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PROSPECTS FOR INTERSTELLAR PROPULSION

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In recognition of the increasing prospects for Earth-like exoplanet discoveries and its significance for spurring future interstellar voyages of discovery, the United States Congress recently directed NASA to undertake an interstellar mission technology assessment report.[‡] In response to this legislative charge to action, NASA has undertaken a series of extramural interstellar workshops aimed at identifying and evaluating technology concepts for enabling an interstellar scientific probe mission, associated technical challenges, technology readiness level assessments, risks, potential near-term milestones, and funding requirements. This paper summarizes these activities and discusses the scientific and technical rationale for a long-term program consisting of incremental, staged technical developments that are extensible for interstellar travel to a nearby star system over many decades.

INTRODUCTION

The accelerating pace of exoplanet discovery is significantly increasing the prospects for detecting Earth-like planets in nearby star systems. The implications of such discoveries are profound, and NASA is actively pursuing the development of improved detection and characterization technology for future space-based observatories. Moreover, the identification of the atmospheric chemical signatures associated with life on planets around other stars could spur the interest and the international cooperation needed to realize the vision of interstellar scientific missions.

The challenges associated with interstellar travel are truly immense, however, and an obvious question is whether practical interstellar travel is even possible based on conceivable technologies. The answer to this question turns on critical challenges associated with distance/time scales to even the nearest stars, as illustrated in Figure 1, as well as the hostility of the interstellar environment. Most imperative is the ability to traverse interstellar gulfs of 4.5-20 lightyears within a time span dictated by system reliability, but also with reasonable payloads to ensure relevant observations of the target, and communications of those observations back to Earth, or to a relay.

The distance scales and energy requirements for practical interplanetary missions are truly staggering. For example, Pluto is 4.28 billion kilometers from Earth at its closest approach to the sun, and the closest star system, Alpha Centauri, is about 10,000 times farther away. Even if a

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[‡] House Report 114-605, accompanying H.R. 5393, the FY 2017 Commerce, Justice, Science, and Related Agencies appropriations bill.

spacecraft was 100% efficient in converting an energy source into propulsion, the energy required to accelerate even one kilogram – about the mass of the smallest (1U) cubesat – to one-tenth of the speed of light (0.1*c*, or about 30,000 kilometers per second) is about 450 trillion joules. Accelerating a spacecraft the size of the 720-kilogram *Voyager* probes (one of which is the only spacecraft verified to have left our solar system and entered interstellar space) to 0.1*c* would require 720 times more energy, which is an amount equivalent to an appreciable fraction (about 0.06%) of the entire world energy output for one year. The demands of decelerating prior to reaching the intended target would increase the energy requirement by as much as a factor of two.

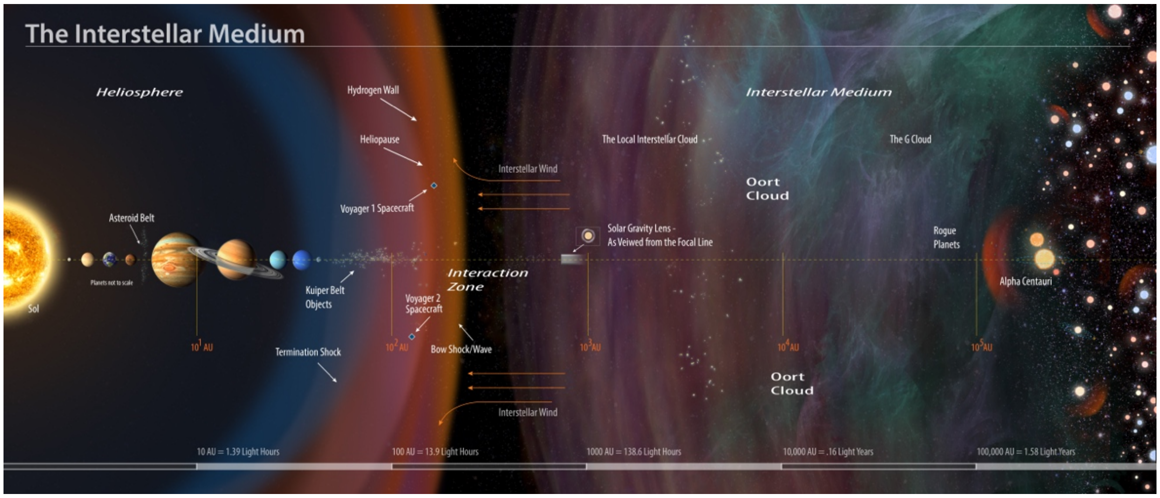

Figure 1. Conceptual depiction of the solar system and interstellar objects on a logarithmic distance scale. Interstellar medium missions would reach beyond the heliosphere to study the local interaction zone and the unperturbed deep space environment beyond. Interstellar missions would reach nearby star systems, such as Alpha Centauri.

