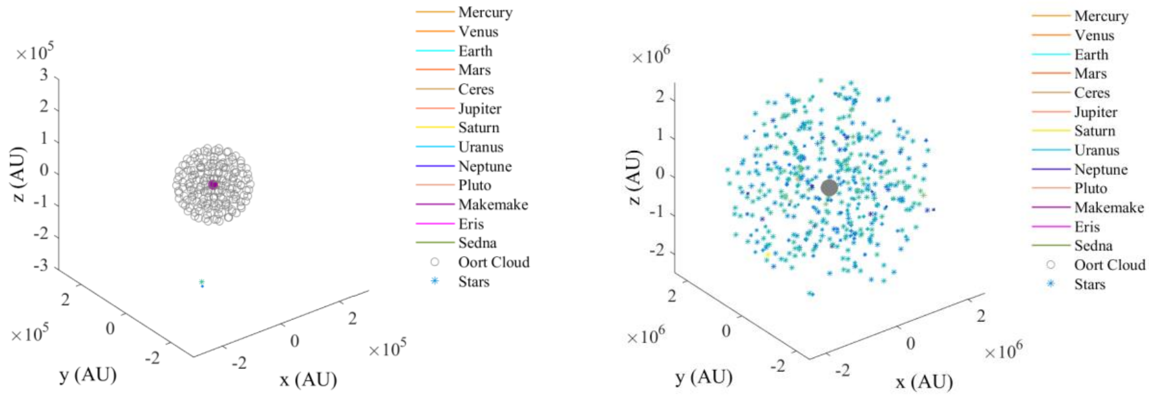
More ambitious trips were considered for the gas giants, and the trajectories are shown in Figure 6 for Jupiter and Saturn. These journeys require 2 and 4 years respectively, not including mission duration at the destination. While not shown, the Uranus and Neptune mission trajectories required 8 and 17 years to complete respectively. Of interest in these gas giant missions are that each planet contains at least one moon with gravity of the order of 10% of Earth's and possibly liquid water. A single propulsion system and lander payload could be utilized with only minor changes for exploring and returning samples from each one, within a span of 2-3 years for Jupiter and 20 years for Neptune.



(a) (b)

Figure 7. Patched conic trajectories to and from a) Jupiter and b) Saturn.

Figure 7 shows the solar system at the scale that alpha centauri and a notional Oort cloud are visible (Figure 7a) and the actual positions of the nearest 550 stars within 12 parsecs of the solar system (Figure 7b). For these missions the trajectories look like straight lines, and require significant advancements in the propulsion technology, pushing the limits of what can be theoretically possible with fusion. The trip times are on the order of a century or longer.



(a) (b)

Figure 8. Patched conic trajectories were performed out to a) Alpha Centauri and b) a distance of 12 parsecs. The plots show a representative Oort cloud and the Alpha Centauri system in a) and the nearest stars with a 12 parsec radius in b).

Summary

A state of the art pulsed power facility is being refurbished to conduct fusion propulsion experiments at the University of Alabama in Huntsville (UAH). Specifically, we will be exploring the yield scaling for solid state fuels including lithium deuteride and frozen fiber deuterium in a pulsed z-pinch configuration, and assisting in the development and study of fission fusion hybrid targets envisaged by researchers at NASA MSFC. Mission analysis using patched conic trajectories show that a relatively near term fusion propulsion system could enable rapid human interplanetary missions as far out as Neptune (17 years round trip) and Mars missions can be accomplished in 4 months excluding the duration at Mars. Deep space missions through the Kuiper belt, Oort cloud, and interstellar missions require significant advancements, pushing the limits of what can be enabled by fusion propulsion. Development of these technologies have begun at UAH in collaboration with NASA MSFC, the Boeing Company, and Y-12 National Security Complex

Acknowledgements

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Matter-Antimatter Propulsion via QFT Effects from Parallel Electric and Magnetic Fields

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Matter-Antimatter Propulsion via

QFT Effects from Parallel Electric and Magnetic Fields

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Introduction

Matter-Antimatter (MAM) (a.k.a., particle/anti-particle) pair production from the spacetime vacuum through intense electric fields has been investigated for nearly a century. This paper reviews its history and examines proposals of MAM production for intra-solar system and interstellar propulsion systems. The quantum mechanical foundation of MAM pair production was developed by Fritz Sauter, Werner Heisenberg, and Hans Euler in the 1930's [1] and then placed on a sound quantum electrodynamics (QED) basis by Julian Schwinger in 1951 [2].

MAM production occurs when the electric field strength E is at or above the critical value E_S (known as the Schwinger limit) at which the electromagnetic fields become non-linear with self-interactions. This non-linearity occurs when the energy within a Compton wavelength of a photon is equal to or greater than twice the rest mass of an electron. It corresponds to an electric field strength $E_S \equiv m^2c^3/(e\hbar) = 1.3 \times 10^{16}$ V/cm (equivalently, an electric field intensity $I_S = 2.1 \times 10^{29}$ W/cm^2).

In a vacuum, the classical Maxwell's equations are perfectly linear differential equations. This implies – by the superposition principle – that the sum of any two solutions to Maxwell's equations is yet another solution to Maxwell's equations. For example, if two beams of light interact linearly when aimed toward each, their electric fields simply add together and pass right through each other. In QED, however, non-linear photon–photon scattering becomes possible when the combined photon energy is large enough to spontaneously create virtual electron–positron pairs. When the average strength of an electric field is above E_S, the pair production rate (PPR) of charged particles per unit time and unit cross-section is found from the probability of quantum mechanical "tunnelling" of virtual MAM pairs from the Dirac sea into real particles.

(It should perhaps be emphasized that MAM production *does not (and cannot) steal energy from the spacetime vacuum*. Rather the energy is drawn from the external electric (and possibly magnetic) fields. The MAM production process is in many ways analogous to particle production near (on the outer side of) the event horizon of a black hole, which reduces the mass of the black hole accordingly. The primary difference between the two processes is, while both particle and antiparticle are produced from a virtual pair by the electromagnetic fields, only one particle in an initially virtual pair escapes from a black hole (as Hawking radiation) and the antiparticle is captured by the black hole.))

As the energy density of lasers approach the critical strength $E_{S,}$ the feasibility and functionality of electron-positron pair production has received growing interest. Current laser intensities are approaching within 1 order of magnitude of this Schwinger limit. Examples are the X-ray free electron lasers at SLAC's the Linac Coherent Light Source and DESY's TESLA. Site four of the Extreme Light Infrastructure (ELI) Ultra-High Field Facility (UHFF) is planned for construction in eastern Europe around 2020 and should reach E_S. It will be composed of ten lasers concentrating 200 petawatts of power into a very narrow beam of 10^{-12} s pulses.

Physical processes for effectively lowering the critical energy density below the Schwinger limit (and simultaneously enhancing MAM PPR above the Schwinger limit) through additional quantum mechanical effects continue to be explored. Research teams at the U. of Connecticut and the U. of Duisburg-Essen are jointly examining critical energy field strength scale reduction/increased PPR via pulsation of inhomogeneous electric fields within a carrier wave [3].

Other investigations have focused on enhancement of quantum effects by addition of a magnetic field $\underline{B}$ parallel to the electric field $\underline{E}$. Magnetic field enhancement to quark/anti-quark production through chiral symmetry breaking effects in quantum chromodynamics (QCD) was investigated theoretically by John Preskill at Caltech in the 1980's [4]. S. Pyo Kim at the Kunsan National University and Don Page at the University of Alberta showed in 2007 that parallel magnetic fields also enhance electron/positron production via an analogous QED effect [5], with enhancement going predominantly as a linear function of B/E, the ratio of the magnitude of the magnetic and electric fields.

MAM production as a highly efficient fuel source for intra solar system and interstellar propulsion was proposed by Devon Crow in 1983 [6] and Robert Forward in 1985 [7]. The viability of this method of propulsion is considered below, especially with regard to the two PPR enhancement methods.

BRIEF History of MAM PRoduction

In 1928, British physicist P.A.M. Dirac showed that Einstein's relativity implied every type of particle has a corresponding antiparticle, with an identical mass, but opposite electric charge. Then in 1932, Carl Anderson at Caltech recorded discovery of a positively charged electron (i.e., positron) passing through a lead plate in a cloud chamber, for which he received the Nobel Prize in Physics. Two decades later in 1955, the antiproton was experimentally confirmed at Berkeley by Emilio Segre and Owen Chamberlain, earning them the 1959 Nobel Prize in Physics. Within one year, the antineutron was discovered at the Bevatron at Lawrence Berkeley Nation Lab by Bruce Cork and colleagues.

By 1995, researchers were using CERN's Low Energy Antiproton Ring (LEAR) to slow down antiprotons. They managed to pair positrons and antiprotons together, producing nine hydrogen anti-atoms, each lasting a mere 40 nanoseconds. Within three more years, CERN was producing approximately 2000 anti-hydrogen atoms per hour. Production rates of antimatter at CERN's Large Hadron Collider have steadily increased significantly since. (Likewise at Fermilab's Tevatron accelerator until its 2011 shut down).

MAM AS PRopulsion Source

MAM could be an ideal rocket fuel because all of the mass in MAM collisions can be converted into energy and used for thrust. MAM reactions produce 10 million times the energy produced by conventional chemical reactions used to fuel the space shuttle. It is 1,000 times more powerful than nuclear fission produced at a nuclear power plant & 300 times more powerful than the energy released by nuclear fusion. (Note however that should such an amount of antimatter be produced or collected, unless used for propulsion very soon thereafter, a secure means of long-term storage (i.e., magnetic confinement) would likely need to be devised. Antimatter must be kept separate from matter until a spacecraft needs more power, unless stored as anti-hydrogen. The alternative is for MAM to be created in situ and immediately emitted as propellant.