The distance scales and energy requirements for practical interplanetary missions are truly staggering. For example, Pluto is 4.28 billion kilometers from Earth at its closest approach to the sun, and the closest star system, Alpha Centauri, is about 10,000 times farther away. Even if a spacecraft was 100% efficient in converting an energy source into propulsion, the energy required to accelerate even one kilogram – about the mass of the smallest (1U) cubesat – to one-tenth of the speed of light (0.1*c*, or about 30,000 kilometers per second) is about 450 trillion joules. Accelerating a spacecraft the size of the 720-kilogram *Voyager* probes (one of which is the only spacecraft verified to have left our solar system and entered interstellar space) to 0.1*c* would require 720 times more energy, which is an amount equivalent to an appreciable fraction (about 0.06%) of the entire world energy output for one year. The demands of decelerating prior to reaching the intended target would increase the energy requirement by as much as a factor of two.

Meeting the propulsive energy requirements for relativistic flight is a daunting challenge in itself, but huge technology advancements would also be needed for a variety of spacecraft functions. For instance, communication time delays measured in years preclude ground-controlled operations, and all spacecraft subsystems – propulsion, power, thermal control, communications, attitude determination and control, command and data handling, fault management, and scientific instrument payload – would need to be fully autonomous. Not only would the spacecraft need to identify, isolate, and recover from faults without any operator intervention, but it must navigate and survive an adverse interstellar environment, including hypervelocity dust impacts at extraordinarily high spacecraft speeds and, upon arrival, autonomously rendezvous with the target star system and relay collected scientific data back to

Earth. Ensuring mission reliability and continuous support across multiple generations will demand a radical transformational approach to both spacecraft design and engineering and mission operations.

In recognition of the rapidly increasing prospects for Earth-like exoplanet discoveries and broadened societal interest, the United States Congress recently directed NASA to undertake an interstellar mission technology assessment report pursuant to House Report 114-605, accompanying H.R. 5393, the FY 2017 Commerce, Justice, Science, and Related Agencies appropriations bill. In directing NASA to provide a technology assessment report for an interstellar propulsion system, Congress recognized the audaciousness of the task by suggesting a long-term guiding mission objective of launching a scientific interstellar probe mission to Alpha Centauri by the year 2069 in commemoration of the one-hundredth anniversary of the Apollo-11 moon landing.

In response to this legislative charge to action, NASA has undertaken a series of extramural interstellar workshops aimed at identifying and evaluating technology concepts for enabling an interstellar scientific probe mission, associated technical challenges, technology readiness level assessments, risks, potential near-term milestones, and funding requirements. This paper summarizes these activities and discusses the scientific and technical rationale for a long-term program consisting of incremental, staged technical developments that are extensible for interstellar travel to a nearby star system over many decades.

The suggested approach is to create an evolvable technology infrastructure that will, step-by-step, build confidence and make steady continual progress toward spacecraft velocity exceeding 10% of the speed of light. Along the way, it is also imperative that we gain a better understanding of the interstellar medium near our own solar system as well as the deep interstellar gulfs between stars. As such, we suggest a series of phased science goals and missions that will support the incremental development of interstellar propulsion technologies, spacecraft subsystems, and the operational experience needed to mount a fully integrated scientific probe to nearby stars.

ADVANCED IN-SPACE PROPULSION TECHNOLOGY OPTIONS

Penetrating the heliosphere and traversing the vast distances between star systems will require revolutionary advancements in spacecraft propulsion. Conventional technologies leveraging Jupiter Gravity Assists (JGA) and/or close solar perihelion propulsive Oberth maneuvers are limited to terminal spacecraft velocities of no more than 15 – 20 AU/yr at best whereas a 40-year one-way interstellar flyby mission to the nearest stars will require a relativistic spacecraft speed in excess of 6000 AU/yr (i.e., $\approx 0.1c$).

As a means of assessing the interstellar mission capability of conceivable propulsion system concepts, it is useful to compare characteristic propellant utilization efficiency (i.e., the specific impulse) versus achievable spacecraft acceleration (i.e., thrust-to-weight ratio), as shown in Figure 2. Depending on the achievable performance characteristics of a particular concept family, it is possible to deduce its applicability for various types of missions. For example, large-scale exploration class missions point to the need for high thrust-to-weight technology solutions that lie on the right-hand side of the graph at the expense of decreased propellant utilization efficiency. Technologies within this domain typically include chemical rockets and nuclear thermal fission. On the other hand, smaller robotic science missions within the solar system are less constrained by transit time requirements and therefore more amenable to solutions on the left-hand side of the graph where propellant utilization efficiency is higher at the expense of reduced spacecraft acceleration. Technologies within this domain commonly include solar electric powered electrostatic and electromagnetic thrusters.

Of the propulsion technologies that either exist or have firmly established technical feasibility, none are capable of achieving relativistic spacecraft velocities and are unsuitable for realistic interstellar missions. The historical record for spacecraft velocity extremes includes Helios-2 (1976) at 0.024% c and Parker Solar Probe (2018) at 0.067% c, both of which relied upon chemical propulsion technology. Today's chemical rockets could certainly place a spacecraft on an interstellar trajectory, but the trip time to the nearest star would take approximately seventy thousand years. Highly efficient electric thrusters, such as ion and Hall thrusters, or even the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) would still require many tens of thousands of years to make the voyage when coupled with large nuclear fission space power sources. Clearly, mission times of this magnitude are nonviable and fall far short of the interstellar mission goal.

In order to achieve realistic interstellar flight, we are therefore forced to consider advanced propulsion concepts with the potential of yielding both extremely high specific impulse and high spacecraft acceleration. Based on the inherent physics underlying the rocket equation, which governs the ultimate performance of any rocket-based propulsion system that consumes onboard propellant, the Isp required for achieving 0.1c is approximately 400,000 seconds, as indicated by the dark horizontal line on Figure 2. Only propulsion technology solutions that lie in the green shaded region above the line are potentially capable of supporting the desired flight regime.

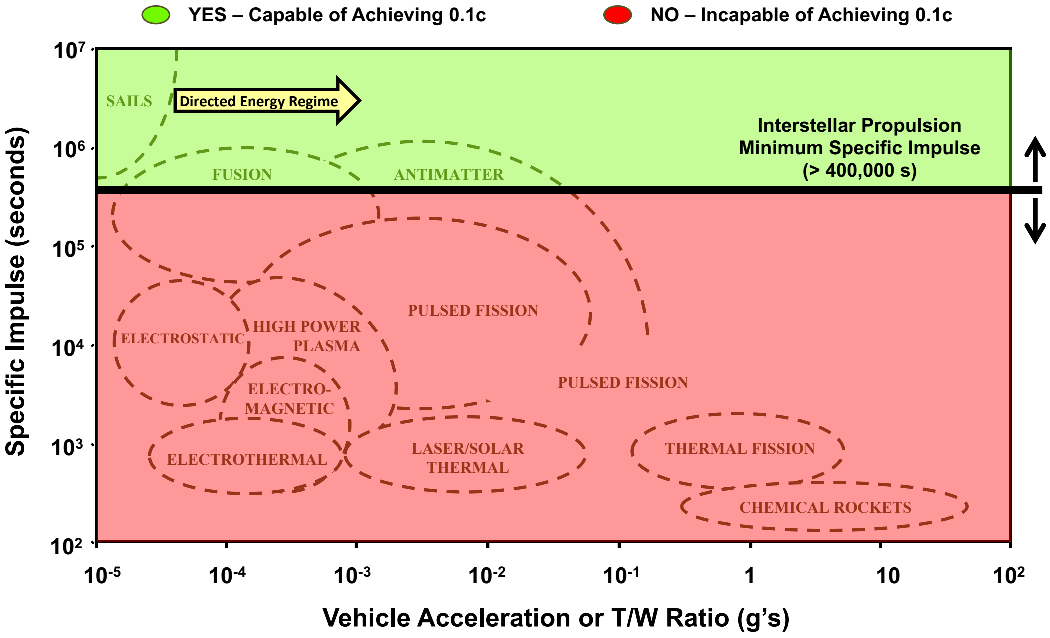

Figure 2. Landscape of known in-space propulsion technologies depicting characteristic propellant utilization efficiency (i.e., the specific impulse) versus achievable spacecraft acceleration (i.e., thrust-to-weight ratio). Interstellar missions will need both values to be as high as possible. The horizontal line at a specific impulse of 400,000 seconds represents the minimum value needed for interstellar flyby missions at 0.1*c* for concepts utilizing on-board propellants.

Various candidate advanced propulsion technologies are listed in Table 1, which contains a brief concept description, an evaluation of the concept's relative technical maturity as measured on the Technology Readiness Level (TRL) scale, and an assessment of theoretical applicability for interstellar flight regimes. From a perusal of Figure 2 and Table 1, it may be readily surmised that the only viable propulsion technologies relevant for relativistic flight include nuclear fusion, antimatter annihilation, directed energy sails, or a hybrid combination thereof. Various forms of these concepts have been proposed and analyzed for a variety of mission classes, and some of the major considerations and development challenges related specifically to interstellar missions are highlighted in the subsections below.

Table 1. Candidate Interstellar Propulsion Technology Concepts.