In 2000, NASA scientists announced early designs for a MAM engine that might be capable of fueling a spaceship for a trip to Mars using only a few milligram of MAM. In 2012, R. Keane and W.M. Zhang examined magnetic nozzle designs for charged pion emission from quark/ antiquark collisions. Their study indicated that effective exhaust speeds ~ 0.7 c are feasible by optimizing nozzle geometry and magnetic field configuration using a magnetic field of order ~ 10 T. They also estimated an emission efficiency ~ 30% for MAM emission is obtainable for quark/antiquark pair production leading to pion emission and greater than 30% efficiency for electron/positron emission [8].

With MAM production a known technolgy [9], one might wonder what are the main hinderances to construction of MAM propulson systems. A primary issue is antimatter remains *the most expensive substance on Earth*. In 2000, it cost $62.5 trillion per microgram (equivalently, $1.75 quadrillion per ounce) of electron/positron pairs, with Fermilab able to produce only about 15 nanograms a year. However, the price of antimatter has continued to drop with each advancement in particle accelerator intensity and efficiency. CERN's LHC now produces about 1 microgram of antimatter (equivalently, 10^{21} electron/positron pairs) per 12 days at a cost of $200,000 or 1 milligram in about 12,000 days (that is, 30 years) at a cost of around two-hundred-billion dollars.

In its *Status of Antimatter* report, the NASA Glenn Research Center (www.nasa.gov/centers/glenn/technology/warp/antistat.html, dated 14 July 2015) concluded that for MAM to be a commercially viable fuel for travel within our solar system, "the price of antimatter would need to drop by about a factor of ten-thousand." Based on the rate of decline of antimatter production cost over the last 25 years, and its extrapolation into future decades, the NASA cost reduction goal may be obtainable within one to two decades from now. 2025 to 2035 was the time scale for MAM cost viability predicted by Crow and Forward in the 1980's.

Significantly more than just a few milligrams of MAM are required for interstellar travel, even to the closest star systems. Further, if planet reconnaissance or a landing mission is involved, additional MAM is needed to decelerate a spacecraft into the target star system. A spacecraft with a 100-ton payload designed for to cruising at 0.40 c is estimated to require the equivalent of 80 ocean supertankers full of MAM fuel [10]. (However, for somewhat lower cruise speed ~ 0.25 c, MAM requirements are dramatically lowered, but still remain extremely large [11].)

One possible solution to the extremely high cost of MAM production on earth is collecting MAM in space. In 2011, antiprotons were discovered by the international PAMELA (Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics) satellite to be trapped by Earth's magnetic field. The Alpha Magnetic Spectrometer on ISS is also able to detect, identify, and measure antiparticles in Earth orbit. Theoretical studies relatedly suggest that the magneto-spheres of much larger planets, like Jupiter, should have significantly more antiprotons than earth. Keane and Zhang point out that "if feasible, harvesting antimatter in space would completely bypass the obstacle of low energy efficiency when an accelerator is used to produce antimatter" [8].

In Situ MAM GENERATION

In addition, an ideal MAM propelled spacecraft should contain systems for both *collecting and generating* MAM, with creation especially as an emergency option if the stored antimatter leaks out of magnetic containment chambers or is annihilated prematurely by matter leaking in. Significant developments in both theoretical and engineering aspects of MAM production via strong localized electromagnetic fields have occurred in the last decade. For example, in [5] Sang Kim and Don Page derived the MAM production rate from a static plane-symmetric z-dependent electric field E(z): Consider a static plane-symmetric z-dependent electric field E(z) in the z-direction, with maximum value E_0 and of effective length L such that $E_0L = ½ \int E(z)\, dz$.

This arrangement allows pair production of a particle of mass m and charge q if $\varepsilon \equiv m/(qE_0L) < 1$ or equivalently $E_0 > m/(qL)$ (in natural units of $G_N = c = \hbar = 1$). (Alternately, if we want a time varying field E(t) rather than a spatially varying field, replace ε with ε_T, L with T, and dz with dt. (In that case, pair production occurs even with $\varepsilon_T > 1$, but is suppressed.)

In both the spatially-varying and time-varying processes, when E_0 is above the minimum value, MAM PPR of charged particles per unit time and unit cross-section can be computed from tunnelling of virtual pairs from the Dirac sea, where instantons determine the QM tunnelling probabilities. To leading WKB order, for a "Sauter" electric field of the form $E(z) = E_0\, \mathrm{sech}[2(z/L)]$, the PPR is

$$N = (qE_0)^{5/2}L\, (1-\varepsilon^2)^{5/4} \exp[-Z\{1-(1-\varepsilon^2)^{1/2}\}] /(4\, \pi^3\, m) \sim (qE_0)^{5/2}L/(4\, \pi^3\, m) \text{ as } \varepsilon \to 0$$

with $\varepsilon = m/(qE_0L)$ and $Z = 2\pi qE_0L^2$.

Kim and Page showed that the minimum value of E_0 for meaningful MAM production can be lowered significantly below the Schwinger limit by the addition of a constant magnetic field <u>B</u> parallel to the electric field <u>E.</u> In the presence of a parallel magnetic field, the PPR of charged particles per unit time and unit cross-section is modified (as derived in [5]) to,

$$N_B = (B/E_0)(qE_0)^{5/2}L\, (1-\varepsilon^2)^{3/4} \exp[-Z\{1-(1-\varepsilon^2)^{1/2}\}] \coth[\pi B/E_0(1-\varepsilon^2)^{1/2}]/(4\, \pi^2\, m)$$

$$\sim (B/E_0)\, (qE_0)^{5/2}L \coth[\pi B/E_0]/(4\, \pi^2\, m) \text{ as } \varepsilon \to 0).$$

In the $\varepsilon \to 0$ limit we see that, $N_B = (\pi B/E_0) \coth[\pi B/E_0] N$.

In SI [B] = [E/c]. This means that an electric field at the Schwinger limit corresponds to a magnetic field of B = (10^{18} V/M) (3×10^8 m/s) = 3×10^9 T. The magnitude of this required magnetic field is on the same order as that of a magnetar! (Hence not producible presently by humans, nor likely in the long-term future!) Alternately, using present technology PPR can be enhanced by orders 10 to 100 (or greater), if the electric field (in particular, that of a laser) is pulsed with internal modulation [3].

If MAM were produced in situ, it would either be in the form of electron/positron pairs or (for sufficiently stronger electric field strength) quark/antiquark pairs. A quark/anti-quark pair will form an uncharged pion state or multiple charged/uncharged pions, if the quark pair has sufficient kinetic energy to separate sufficiently for the strong force potential interaction energy to be greater than the mass of another quark pair. Then another quark/anti-quark pair will pop into existence and a net effect can be a pair of pions of opposite charge. More likely, an electron/positron pair will pop into existence. The charged pion pairs or electron/positron pairs can be directed by external magnetic fields to produce thrust for a spacecraft.

SUMMARY

MAM production from electric fields near or above the Schwinger limit, $E_S = 1.3 \times 10^{16}$ V/cm, is nearing feasibility. MAM PPR enhancement via the addition of magnetic fields parallel to an electric field appears viable only for a B-field of at least 10^9 T. However, MAM PPR enhancement has proved possible using pulsed electric fields near the Schwinger limit with internal modulation.

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Three Interstellar Ram Jets

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Three Interstellar Ram Jets

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Abstract

The mass ratio problem in interstellar flight presents a major problem[1,[2}; a solution to this is the Interstellar Ramjet[3]. An alternative to the Bussard Ramjet was presented in 1977 [8]. The Laser Powered Interstellar Ramjet, LPIR. This vehicle uses a solar system based laser beaming power to a vehicle which scoops interstellar hydrogen and uses a linear accelerator to boost the collected particle energy for propulsion. This method bypasses the problem of using nuclear fusion to power the ramjet. Engine mass is off loaded to the beaming station. Not much work has been done on this system in last 40 years. Presented here are some ideas about boosting the LPIR with a laser station before engaging the ram mode, using a time dependent power station to keep the LPIR under acceleration. Fishback[4] in 1969 calculated important limitations on the ramjet magnetic intake, these considerations were augmented in a paper by Martin in 1973[6]. Fishback showed there was a limiting Lorentz factor for an interstellar ramjet. In 1977 Dan Whitmire [7] made progress towards solving the fusion reactor of the interstellar ramjet by noting that one could use the CNO process rather than the PP mechanism. Another solution to fusion reactor limitations is to scoop fuel from the interstellar medium , carry a reaction mass , like antimatter, combine to produce thrust [9,10,11]. Limitation issues are addressed, such as structural limitations on the magnetic scoop, radiation losses, drag losses and the accuracy of the pointing of the laser power station. How these limitations affect the dynamic trajectory of the LPIR are also addressed.

1. INTRODUCTION

Three interstellar ramjets are presented, the Interstellar Ramjet, ISR, sometimes known as the Bussard Ramjet, the Laser Powered Interstellar Ramjet, LPIR, and the Ram Augmented Interstellar Ramjet, RAR, see Figure 1.

Project Pluto – a program to develop nuclear-powered ramjet engines – must have been on Robert Bussard's mind one morning at breakfast at Los Alamos. Bussard was a project scientist-engineer on the nuclear thermal rocket program Rover — Bussard and his coauthor DeLauer have the two definitive monographs on nuclear propulsion [1, 2]. Bussard said many times that the idea of the hydrogen scooping fusion ramjet came to him a morning over breakfast. This was sometime in 1958 or 1959 and the SLAM (Supersonic Low Altitude Missile) would have been well known to him. SLAM was a nuclear ramjet, a fearsome thing, sometimes called the Flying Crowbar. Finding a solution to the mass ratio problem for interstellar flight was also something on Bussard's mind. Thus was born the Interstellar Ramjet, published in 1960 [3], Figure 1a.