Concept	TRL	Description	Applicability
Chemical Propulsion	9	Chemical reaction driven thermal propulsion (Isp < 500 s & T/W or $a_c \approx 1\text{-}10^2$ g’s)	Not Applicable (energy density limited)
Solar Photon Sail Propulsion	≤ 4	Thrust production by solar photon pressure momentum exchange with thin, large-area, low-mass reflective sail material (Isp $\rightarrow \infty$ & T/W or $a_c \approx 10^{-5}\text{-}10^{-4}$ g’s)	Not Applicable to Interstellar Missions Applicable to ISM Missions (characteristic acceleration limited)
Solar Electric Propulsion	9	Electric thrusters driven by solar power (Isp < 10^5 s & T/W or $a_c \approx 10^{-4}$ g’s)	Not Applicable (solar power range limited)
Nuclear Electric Propulsion	≤ 2	Electric thrusters driven by fission power (Isp < 10^5 s & T/W or $a_c \approx 10^{-2}$ g’s)	Not Applicable to Interstellar Missions Applicable to ISM Missions (energy density limited)
Nuclear Thermal Propulsion	≤ 4	Nuclear fission driven thermal propulsion (Isp < 10^3 s & T/W or $a_c \approx 1\text{-}5$ g’s)	Not Applicable to Interstellar Missions Applicable to ISM Missions (energy density limited)
Nuclear Fusion Propulsion	≤ 2	Nuclear fusion driven thermal propulsion (Isp < 10^5 s & T/W or $a_c < 10^{-5}\text{-}10^{-3}$ g’s)	Applicable
Antimatter Annihilation Propulsion	≤ 2	Antimatter annihilation driven propulsion (Isp < 10^6 s & T/W or $a_c < 10^{-3}\text{-}10^{-2}$ g’s)	Applicable
Directed Energy Photon/Particle Propulsion	≤ 2	Directed energy driven sail (Isp $\rightarrow \infty$ & T/W or a_c is power scalable)	Applicable

Nuclear Fusion Propulsion

Fusion propulsion has been extensively studied over the past few decades, with potential applicability to a wide range of mission concepts in the solar system and beyond. It has the potential to be enabling for fast transit planetary science and exploration missions, as well as interstellar precursor missions and actual interstellar travel. The latter is facilitated by utilizing fusion reaction products directly to produce thrust, eliminating the inherent conversion inefficiencies of generating electrical power or transferring energy to a working fluid. The most prominent obstacle to implementation is that, despite several decades of heavily funded fusion energy research, development, and facilities construction around the world, a controlled fusion reaction that yields more energy than is required to sustain it has not yet been achieved. There are multiple distinct approaches to controlled fusion reactions, categorized according to the method of confining the plasma of free electrons and nuclei within a limited space at temperatures on the order of 100 million degrees Celsius

In stars, confinement and plasma ignition is achieved through their enormous gravity, but in the laboratory, there are a variety of approaches being pursued. A wide variety of fusion propulsion concepts exist, which can be categorized as either magnetic confinement fusion (MCF), inertial confinement fusion (ICF), magneto-inertial fusion (MIF), or inertial electrostatic confinement (IEC). It should also be noted that fission-fusion hybrids offer an incremental development path towards pure fusion propulsion. In any case, utility for space transportation applications requires highly compact system implementations posing formidable developmental challenges.

MCF uses strong large volume magnetic fields to hold and stabilize a relatively low-density, long-lifetime plasma, which points to very large-scale confinement structures and poor system compactness attributes. ICF, by contrast, uses exceptionally powerful lasers for extremely rapid (nanosecond time scale) compression of a fuel target to provide a short burst of energy, which points to very large-scale compression energy drivers and similarly poor system compactness attributes. MIF is a hybrid of these two approaches using magnetic fields to confine a medium density plasma that is compressed to fusion conditions over microseconds, which relaxes confinement and driver extremes and offers superior system compactness. IEC is a fourth variant using the inertia of recirculating ions in an electrostatic potential to confine the plasma, which is compact in principle but entails enormous scientific challenges.

Achieving high gain controlled fusion conditions that release one or two orders of magnitude more energy than is consumed in sustaining it, by a method that is suitable for implementation on a spacecraft, is a monumental technical challenge. Other challenges include thermal management and related materials considerations; power generation, transfer, and storage; and efficient conversion of the energy released to propulsive thrust. Additionally, a fusion-powered interstellar spacecraft would likely be quite massive and complex, so space robotic manufacturing and assembly technologies and capabilities would need to progress to the point where much of the spacecraft can be constructed on orbit.

A plan of research and development to establish the feasibility of nuclear fusion propulsion may include laboratory-scale development of system components needed to achieve fusion burn, followed by laboratory fusion experiments showing a sufficient balance of confinement time, density, and temperature to achieve net energy gain. Technology maturation could involve a subscale demonstration of thrust and high specific impulse (> 100,000 s).