2. THE INTERSTELLAR RAMJET

The interstellar ramjet scoops hydrogen from the interstellar medium and uses this as both a fuel and energy source by way of fusion reactor. The sun does proton fusion using gravity as the agent of confinement and compressional heating. However, doing fusion in a 'non-gravitational' magnetic reactor makes the process very difficult [3,5,7]. That is, the proton and Deuterium burning is quite difficult to realize on a non-stellar scale. Dan Whitmire attacked this problem by proposing the use of a carbon catalyst using the CNO cycle [7]. The CNO cycle is about 9 orders of magnitude faster than proton-proton fusion. It would still require temperatures and number densities way beyond any technology known at this time.

Bussard noted a number of problems such as losses from bremsstrahlung and synchrotron radiation. He also noted scooping with a material scoop would create a problem with erosion, hinting that magnetic fields might be used, and noting that drag would have to be accounted for.

About 8 years after Bussard's paper, an undergraduate at MIT, John Ford Fishback, took up the problems Bussard had mentioned. He wrote this up for his Bachelor's thesis under the supervision of Philip Morrison. The thesis was published in Astronautica Acta [4] in 1969.

Fishback did three remarkable things in his only journal paper: finding an expression for the 'scoop' magnetic field, computing the stress on the magnetic scoop sources, and working out the equations of motion of the ramjet with radiation losses. These calculations were done using a special relativistic formulation. Fishback's most important finding is noticing that when capturing ionized hydrogen to funnel into the fusion reactor, there is a large momentum flow of the interstellar medium which must be balanced by the scooping and confining magnetic fields. Using very general arguments, Fishback showed that sources (magnetic coils and their support) of the magnetic field determine an upper limit on how fast a ramjet can travel. The convenient measure of starship speed is the Lorentz factor

Fisback derived the following expression for the limiting Lorentz factor γ for a constant acceleration, a, Bussard ramjet:

$$(\gamma\beta)_c = \frac{4en\alpha}{aB_0}\frac{\sigma_{max}}{\rho} \quad (1)$$

Where:

β = velocity/c, c = speed of light.

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

e = charge on an electron – 1.6022 x10^{-19} Coulombs

n = average Galactic hydrogen number density -1000/m^3

a = acceleration in g's

B_0=average galactic magnetic field 1.0x10^{-10} Tesla

∝ = fusion energy yield = 7.1x10^{-3}

σ_{max} = maximum tensile strength of scoop field coils, Pa

ρ = density of ship structural material, kg/m^3

The tensile strength of the scoop field coils is the main limiting constraint as shown in equation (1). At the time, Fishback modeled the upper limit using diamond, because of its shear stress properties, and found that one could only accelerate until the Lorentz factor reaches about 2000 [4]. Tony Martin expanded on Fishback's study [5, 6] in 1971, correcting some numbers and elaborating on Fishback's modeling. Since that time, Graphene has been discovered and has amazing properties, table 1. Graphene has a shear stress that allows a limiting Lorentz factor of about 6000. This in turn implies a range of over 6000 light years when under 1 g acceleration. It does not mean a final range is 6000 light years, but one must travel at a reduced acceleration and then constant speed, which means a longer ship proper time. Table 2 shows some representative values for the Lorentz factor cutoffs. Graphene is close to the upper limit on the maximum tensile strength of a material; however it is possible the theoretical limit may be extrapolated to a limiting Lorentz factor to 10,000. (Note the material Carbyne is approximately twice as strong as Graphene.)

Figure 2 shows a time history of interstellar ramjet acceleration when the overall scoop fields are supported by a structure based on the tensile strength of Graphene. The ship is able to accelerate at 1g for about 10 years before having to throttle back. After about 10 years, ship proper time, the ship is at about 6400 light years distance, of course about 6400 years have elapsed back on earth.

3. OTHER RAMJETS

In 1977 Dan Whitmire and this author published a variation on the Interstellar Ramjet. The vehicle uses a solar system based laser beaming power to a vehicle that scoops interstellar hydrogen and uses this energy to power a linear accelerator boosting the particle energies for propulsion. This method bypasses the problem of using nuclear fusion to power the ramjet. Engine mass is off loaded to the beaming station. Figure 1b.

Another solution to the proton-proton fusion reactor in the Bussard ramjet would be to carry an energy source but extract a 'working fluid' from the interstellar medium by scooping hydrogen. A third ramjet was proposed, the ram augmented ramjet, RAR, Bond [9] and Powell [10], figure 1c. The optimum RAR can be obtained by carrying antimatter and combine with the interstellar medium Figure 3 [11].

One feature of the ISR is that it becomes more efficient at higher speeds [3]. One envisions a mode where the ISR is boosted by the Laser Powered Interstellar Ramjet (LPIR) before engaging the pure ram mode. Figure 5 shows that the instantaneous energy efficiency of the ISR and LPIR cross at roughly a beta of 0.14. At this point there would be a hand off of the two propulsion modes.

A tri-mode is also possible. The start trajectory would be to deploy a sail [12], push the vehicle to a high speed, transition to the laser powered ramjet mode and transition to the interstellar ramjet at high beta.

Such a vehicle might be schematically represented by figure 4. The para-sail acts as a plain radiation pushed sail and then an absorber for the pushed and the powered mode. Because of the remarkable electrical, thermal and strength properties of Graphene such a sail would have multiple uses. After the ‘boost’ phases the sail could even be consumed as source of carbon catalyst when in the interstellar ramjet mode.

4. CONCLUSTION

In conclusion one notes many questions about the interstellar ramjet: (1) Could one really make the whole ship out of Graphene?(Or something like it?). (2) Will one always be γ limited by strength of source of magnetic field? (3) Does the CMB limit the sail acceleration [13]? (4) Bremsstrahlung and Synchrotron scoop radiation losses need further refinements. (5) Need to explore the Interstellar Ramjet reactor in more detail. (6)Even at 100% efficiency will waste heat melt the ship?

The ‘laser’ powered ramjet needs to be looked at again. The antimatter augmented ram scoop needs a revisit. The SETI observables need a look: The laser or microwave ‘booster stations’ can we see them? Beamed waste heat? Decelerating ramjets in stellar atmospheres or high density regions?

Acknowledgment: Figure 3 by Douglas Potter.