Antimatter Annihilation Propulsion

Antimatter is the material composed of antiparticles that correspond to the particles of ordinary matter. A particle and its antiparticle (for example, a proton and an antiproton) have the same mass but opposite electric charge (and other differences in quantum numbers). The interaction of matter and antimatter results in mutual annihilation, producing some combination of very high energy photons (gamma rays), pi mesons, neutrinos, and less-massive particle-antiparticle pairs, depending on the particular species of matter and antimatter. The ideal energy density of the antimatter annihilation reaction is the highest of any known physical process, two orders of magnitude higher than that nuclear fusion and three orders of magnitude higher than nuclear fission, so it is particularly tantalizing as a means of achieving spacecraft speeds that are a significant fraction of the speed of light.

The proton-antiproton annihilation reaction is the most commonly discussed variant for propulsion applications, where the antimatter is stored as antihydrogen atoms (an antiproton coupled with a positron) in order to overcome the limitations of charged particle (negatively charged antiproton) storage density. Near term applications could use small quantities of antimatter to catalyze fission and/or fusion reactions for fusion propulsion. Extremely large quantities of antimatter would be needed for direct antimatter annihilation propulsion and the highest specific impulse.

Whereas antimatter is produced by cosmic rays and can be found in small quantities in space, on Earth it must be synthesized in particle accelerators. At best, antiprotons can currently be produced at a rate of about 10 million per minute, which is only about 10 picogram per year. Under those circumstances, it would take about 100 billion years to produce even one gram of antiprotons. Concept studies suitable for interstellar propulsion utilize between tens of grams and tens of kilograms of antihydrogen. Obviously, increasing the production rate of antiprotons is an enormous technical challenge for implementation of antimatter propulsion. The cost of antimatter production is also unacceptably high, but that situation may improve in tandem with increases in the production rate.

Long-term storage of significant quantities of antimatter may be as daunting a challenge as production. Antihydrogen can be stored in a magnetic trap, but it had never been accomplished until 2010, and to date only a few hundred antihydrogen atoms have been trapped for durations of no more than a few tens of minutes. To be viable as the basis for interstellar propulsion, the stored quantity must increase by 23 orders of magnitude (from a few hundred particles to a few hundred grams) and the storage time must increase by 6 or 7 orders of magnitude (from minutes to decades). It may be possible to dramatically increase the storage capability by condensing antihydrogen molecules into a liquid or solid, but that also represents a very large technical challenge, along with transporting stored antimatter from the point of production to the launch site.

Other major challenges include analogues to those for fusion propulsion, such as thermal management and related materials considerations; power generation, transfer, and storage; efficient conversion of the energy released to propulsive thrust; and on-orbit construction of a large and complex spacecraft. A research and development plan to establish the feasibility of antimatter propulsion may include laboratory experiments aimed at efficient production and storage of antimatter, as well as demonstrating controlled annihilation and concepts for efficient propulsive thrust. Technology maturation may involve a design study for an antimatter mass production facility; storing and transporting larger quantities of antihydrogen; and using antihydrogen in subscale annihilation experiments that produce thrust and high specific impulse (greater than 100,000 s).

Directed Energy Propulsion

Photon sails use light to propel spacecraft by imposing radiation pressure on a large sheet made of thin, lightweight, highly reflective material where the reflected photons transfer momentum to the sail. All objects in space experience radiation pressure from the sun, and trajectories must correct for its effect or spacecraft will drift off course. The few photon sails that have flown or are scheduled to fly in the near term all rely on sunlight for propulsion, and in principle, a sufficiently large solar sail could accelerate to an appreciable fraction of the speed of light. However, the intensity of solar radiation follows an inverse square law with distance, so the sail would have to be immense (10-100 square kilometers) as well as extraordinarily lightweight (very low areal density) to achieve the required coast speed during the early portion of the mission, when it experiences a significant effect from solar photons. Consequently, solar sail propulsion may be best suited to missions within the solar system, and possibly interstellar precursor missions.

A more versatile derived approach would employ directed energy photons (e.g., laser or microwave) or particles rather than solar photons, where the receiving sail must be sufficiently large to account for increasing beam divergence with distance from the source. In recent years, an alternative beamed photon sail propulsion approach has received significant research and analysis attention due largely to a $100 million private equity commitment called Breakthrough Starshot. Their goal is to perform a flight demonstration of ultra-light unmanned spacecraft at 0.2c, laying the foundations for a flyby mission to the Alpha Centauri system within a generation. Their approach centers around avoiding issues associated with laser beam divergence and extremely large sails by performing all of the acceleration very early in the mission, in as little as a few tens of minutes. This places radically different requirements on the sail, which may only measure a few square meters: It must be able to reflect or dissipate gigawatts of power through extremely high reflectivity or other means, and it must be able to withstand accelerations of about 60,000 times the gravity of Earth (60,000 *g*). A stated intention has been to fly a large fleet of very small (possibly 10s of grams) payloads.

A critical technical challenge for any directed energy propulsion implementation is the development of scalable, high-power, large-aperture laser/microwave/particle beam sources including technologies enabling stringent beam divergence, pointing accuracy, and jitter control requirements. Other major challenges include very low areal-density, ultra-low absorption sail metamaterials; managing large-scale structural dynamics; meeting spacecraft guidance and flight dynamics requirements; and on-orbit construction.

Because the sail technology area has attracted notable attention in recent years, high-level roadmaps have already been laid out by Breakthrough Starshot, NASA, and others. Figure 3 depicts the progression of large sail implementatons from previous and current missions to interstellar precursors and potentially even interstellar missions, listing the advances needed in deployed sail size and areal density at each step in the progression.

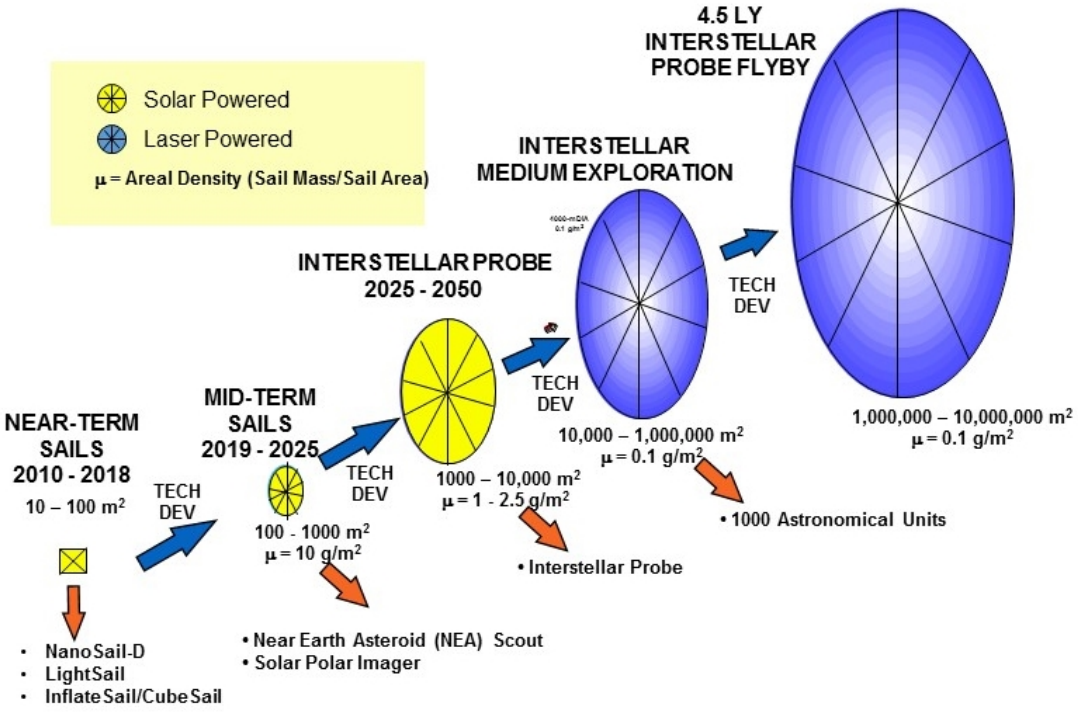

Figure 3. Past and current solar sail demonstration missions are important stepping stones toward advancing key photon sail propulsion technologies. Near Earth Asteroid Scout will launch on Exploration Mission-1, planned for 2020. To achieve missions beyond the solar system, a progression of increasingly capable demonstration missions would target increasing sail area and decreasing areal density by an order of magnitude over the previous step. A transition from solar photon to beamed energy photons would be required to enable the most ambitious photon sail missions.

Breakthrough Propulsion Science

The conceptual roadmap includes the evaluation of breakthrough propulsion concepts. Whereas this report has identified three candidate propulsion technologies that may ultimately permit interstellar travel at 0.1*c* or greater, established physics places severe constraints on the acceleration of large mass to relativistic speeds. As such, the investigation of breakthrough concepts based on credible new physics that could enable interstellar flight is relevant. Researchers continue to pursue foundational studies of gravitation, inertia, and vacuum energy, and a breakthrough discovery with technological implications remains a distinct if remote possibility. Therefore, a complete interstellar technology development roadmap should include consideration of breakthrough concept feasibility studies and laboratory evaluations.

ADDITIONAL INTERSTELLAR MISSION KNOWLEDGE GAPS

Determining the Target

Before a robotic spacecraft can embark on a long journey to an exoplanet, one needs to image such an exoplanet at high resolution. That is, not only on a single pixel level, but at resolutions of 1000x1000 pixels. The key is to determine that the exoplanet is a target worth visiting based on multiple imaged data including visible and multi-spectral. One has to make sure it is not veiled like Venus but worth visiting based on detailed information at the continental level; weather reports; multispectral images indicating signatures of water, methane or other volatiles; and that it is indeed an Earth-like exoplanet in the goldilocks zone of habitation.