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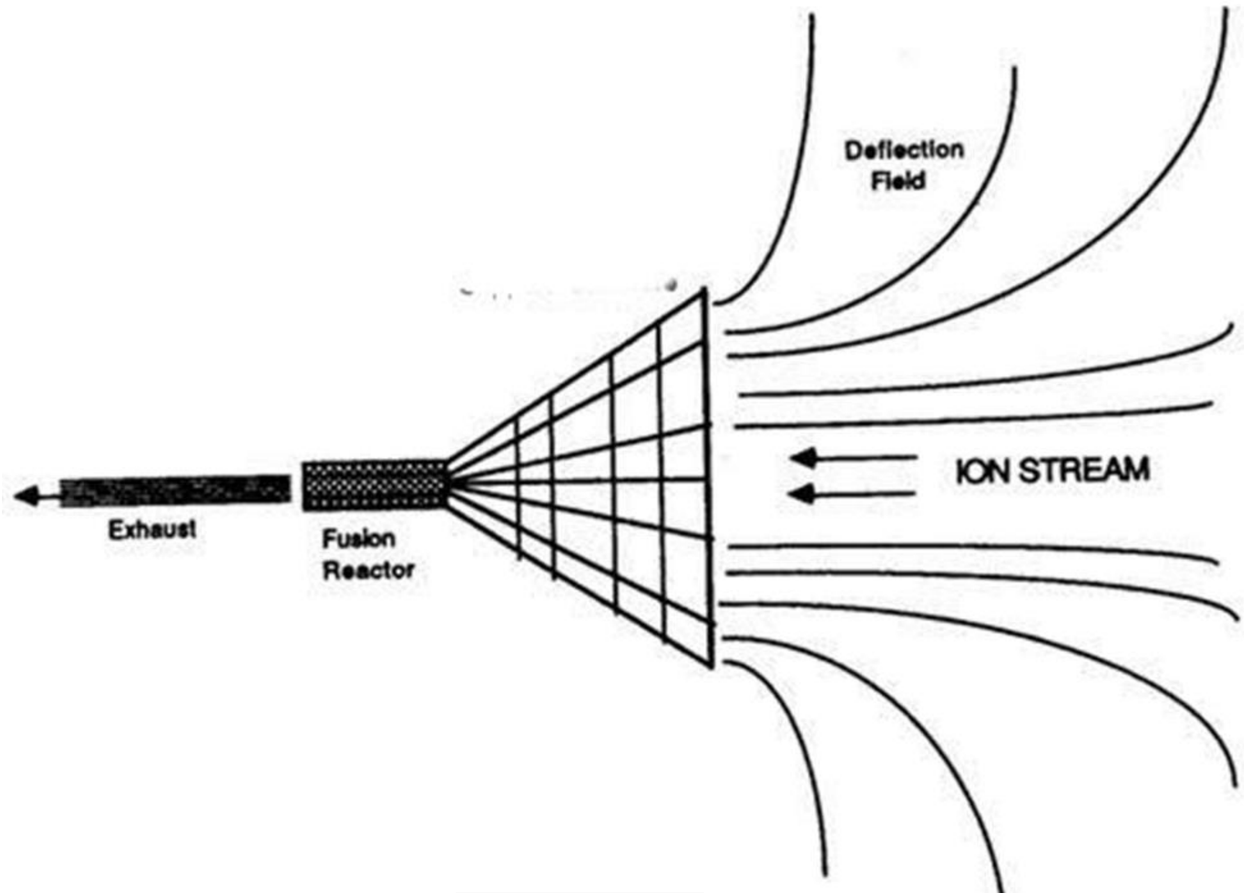
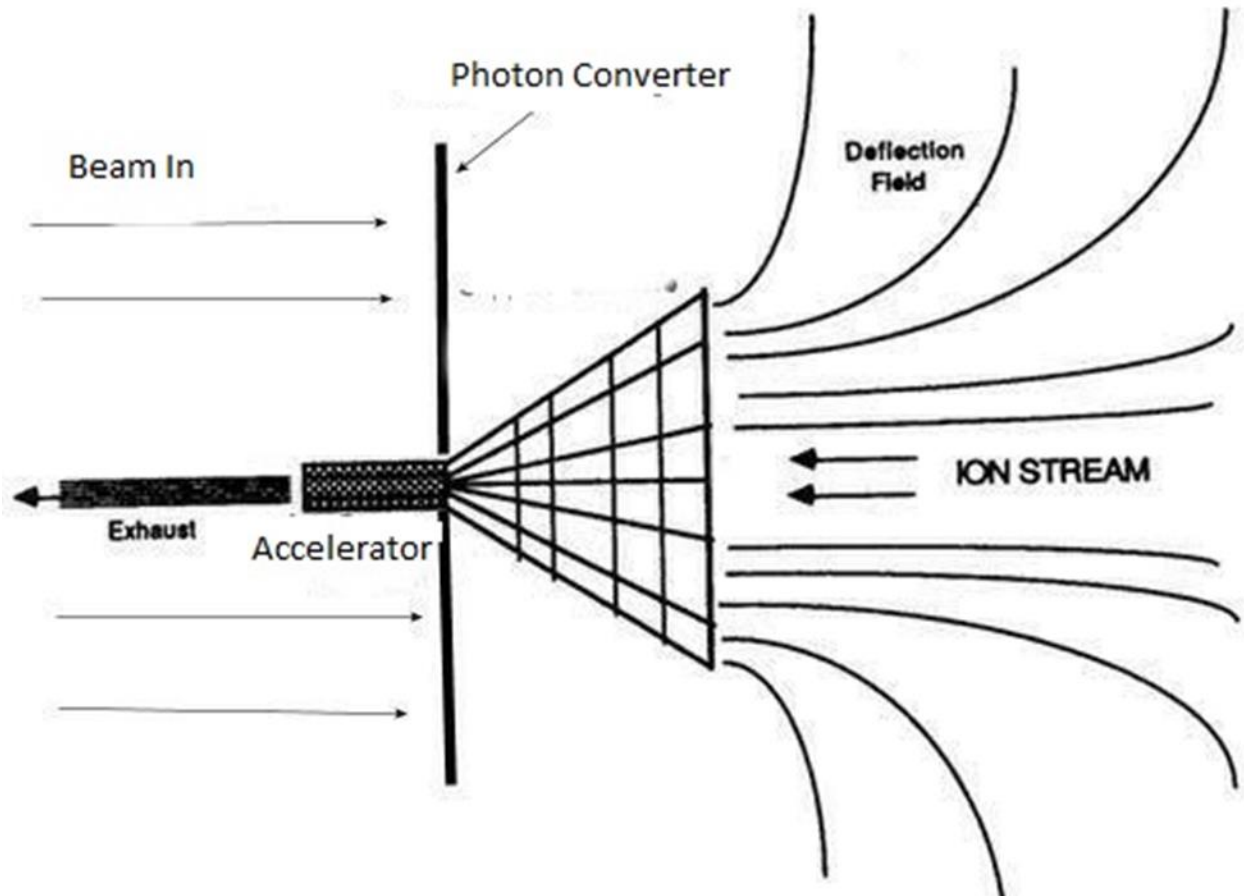
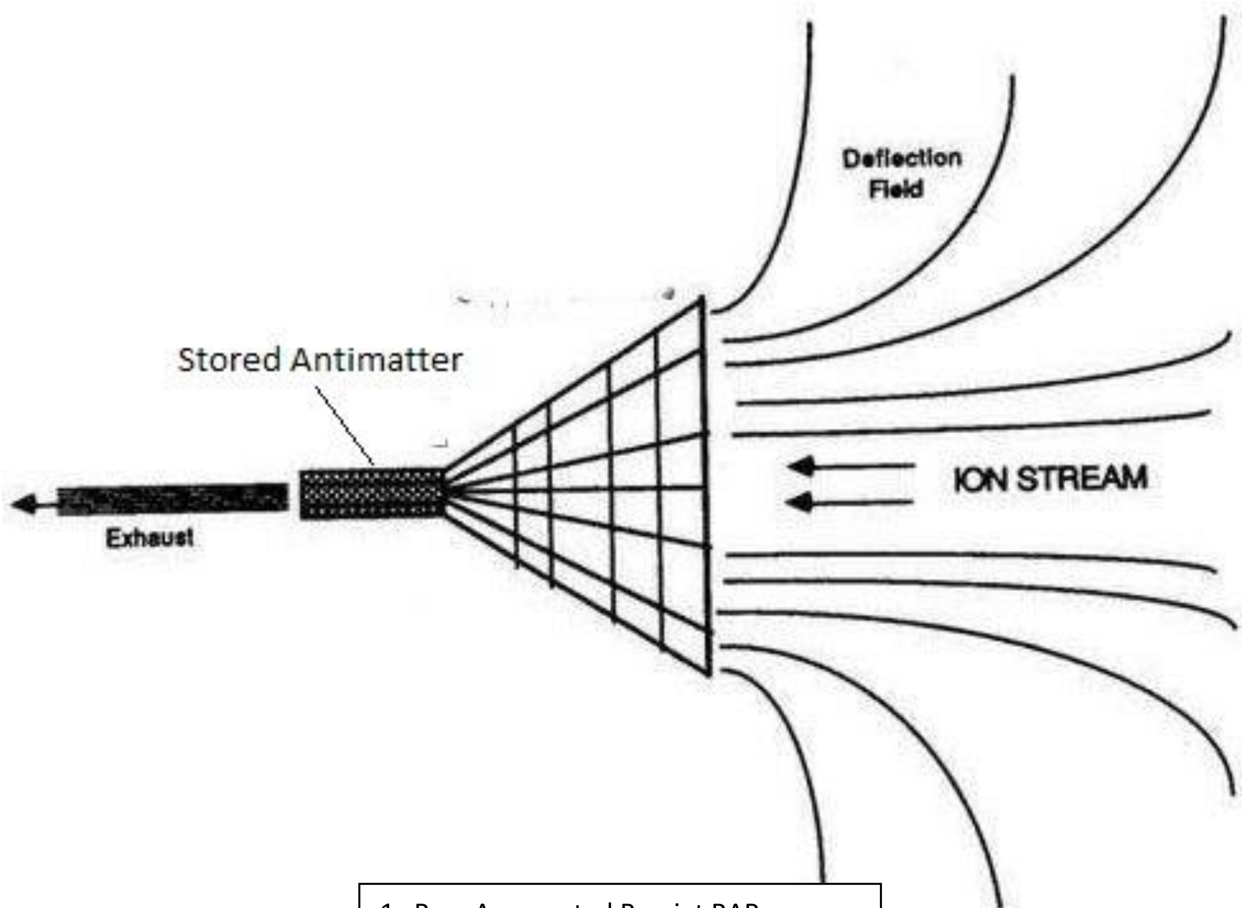
Tables and Figures:



1a Interstellar



1b Laser Powered
Interstellar Ramjet



1c Ram Augmented Ramjet RAR

Figure 1: Three interstellar ramjets

Material	Copper	Graphene	
Tensile Strength*	.22	130.0	GPa
Thermal Conductivity	.385	3-5	10^3 W/m-K
Max current density	~106	>1x10^8	A/cm^2
Melting Point	1356	3800	K

Table 1 : Comparison Copper and Graphene

Structural Material	**σ/ρ** dyn cm^{-2}/gcm^{-33} 10^{10}	**γβ**$_c$ Proton	Range LY
Aluminum	.062	8.6	12.6
Stainless Steel	.261	36.2	7.5
Diamond	15.2	2110	3550

Graphene	600.0	6628.0	6418.0

Table 2: Lorentz factor cut-offs and range of the Bussard Ramjet accelerating at 1g. Interstellar medium 1/cm-3 using the p-p fusion reaction.

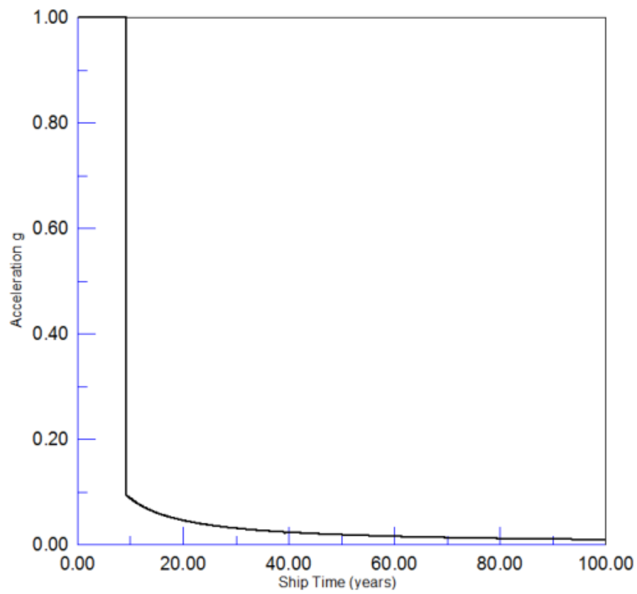


Figure 2: Ramjet acceleration profile due to stress on the magnetic scoop field sources.