Another possible approach to achieve such detailed images is to obtain them from the vantage point of the Solar Gravity Lens focus area where the gravity from our Sun focuses the light from an exoplanet into a region that can then be imaged by a single or a series of imaging telescopes. This region, 550 – 700 AU from the Sun, could be reached by a precursory robotic interstellar probe using advanced propulsion techniques and clever mission design techniques, in a time frame of 20-40 years if an escape velocity of 20 AU/year is achieved.

Composition of the Interstellar Medium

Our solar system sits within a bubble called the heliosphere, carved out of the Interstellar Medium (ISM) by the supersonic solar wind and its magnetic field. Whereas the solar wind streams away from the Sun in all directions and its speed is several hundred kilometers per second in the vicinity of Earth, at some distance from the Sun this supersonic stream of energetic particles must slow down to meet the gases in the interstellar medium. This complex interaction between the solar wind and the interstellar medium, as well as the composition of the interstellar medium, are poorly understood. Voyager 1, launched in 1977 and traveling at about 0.000057c, is the only spacecraft confirmed to have exited the heliosphere and entered interstellar space. Its scientific instruments have revealed new information about the outer regions of the heliosphere (specifically the heliosheath and heliopause) and certain characteristics of the interstellar medium.

Our lack of knowledge as to how all of these observations fit in a coherent way indicate the need to revisit that region with modern instrumentation. Therefore, other progressively ambitious mission elements penetrating beyond the heliosphere and into the interstellar medium would be necessary before undertaking an interstellar mission, as illustrated in Figure 4.

Such missions could characterize the region of space that an interstellar spacecraft would be traveling through for a large portion of its journey and could also offer demonstration opportunities for the wide range of technologies that will be needed for an interstellar mission. In addition to propulsion technologies, items that could be demonstrated on interstellar precursor missions include very long-life power systems; lightweight, multifunctional, deployable structures; highly miniaturized spacecraft systems; thermal management in extreme environments; interstellar-range communications; avionics with long-term survivability and autonomous operations; and advanced scientific instruments.

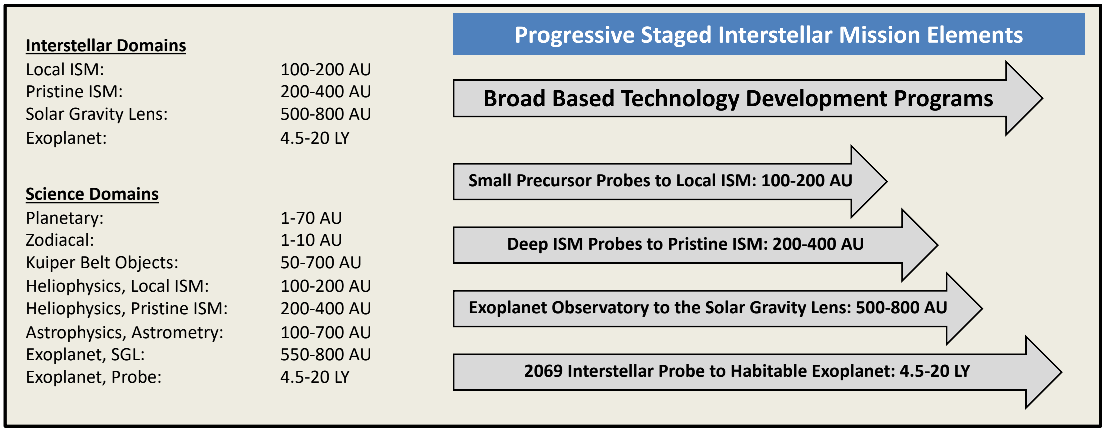

Figure 4. Progressively staged interstellar mission elements. Realizing these visionary progressively staged interstellar mission concepts, culminating in a 2069 interstellar probe mission to Alpha Centauri or some alternate exoplanet destination, will require sustained commitment to a long-range multi-disciplinary research and development initiative across a broad scope of space technology areas including the following.

NOTIONAL INTERSTELLAR PROPULSION TECHNOLOGY ROADMAP

As discussed in the foregoing sections, the challenges of interstellar travel are immense, requiring monumental advancements in many technology areas. There are three main candidate propulsion technologies for interstellar propulsion, each with multiple variants, and each delivering different capabilities in their ultimate implementations. Solar sails missions will likely always be limited to substantially smaller payloads than could be transported by nuclear fusion or antimatter rockets. Antimatter has the highest energy density, so theoretically it should offer the highest payload capacity, but decades of intense development would be needed to establish how much of that energy can be extracted for propulsive force by comparison with nuclear fusion. Hybrid approaches, such as fission-fusion propulsion, or antimatter catalyzed fusion propulsion, may provide incremental development paths towards full implementations of fusion or antimatter drives, offering relatively nearer term opportunities to demonstrate key technology elements.