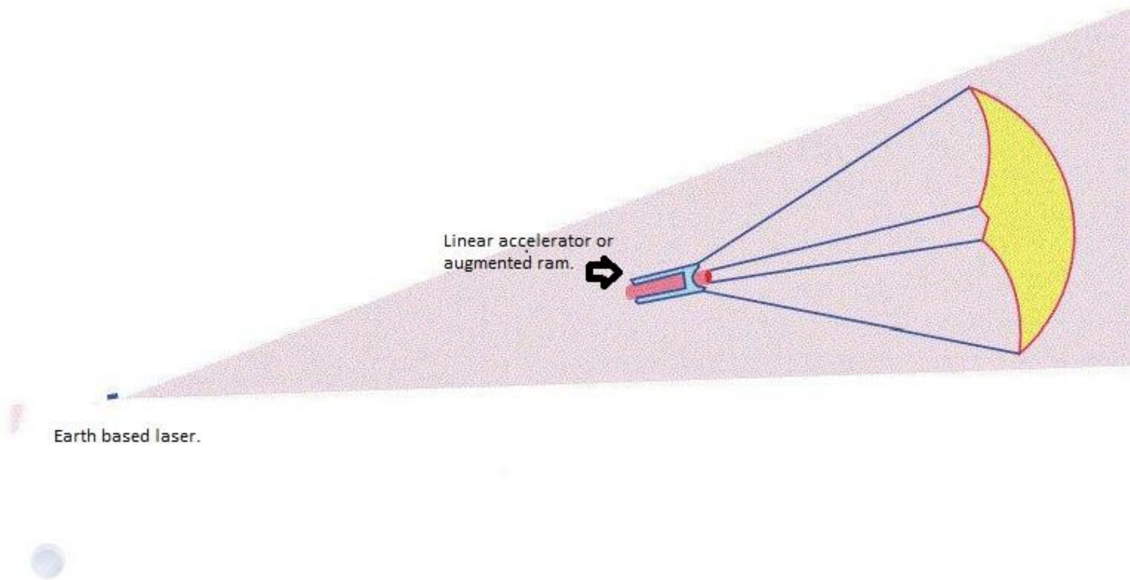


Figure 3. Schematic of Laser Powered or Augmented Ramjet.

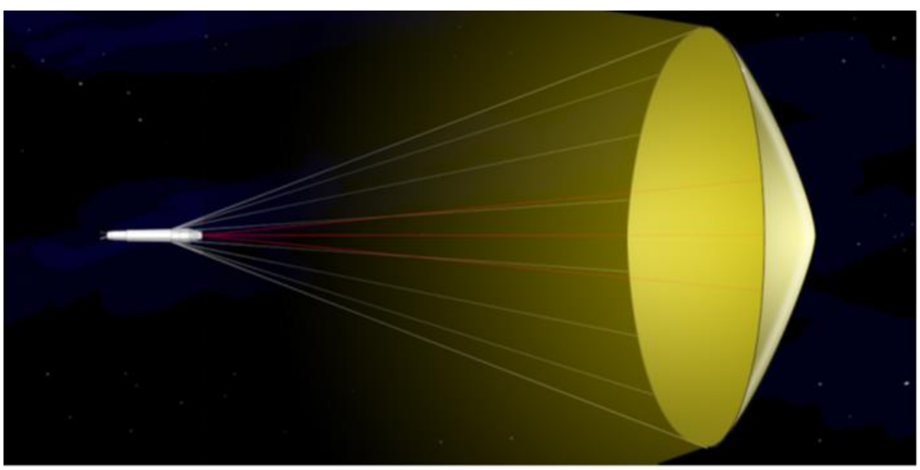


Figure 4. The ‘para-sail’ laser collector hybrid interstellar ramjet, before transition to interstellar ramjet mode. The graphene sail could be eaten as fuel.

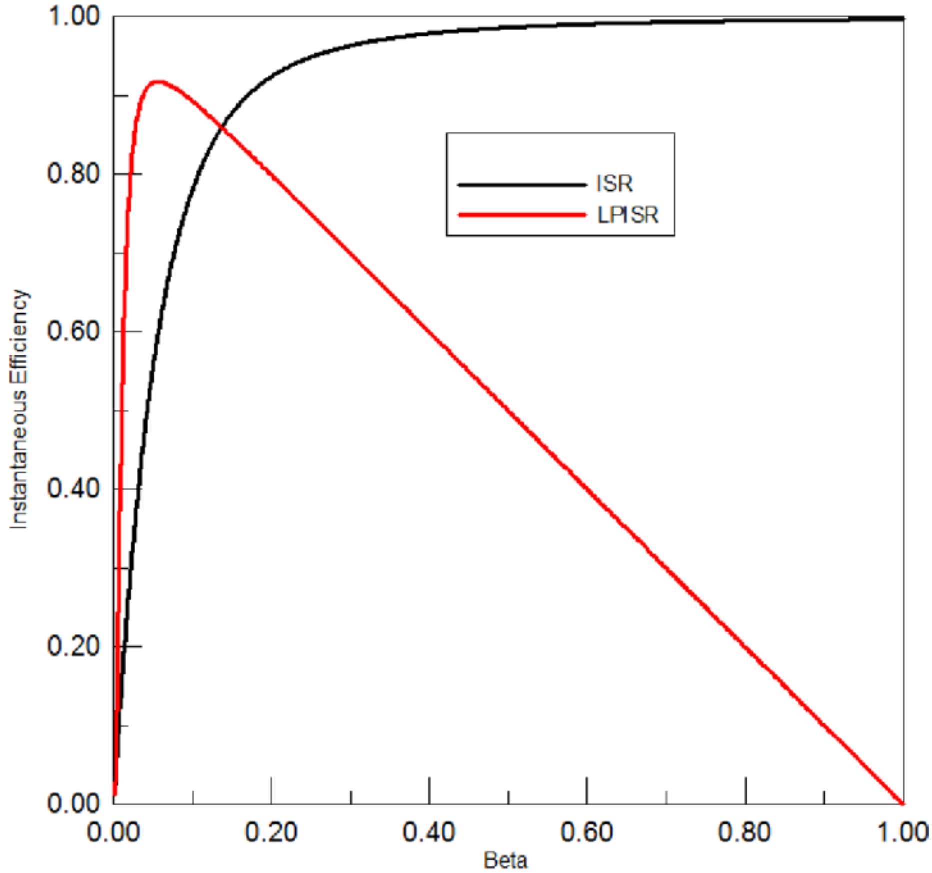


Figure 5: Ramjet efficiency vs beta = v/c.

The LightSail Program: Solar Sailing from a CubeSat Platform

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The LightSail Program: Solar Sailing from a CubeSat Platform

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Introduction

This presentation reports on the status of the dual CubeSat program called LightSail, which has been fully active since late 2013 after an 18-month pause. Conceived by The Planetary Society, the LightSail program is privately funded via citizen donations and contributions and seeks to demonstrate controlled solar sailing using a 3U CubeSat package.

Nearly identical spacecraft, LightSail A and LightSail B, were designed by Stellar Exploration, Inc., San Luis Obispo, CA, who completed preliminary integration of both spacecraft in 2012. Currently, the lead contractor for LightSail final integration and testing is Pasadena-based Ecliptic Enterprises Corporation. The rest of the LightSail team, providing hardware, software and ground station support, consists of Boreal Space, Half Band Technologies, Aquila Space Systems, California Polytechnic University San Luis Obispo, Georgia Institute of Technology and others.

Integrated and tested during most of 2014, LightSail A was inserted into its flight P-POD carrier/deployer system in mid-January 2015 and launched to orbit in a NPS-Cul secondary payload carrier aboard an Atlas 5 on May 20, 2015. During its 24-day mission, LightSail A demonstrated and validated several key functions of its system design, including the principal mission objective of sail deployment. Elements of the power, attitude control, telecommunications and imaging subsystems were also demonstrated, but not without considerable drama. LightSail-A's relatively low orbit and resultant atmospheric drag, however, precluded demonstration of controlled solar sailing. Total mission success was declared on June 9, and the spacecraft re-entered the atmosphere on June 14.

The LightSail-B mission will build on the results of the LightSail-A effort and conduct a full demonstration of solar sailing in Earth orbit. With LightSail B packaged inside a small spacecraft called Prox-1, the spacecraft duo will be launched into a higher, longer lasting orbit than that of LightSail A aboard a Falcon heavy launcher, most likely in late 2017 or 2018. Prox-1 will deploy LightSail B and use it as a test target for its own demonstration of in-space rendezvous and inspection technologies. Prox-1 will then image LightSail B as its sails deploy and the solar sailing mission starts. The months-long orbit will allow the LightSail team to fully test all subsystems (including a momentum wheel for improved attitude control, which LightSail A did not have) and measure orbit changes due to solar radiation pressure. If successful, this will be the first controlled, Earth-orbiting solar sailing mission.

This presentation also briefly addresses the history and evolution of the LightSail program, generation and evolution of key mission and system requirements and related analyses, hardware and software changes made since the initial design and integration effort, LightSail-A and -B mission operations differences, integration and testing challenges, the launch integration experience, regulatory issues and overall programmatic lessons learned.

Historical Comment

This oral presentation given at the 2016 Tennessee Valley Interstellar Workshop [1] reprises a similar presentation given at the 2015 Conference on Small Satellites held in Logan, UT, in 2015 August. A thorough technical paper [2] was also prepared for the SmallSat conference and serves as an excellent companion to this TVIW presentation.

The LightSail program in general and LightSail-A mission in particular has been well-received by the space community. At the 2015 Conference on Small Satellites the LightSail-A mission was voted as “Small Satellite of the Year”.

Note: as of spring 2016, the two missions of the LightSail program were renamed LightSail 1 and LightSail 2, but for consistency with the TVIW presentation the original project names have been retained here.

Summary

The LightSail program seeks to advance the state of the art in solar sailing technology by demonstrating that a sail may be deployed and controlled from the standard 3U CubeSat platform. The LightSail A test mission successfully demonstrated the solar sail deployment sequence. A number of technical issues were identified during pre-launch testing and mission operations that will be corrected for the follow-on LightSail B mission. LightSail B will complete the program technology demonstration objectives by controlling the solar sail and increasing the orbit apogee via solar radiation pressure, the first time that this will be accomplished from a CubeSat platform.

The LightSail program demonstrates technology that will enable future solar sailing missions, with applications spanning the inner and outer solar system, and potentially interstellar travel. NASA’s planned NEA Scout mission will utilize a solar sail to propel a spacecraft to a near-Earth asteroid in 2018. It is hoped that the LightSail program will provide a lasting benefit to the global space community, establishing solar sailing as a proven technique for spacecraft propulsion in achieving science and technology mission objectives.

Acknowledgements

The LightSail program has spanned over seven years, and is expected to continue for at least another two years. Many people and organizations have been directly involved with the technical execution of the program, still more have served in various supporting roles, and many thousands of others have provided support and contributions. It would be a significant challenge if not impossible to list them all. But certainly Executive Director Emeritus and Co-founder of The Planetary Society Lou Friedman deserves credit for keeping the vision of a solar sailing demonstration mission alive since 1976.

The experience with the NASA Marshall/NASA Ames NanoSail-D CubeSat program served as a worthy architectural precursor to LightSail. For LightSail, engineers at Stellar Exploration, Inc. managed to double the solar sail area and add active attitude control, cameras and other diagnostics while maintaining the 3U CubeSat form factor set by the NanoSail-D effort. NASA, Georgia Tech, and the USAF Space Test Program enabled the restart of the program by securing firm launch opportunities for LightSail A and LightSail B, respectively.

Staff and students at Cal Poly, Georgia Tech, Tyvak and SRI provided essential support during the LightSail 1 integration and testing effort, during several mission operations readiness tests and on console during mission operations. Helping everyone to understand what was happening with LightSail A during the mission, many amateur and serious astronomers and spacecraft observers around the world contributed analyses, predictions, received beacon packets, images and video clips for consideration. And thanks to Scott Wetzel, Dave Arnold and team from the International Laser Ranging Service (http://ilrs.gsfc.nasa.gov/index.html) for their efforts in laser ranging of LightSail A.

Management and staff at The Planetary Society encouraged the technical team to act quickly when the schedule was tight, and secured all funding for this work. They also did an admirable job of spreading the word about the program to conventional and social media before, during and after the LightSail A mission [3].

Finally, the core LightSail team thanks the ~40,000 members of The Planetary Society, key donors, and the 23,331 contributors to its LightSail Kickstarter campaign conducted during spring 2015. These interested and generous people actually funded these missions, and their support was essential.

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Interplanetary Exploration: Application of the Solar Sail and Falcon Heavy

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Interplanetary Exploration Using Solar Sail & Falcon Heavy

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INTRODUCTION: US OPTIONS FOR HUMAN SPACE EXPLORATION

Two approaches for the ~2020 launch of crewed interplanetary exploration vehicles are under development: the NASA Space Launch System (SLS) and the Space-X Falcon Heavy [1,2]. Although SLS has a greater interplanetary throw weight, politics and cost limit launch frequency. Falcon Heavy is based on the reliable Falcon 9 ; cost may be reduced by booster recovery.

This paper considers interplanetary ventures using a single Falcon Heavy and a 2-4 person crew. The spacecraft (s/c) consists of a Space-X Dragon V2 modified for interplanetary flight[3] and an inflatable Bigelow BEAM space habitat like the module recently launched to the International Space Station (ISS). Life support for the crew on their ~1-year venture will utilize oxygen and water recycling. Food recycling by biological means will likely not be ready by 2020.After the s/c is launched, a state-of-the-art $\approx 1 km^2$ solar photon sail will be unfurled. This will allow non-rocket accelerations of 1-2 km/s per month near Earth's solar orbit.

A recent study of in-space radiation effects reveals that galactic cosmic radiation beyond LEO is reduced by a factor of ~5 above LEO, if missions are conducted during solar maximum [5]. During solar flares and coronal plasma discharges, the crew could be protected by aligning the Dragon's heat shield between the crew quarters and the Sun.

Human Mars visits will be impossible using a single Falcon-Heavy launch. But many Near Earth Objects will be open to human explorers. But any human expedition beyond the Moon requires cruise durations of months to years. Cosmic radiation will be a limiting issue. The possibilities and effectiveness of using the capsule and habitat mass for self-shielding is discussed.

FALCON-HEAVY THROW MASS AND COSMIC-RAY SHIELDING

Falcon Heavy can project 13,200 kg towards Mars [2]. The dry mass of a Dragon V2 is 4,200 kg and this spacecraft can endure ~2 years in space. The BEAM module mass is 1360 kg [4].
The Dragon configuration can be approximated by a cone with a 3.7-m diameter and a 6.1-m height [3]. The BEAM can be approximated by a cylinder with a 3.2-m diameter and a 4-m length. Since the base of the Dragon abuts one of the circular end caps of the BEAM, it is easy to demonstrate that the surface area of the spacecraft is $\approx 100\ m^2$. If all the Falcon's throw mass is used for cosmic-ray self-shielding, the areal mass shielding thickness is $\approx 130\ kg/m^2$ ($\approx 13\ g/cm^2$).

Beyond Earth's magnetosphere, there are two sources of cosmic radiation. Eruptions of solar energetic particles (SEPs) usually occur during solar maximum; galactic cosmic rays (GCRs) are always present and are more intense during solar minimum. Figure 6 of Ref. 5 compares predicted Effective Dose Equivalent incurred by an astronaut from 4 SEP events: a 20-year event, a 10-year event, a worst-case modeled event and a Carrington-event. This data are plotted against aluminum shield thickness and compared with currently recommended European Space Agency (ESA) career dose limits. In all cases, a 13 g/cm^2 aluminum shield is adequate. Figure 7 of Ref. 5 presents similar information and compares predicted doses from the above SEP events with the 30-day and annual ESA limit. Once again, a 13 g/cm^2 aluminum shield seems adequate, although the Carrington-event dose rate is very close to the 30-day limit. Therefore, SEPs do not pose insurmountable health risks to crews venturing beyond LEO with an equivalent 13 g/cm^2 aluminum shield. Additional shielding could be affected by orienting the Dragon heat shield towards the Sun during an SEP event.

Galactic cosmic rays, pose a larger risk to the crew's health. Energetic galactic cosmic rays more massive than helium nuclei (high-Z GCR) are potentially dangerous to human health and very difficult to shield against [6]. Figure 1 of Ref. 5 reveals that during solar maximum, the modeled flux of galactic hydrogen and helium nuclei are reduced by a factor of 5-10 when compared with fluxes of the same ions during solar minimum. But the fluxes of galactic lithium and iron nuclei are apparently independent of the solar activity cycle. During an interplanetary transfer, the high-Z GCR dose might be 1-2 mSv per day or 0.4-0.8 Sv per year [7]. From Tables 1 and 2 of Ref. 5 the NASA one-year dose limits for 40-year old female and male astronauts are respectively 0.7 and 0.88 Sv. For older astronauts, the limits are higher. Dose limits for men are higher than dose limits for women. During a 1-year voyage, the dose limits for 40-year old astronauts may be exceeded. Exposures beyond these recommended limits may result in a 3% increased risk of fatal cancers. Health effects on interplanetary astronauts from high-Z galactic cosmic rays is an on-going field of research. Interplanetary voyagers will experience a higher galactic dose during solar minimum than during solar maximum. A thin aluminum shield of ~3 g/cm^2 may reduce solar minimum dose rates to the NASA LEO career limit of 50 cSv for a 1-year interplanetary round trip [8]. It should also be mentioned that it is not always possible to predict future GCR doses in interplanetary space from data obtained during previous solar cycles. Unusually high levels of GCRs were measured during a prolonged solar minimum in 2009 [9].

CREW LIFE SUPPORT

Mass requirements to support a 2-4 person crew during a ~1-year interplanetary expedition are now considered. From Wikipedia and a classic reference [10], daily average human metabolic requirements are summarized— oxygen: 0.84 kg, food: 0.62 kg, water: 3.52 kg. If partial recycling was not used, a 2-person crew could not be supported in the proposed s/c for missions of ~1-year duration. Projections ISS technology indicates that a near-term goal for water recycling is 85% and the oxygen recovery rate can be raised to 75% [11,12]. Applying these values for an interplanetary mission, the daily consumable requirement per astronaut is 0.21 kg oxygen, 0.62 kg food, and 0.53 kg of water. Each crew member consumes ≈ 1.4 kg per day of these resources or ≈ 500 kg per year. A 4-person crew therefore requires ≈ 2,000 kg of these resources for a 360-day duration interplanetary voyage.

The mass of Environmental Control and Life Support System (ECLSS) equipment, not including consumables, is now estimated. In Table 4.3 of Ref. 13, the mass of the water-recovery system for a 180-day transit to Mars is ~1,400 kg and the mass of the oxygen recovery system is ~500 kg for a 6-person crew. Since we have no idea regarding ECLSS reliability on a deep-space mission and we are assuming a ~1-year trip duration for a smaller crew, we assume that ECLSS equipment mass = 3,000 kg. Including O_2, food and H_2O, total ECLSS mass is ≈5,000 kg.