Figure 4 shows a notional preliminary interstellar propulsion technology roadmap leading to the launch (by year 2069) of a scientific probe capable of achieving a cruise speed of 0.1*c* to Alpha Centauri. The major candidate concepts are listed, along with selected cross-cutting technologies. As one or more of the candidate concepts graduate from component-level and laboratory-scale tests to higher levels of subsystem and system integration, and specialized facilities would be needed, as indicated.

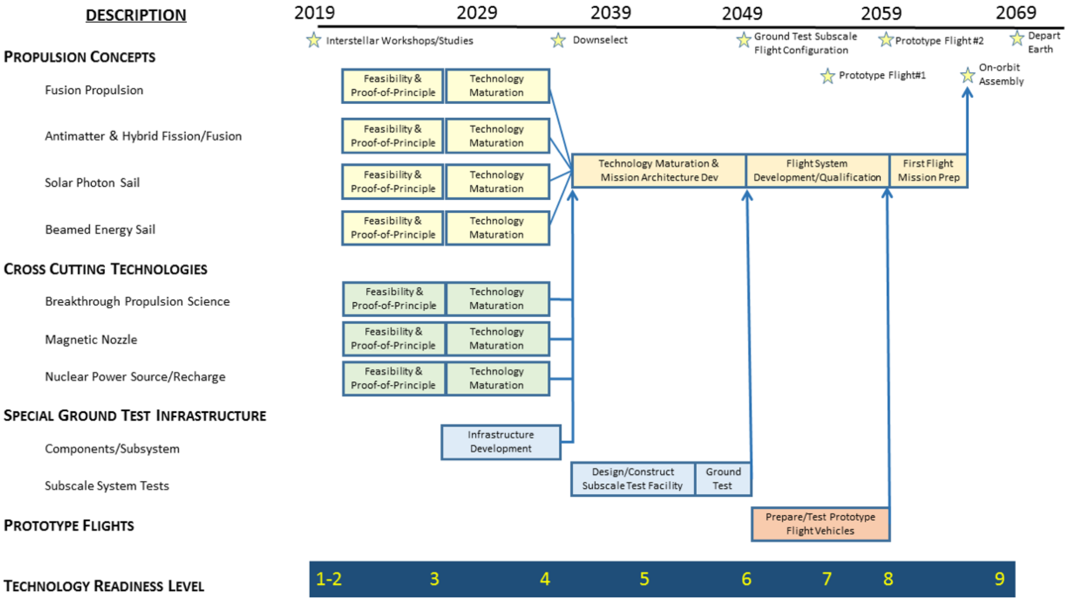

Figure 4. Notional preliminary interstellar propulsion technology roadmap leading to the launch (by year 2069) of a scientific probe capable of achieving a cruise speed of 0.1*c* to Alpha Centauri.

NASA Interstellar Workshops

A major objective of the first few years of an interstellar propulsion project would be to refine this conceptual roadmap. In developing a response to the United States Congress's direction, NASA has organized a series of three workshops to thoroughly assess the candidate propulsion technologies identified in this report and, if any are found to be promising, to established specific technology development milestones. Such workshops have been employed successfully by many past projects and programs; tapping into the community of expert practitioners in a technology area facilitates detailed assessment of the state of the art and the level of external interest and investment. The three NASA sponsored interstellar topical workshops were as follows:

- **OSA Incubator: Metamaterial Films for In-Space Propulsion by Radiation Pressure**, OSA Headquarters, Washington DC, 7-9 October 2018.
- **Interstellar Medium Technology Workshop**, NASA HQ, Washington DC, 10-11 September 2019.
- **NASA Advanced Interstellar Propulsion Workshop**, Hosted by Wichita State University & Ad Astra Kansas Foundation, Wichita KS, 10-15 November 2019.

These public outreach workshops have provided NASA with a diverse array of detailed and insightful perspectives concerning the technical challenges and development approaches to enable missions to the stars. The outcomes and conclusions of these workshops have been collected and are currently being integrated and analyzed by NASA as the basis for a long-term technology development roadmap and guide.

CONCLUSION

The challenges of interstellar travel are immense; the distances that need to be traversed are staggering, the energy requirements are stupendous, and the engineering demands are enormous. Accelerating a spacecraft the size of the Voyager 1 to 0.1c would require an amount equivalent to about 0.06% of the entire world energy output for one year. Consequently, evolving the notional preliminary roadmap discussed above into a game plan for a program of interstellar propulsion research, development, and demonstration would require extensive long-term efforts and the prioritization of resources. NASA has organized a series of three workshops to thoroughly assess candidate interstellar propulsion technologies. The outcomes and conclusions of these workshops have been collected and are currently being integrated and analyzed by NASA as the basis for a long-term technology development roadmap and guide.