RESULTS: APPLICATION OF NEAR-TERM SOLAR- PHOTON SAILS

From the above discussion, the remaining s/c mass is ~2,640 kg. If ~640 kg are allowed for scientific equipment, the maximum sail mass is ~2,000 kg. For a 90% reflective (REF) opaque 1-km^2 sail with an areal mass density of 2 g/m^2, the areal mass density of the spacecraft (σ_{eff}) = 0.0132 kg/m^2. The lightness factor (β) of a solar-photon sail [(solar radiation-pressure acceleration)/ (solar gravitational acceleration)] can be calculated as 0.11 by modifying Eq. (4.19) of Ref.14 for a solar constant of 1,366) W/m^2:

$$\beta = 0.000768\left(\frac{1+REF}{\sigma_{eff}}\right) \quad . \qquad (1)$$

Near 1 Astronomical Unit (AU), the Sun's gravitational acceleration is ≈ 0.006 m/s^2, so the solar-radiation-pressure acceleration on the sail is ≈ 0.00066 m/s^2 for a sail oriented normal to the Sun. The sail can alter the s/c velocity by ≈1.6 km/s/month. At Mars's 1.52-AU solar distance, the sail can alter the s/c velocity by ≈0.69 km/s/month.

From Table 4.2 of Ref. 15, Hohmann Earth-Mars transfer duration is 259 days. Although the sail could reduce this a bit, an auxiliary propulsion system is required for Mars capture. Earth-Mars transit time for a sail with β = 0.1 and a sail pitch angle of ≈ 35 degrees is about 431 days [15].

The configuration presented here is therefore incapable of Martian exploration and is very marginal at best for exploration of Mars's satellites. A possible application is exploration of Near Earth Objects (NEOs) orbiting the Sun close to Earth's solar orbit. Suitable NEOs would be in near-circular, low-inclination solar orbits ≈ 1-AU from the Sun. The duration should be less than that required to reach Mars and Falcon-Heavy throw weight should be greater than that for a Mars mission. A NEO class of interest contains Earth's quasi-satellites in "corkscrew orbits [16].
A NASA on-line trajectory browser was accessed in May 2015 to investigate mission possibilities during the 2025-2026 solar maximum. Round-trip 360-day missions and 180-day one-way rendezvous missions were consideredThe results of this exercise are presented in Table 1. The destination NEO is Asteroid 2009. Physical data for this object was obtained from the NASA JPL data base.

Table 1. Details for a NEO Visit in 2025-2026.

Data Type	Specifications	Source

Object ID, Specs	SPK ID: 3457386 Name: 2009 HC Absolute Magnitude: 24.7 Size: 31-68 m	trajbrowser.arc.nasa.gov
Round-Trip Data	Earth Departure: 10/21/25 NEO Arrival: 1/9/26 Stay Time: 20 days Trip Duration: 350 days Injection delta-V: 3.74 km/s Post-Injection delta-V: 1.05 km/s Total delta-V: 4.79 km/s Reentry Speed: 11.44 km/s	trajbrowser.arc.nasa.gov
One-Way Rendezvous Data	Earth Departure: 10/20/25 NEO Arrival: 2/09/26 Rendezvous Duration: 112 days Injection delta-V: 3.72 km/s Post-injection delta-V: 0.26 km/s Total delta-V: 3.98 km/s	trajbrowser.arc.nasa.gov
NEO Parameters	Eccentricity: 0.12566 Semi-Major Axis: 1.0758 AU Perihelion: 0.9088 AU Inclination: 3.778 degrees Orbital Period: 1.06 years	ssd.jpl.nasa.gov

Pre-rendezvous propulsion requirements are assumed to be met by the Falcon upper stage Because of the low post-injection delta-V, the sail could achieve NEO rendezvous without greatly increasing mission duration. Note from Table 1 that post-injection delta-V for one-way and round-trip missions are very close. Use of the sail to power the Earth-return phase will therefore not significantly increase mission duration. Equation (5-74) of Ref. 15 can be used to calculate orbital-inclination “cranking”using the sail. Inclination correction for Earth-return will add no more than a few months to the mission duration.

If the NASA SLS is available to conduct NEO visits, the sail could serve at two additional functions. Since SLS has 2-3X the throw weight of Falcon Heavy, the sail provides a pre-rendezvous abort option or as a back-up Earth-return rocket propulsion. The sail could steer the BEAM into Earth orbit for reuse after the Dragon or Orion detaches for Earth atmosphere entry.

SUMMARY

A single-launch human NEO-exploration option using Falcon Heavy, Dragon, Beam and a solar-photon sail has been investigated. Crew life support and cosmic ray shielding for ~1-year voyages have been considered. At least one suitable NEO exists for an expedition of a 2-4 person crew in 2025-2026,

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Roadmap to Interstellar Flight

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Roadmap to Interstellar Flight

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We propose a roadmap that will lead to sending relativistic probes to the nearest stars and will open up a vast array of possibilities of flight, both within our solar system and far beyond. Recent advances in directed energy systems now allow what was only a decade ago simply science fiction. It is no longer. Spacecraft from fully-functional gram-level wafer-scale systems ("wafer sats") capable of speeds greater than ¼ c and that could reach the nearest star in less than 20 years to spacecraft for large missions capable of supporting human life with masses more than 10^5 kg (100 tons) that could reach speeds of greater than 1000 km/s. With this technology spacecraft can be propelled to speeds currently unimaginable with our existing propulsion technologies.
To do so requires a fundamental change in our thinking of both propulsion and our definition of what a spacecraft is. In addition to larger spacecraft, capable of transporting humans, we consider "wafer sats" that include integrated optical communications, optical systems, and sensors combined with directed energy propulsion. Since "at home" the costs can be amortized over a very large number of missions. In addition, the same photon driver can be used for planetary defense, beaming energy to distant spacecraft, sending power back to Earth as needed, stand-off composition analysis, long range laser communications, SETI searches, and even terraforming. This would be a profound voyage for humanity, one whose non-scientific implications would be enormous. It is time to begin this inevitable journey along the road beyond our home.

Radio Astronomy Adaptive Technology for the Interstellar Age

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Radio Astronomy Adaptive Technology for the Interstellar Age[2]

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ABSTRACT

Mission concepts for interstellar travel are being considered with the expectation that computer programs will apply an evolving response subject to unexpected communication and survival-related demands. Dealing with unanticipated changes in interstellar environment, interference from natural and other sources, and the possible detection of new forms of signal modulation in SETI (Search for Extraterrestrial Intelligence) requires a flexible, purpose-driven algorithmic structure. The basis for such thinking is traceable to discussions of "learning automata"[1] and this basis is already being applied to software designed to facilitate research in Radio Astronomy with an eye toward eventual generalized Interstellar applicability[2]. The algorithmic process of minimizing nested objective functions, and the biological process of evolving a new organism in a complex environment, are analogous[3]. The goal is an Algorithm Defined Receiver (ADR).

The authors have developed the first low-cost Radio Astronomy Software-Defined Receiver (RASDR), and it's software[4] incorporates elements of learning automata -- an Algorithm-Defined Receiver(ADR). RASDR has been implemented in stages, all supported by evolving software[4]. The initial "suitcase SDR" was a single unit. Production of RASDR2 consisted of 7 units, which were widely circulated and applied[5].

The latest RASDR design, RASDR4 is based on LimeSDR USB v1.2 board [6] and has on the order of twice the bandwidth and twice number of receiver modules of RASDR2.

Introduction

Radio communication is the transfer of information between complimentary instruments (transmitter and receiver). The design of these instruments has been an engineering process that balances required information decoding and transfer rate vs. system complexity and cost. The transmitter must provide sufficient power while its antenna provides sufficient directionality and gain. The receiver antenna must be engineered with similar considerations (excepting power-handling capability) to that of the transmitter antenna. Furthermore, the receiver must provide sufficient sensitivity, selectivity, and noise rejection. The receiver, from the information-handling perspective, has more often been the more complex instrument. It

[2] This is the extended abstract for the poster presented on Feb. 28, 2016 at the Tennessee Valley Interstellar Workshop, Chattanooga, TN.

must detect and demodulate the signal, reject interference, and convert the signal to a form appreciated as data.

The twentieth century saw the evolution of HDR (Hardware Defined Receivers), with implications for discrete component capability and signal complexity. The twenty-first century will see a major shift in engineered design focus from HDR to SDR (Software-Defined Receivers).

This paper chart the motivation and beginnings of the algorithm defined receiver (ADR) which will be necessary for successful interstellar exploration. The requirements of interstellar travel missions do not currently drive ADR development. This development is already underway in well-funded military and economic circles. Also included is a brief discussion of driving forces for development of a relatively simple SDR (RASDR).

Advent of digital processing

Signal processing in the analog domain uses circuit components having function defined by hardware design. The components function together to implement analog approximations of precise mathematical functions. By contrast, signal processing in the digital domain (software), uses more precisely-defined mathematical functions. Thus digital signal processing has a rigorous theoretical foundation that is coded in software and applied in a more robust fashion.

In the last two decades of the twentieth century, demodulation and limited processing functions moved into the digital domain, as microprocessors were used to process the signals. Digital Signal Processing (DSP) was the first mathematical manipulation of signals to modify or improve the received data. Digital filtering involved linear transformations of the signal, while Fourier transforms permitted transformation of received signal from the time-domain (a series of analogue values or pulses) to the digital-domain (a representation of signal power vs. frequency). Functions that may be simulated in SDR software includes detection, mixing, amplifying, and demodulating -- plus higher-level functions that include alerting, decision-making, component selection, and more complex system response.

Ascendency of software-defined receivers (SDR) over HDR

The situation a the end of the twentieth century was that hardware devices were being produced with the momentum of assured performance and a robust manufacturing industry – but that the flexibility that would be accrued by a software defined receiver (in which functions were defined by digital algorithms) was obvious. The cost curve was to the benefit of Software Defined Receivers (SDR).

The earlier in the signal stream that the analog to digital conversion occurs, the earlier can be applied the flexibility and precision offered by digital processing.

Digital procession had the firm foundations of Information Theory giants such as Nyquist, Shannon, and Whittaker. Digital processing of a frequency F was only possible with sampling at a frequency 2F. Thus SDR was also driven by the availability of high-speed sampling hardware and high-speed processing. SDR was only possible with the advent of fast computers, and SDR availability and applications have closely tracked the development of high-speed back-end processors.

SDR frontiers in radio astronomy

Software Designed Receivers are an important part of radio astronomy research, and are implemented and applied at most radio astronomy research sites. SDR is also applied at smaller sites by individuals interested in developing and applying new techniques. One early application[7] used modified, public-domain software.

Probably the most advanced area in this regard is correlation software for very long baseline interferometry (VLBI). Previous to about 2005 virtually all VLBI observations were recorded to tape or disk at the antenna, then the various media were gathered in a central location where a custom-designed hardware correlator would process the various signals. Limitations of the hardware translated into limited bandwidth for the observations and hence limited sensitivity. Moreover, multiple correlations were prohibitively expensive because they took up too much of the scarce hardware correlator time.

Since about 2005 the VLBI community has rapidly abandoned hardware correlators as software equivalents have become available. Although the media (or at least the raw data) must still be gathered together on one computer, the specialized correlation hardware is no longer necessary.

Correlations are now performed directly on the computer using special purpose (i.e., highly efficient) software. This has permitted wider bandwidths (and hence greater sensitivity) and multiple correlations (and hence the ability to image different fields of view after the fact).

Moreover, because additional CPU power is mostly a matter of money and Moore's law, the same software can provide greater throughput if more CPUs are purchased and as they become more powerful with time. Hardware correlators are not so easily scaled-up, and remain static until they are so obsolete that they limit performance of the observing system[8].

Design/construction of an SDR that is optimized for radio astronomy

A design team of amateur radio astronomers are designing and building a Software Defined Radio (RASDR) that is optimized for Radio Astronomy. The equipment costs are partially supported by the Society of Amateur Radio Astronomers (SARA). RASDR has the potential to be a common digital receiver interface that is useful in many applications Unfortunately, existing SDR products are some combination of expensive, difficult to use, or optimized for the communications market. Consequently, they lack many capabilities useful for radio astronomy.

RASDR progress is being tracked in SARA Journals, on the SARA website[3], on the RASDR Yahoo group[4], and on Sourceforge[5].

Applicable to a wide variety of SARA projects, RASDR includes an analog RF front end with a digital computer interface via a universal serial bus (USB). A user supplies the computer for which software is available to complete the receiver function [9][10]. The analog front end uses a computer chip, LMS6002D [11][12] or the LMS7002M[13] that contains the entire RF receiver chain. The user's computer [14] controls the hardware and affects the receiver functions, displays signals and performs analysis functions (averaging, computation of spectrograms, determination of power time-spectrum, and producing output files). This design addresses the need to have the widest possible signal capture bandwidth as well as the highest flexibility in spectrum analysis for radio astronomy applications.

Several updates of the User Manual have been published and shared at SARA meetings. RASDR2 has been used to monitor L-band (H1 frequency) and wide portions of the HF, VHF and UHF bands[15], detect hydrogen H1 spectra, record continuum data from celestial sources, and serve as a laboratory instrument.

The RASDR project is in transition. Two RASDR approaches were discussed[16] at the SARA 2016 meeting. Work is continuing on RASDR2 software and a possible RASDR3 design. Radio Astronomy software for RASDR2 has profited from three years development beyond the FFTviewer software obtained from Lime Microsystems. RASDR2 hardware and software options are discussed here[17].

An upgraded SDR, RASDR4, will be available at the end of 2016. The RASDR4 approach employs LimeSDR, a more advanced design with two Rx-Tx sections and increased bandwidth that includes a more powerful electronics package. The RASDR4 design appears to provide significant cost savings, a full RF spectrum capability covering 0.1-3200MHz, and additional hardware functions. The additional hardware functions include on-chip decimation that allows over sampling for noise improvement and a register controlled mixer that allows the lower input frequencies. Radio Astronomy software for RASDR4, is being developed from core LimeSuite software[18] that controls the LimeSDR board for several operating systems, including Win OS. The LimeSDR USB v1.2 board, the basis for RASDR4, is available for order with shipment from the manufacturer starting November 30th. Further information on the ordering can be obtained here.[6]

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[3] www.radio-astronomy.org

[4] rasdr@yahoogroups.com

[5] http://sourceforge.net/scm/?type=svn&group_id=537344 and https://rf-sampler.svn.sourceforge.net/svnroot/rf-sampler/trunk/data/.

Goal-driven algorithmic software: military and monetary incentives

Goal-driven software are making the first inroads in business and military arenas. Driving the competition for successful algorithms are financial success, military conquest, and lucrative prizes.

Key financial algorithms predict commercial success, or stay microseconds ahead of the Wall Street competition. For example, Epagogix is a UK-based company founded in 2003 that uses neural networks and analytical software to predict which screenplays or movies will provide a good possibility of return on investments.[19]. Algo-Trading is rampart, with over 80% of market trade entries based on computer-generated trades, but these are not, except for the trading practices designated ‘high frequency trading’ using evolving algorithms of the sort considered in this article.

As to military interest, one of several approaches to algorithmic approaches already being used in receiver design is "AMR" Automatic Modulation Recognition (AMR), which has received strong military support. [20].

Prize-driven algorithm developments come from various sources. For example, on September 21, 2009, BellKor's Pragmatic Chaos algorithm was announced as the winner of the $1M Netflix Prize at a ceremony in New York City. The evolving Pragmatic Chaos algorithms provided more than a sustainable 10% improvement over previous strategies. The 2012 Nobel prize in Economics was awarded for development of algorithms *"for the theory of stable allocations and the practice of market design"*[21]. Algorithms in the health field are exemplified by the Heritage $3M Health Prize for algorithms to identify future hospital admissions based on patient history.[22].

Finally a prize-driven algorithm development prize with direct relevance to ADR is the DARPA Spectrum Prize[23][24] in which the challenges are as follows:

- Can you and your team program a radio to dominate the spectrum?
- Can you engineer software-based radios that transmit data faster than a competitor using identical hardware?

Winners received $200,000 in monetary awards[25].

Even in the realm of law enforcement, algorithmic approaches are being developed at Stanford and other institutions[26] and discussed at the Stanford “We, Robot” conference [27].

The algorithmic approach in SDR (or ADR)

Software that optimizes I/Q balance is implemented in current SDR software[28]. These algorithms converge to values for optimal parameters (for dc offset values and good image rejection), and can be validated by observing the I/Q phase relationships in the data stream[29]. The software coding is not modified, but parameter values are optimized, thus improving the receiver operation under computer control.

Algorithmic design concepts for large information processing tasks (not yet applied to ADR) are implicit in recent DARPA initiatives, including Stanford-research based Ayasdi. Ayasdi's Topological Data Analysis approach[30] was considered one of the top 10 innovations developed at *DARPA* in the last decade. Additional support is being received from the FDA, USDA, and Merck. Topographic Data Analysis is purely algorithm based, and for large data bases is judged far faster than existing approaches using business or mathematics software.

In addition, DARPA is stimulated receiver design by offering radio data encoding/extraction prizes, as indicated above[23].

Algorithm Defined Receiver concepts are already on the design board, although applications developments for the demanding and novel demands of interstellar missions have apparently not yet been undertaken.

Importance of an Algorithm Defined Receiver (ADR) to interstellar travel and SETI

The communications demands of an interstellar mission will merge in purpose and control with conventional data collection, mission implementation and control systems. ADR will include the following:

- Detection of new and novel data[2][31]
- Selection/Evolution of receiving algorithm (modulation and decoding)
- Optimizing demodulation/decoding algorithms
- Extraction of information contained in received data stream
- Interpretation of information
- Identification of critical actionable items (Alerts, IFF)
- Inversion of ADR parameters and other information for transmitter control (antenna, power, modulation, cloaking)
- Tactical mission modification

These demands mitigate an evolving algorithmic approach to receiver design that is totally beyond the capability of static hardware designs and in fact, lies outside the framework of modern software defined receivers.

Conclusion and Synthesis

Challenges of interstellar travel will far exceed the demands for communication using HDR and SDR receivers. Even for short interstellar hops, it is probable that current approaches will prove inadequate.

Providing starships with robotic, goal-seeking algorithmic receivers (and transmitters) that without human intervention will spawn and adjust evolving system capabilities to permit continuing communications between a starship and home planet, reject undesired interference, and discover/enhance novel and valuable signals, is a first step in providing algorithmic mission control. SETI activities are a corollary function that arises from the need to communicate and survive.

HDR was the hardware-based receiver technology of the 20 century. In the first quartile of the 21th century, with evolving SDR design principles, we are reaching the first stage of algorithmic receivers. This is the first of the Algorithm Defined Receivers that may take us to the stars.

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Toward a Visionary Interstellar Worldview

Thanks again to the authors, who generously contributed extended abstracts of their presentations.

We hope that you have enjoyed the Proceedings of TVIW 2016, and that you will join us as we plot a course to an Interstellar future. Please visit our 2017 Symposium web site at http://tviw.us and our future Organizational web site at http://tviw.space