A Science-Driven Mission Concept to an Exoplanet

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A concept for a science-driven robotic mission to an exoplanet was developed by a team of scientists and engineers from NASA and academia. The concept and scope were based on key mission and science requirements designed to address the question: "What makes a flight mission to an exoplanet compelling, in terms of science return, compared to what we will be able to learn in the next few decades with large near-Earth telescopes or other remote sensing techniques such as a telescope at the Solar Gravity Lens Focus?" By thinking systematically through mission and science goals and objectives, key requirements were developed that would drive technology developments in all necessary aspects, not just on propulsion. Unique science measurements would be performed en route to the exoplanet, including exploring the environment in the outer regions of our solar system, the Oort Cloud, the local interstellar medium, and the astrospheric environment around the host star. One of the key mission science objectives, and one that addresses why a mission to an exoplanet is compelling, was to confirm and characterize life. This objective is fundamental and drives the need for a precursor exoplanet characterization program to search for Earth-centric biosignatures and also drives key aspects of the mission concept. The team concluded that a direct confirmation of life would require in situ observations and measurements which cannot be performed on a fast (~10% of the speed of light) flyby; thus, the mission would require a method to slow down, orbit, or send a probe to the exoplanet's surface. This capability drives a trade between interstellar travel velocity, trip duration, and propulsion architecture, as well as a high level of onboard autonomy, including adaptive science data collection, on-board data processing, and analysis. This paper describes our mission concept, the key requirements, and open trades.

Keywords: interstellar, exoplanet, science, mission, spacecraft

1. INTRODUCTION

Thirty years ago, the existence of planets orbiting other stars (exoplanets) was still unproven after centuries of speculation. Today, over 3,500 exoplanets have been discovered over the past three decades, another thousand possible candidates are awaiting confirmation, and the search techniques continue to improve [1,2,3,4]. Recent identification of Habitable Zone [5] planets such as Proxima Centauri b [6] and TRAPPIST-1e [7] begs the question "When will a spacecraft be sent to investigate?" Thus, a study team was formed to develop a science-driven mission concept to an exoplanet. The primary mission objective was to confirm and characterize life at the exoplanet, which is in-line with NASA's strategic objectives [8]. The team membership included experienced scientists and engineers from NASA centers, academia, independent institutions, and consultants; members typically had participated in multiple space science missions. A key groundrule of the study was to think "out of the box" and be creative, but be prepared to defend innovative ideas with sound physics.

The philosophy of developing a complete mission concept as opposed to focusing on one or two key technologies was used to drive out mission-wide key requirements and trades. Choosing a science-driven concept was important for determining what the mission needed to do upon exoplanet arrival. The team debated whether a science-driven mission or a technology-drive mission would be the best mission concept to study, since the answer has enormous ramifications for the science return and the mission technology requirements. In the end, the science-driven concept was chosen since it answers the question "what makes a mission to an exoplanet compelling?" and it would best ensure the development of an extensible architectural framework for the future. This choice should not exclude or diminish the value of precursor missions with other objectives, such as to investigate the interstellar medium or validate required technologies – such precursor missions will likely be required and their mission concept studies are encouraged.

1. SYSTEM DESIGN

The system design of an interstellar vehicle would be largely driven by the propulsion system that is selected. A nuclear fission- or fusion-powered vehicle design would be driven by radiation shielding and radiator surface area for dissipating waste heat and heat from the shielding. A beamed energy sail would be built around a thin film structure that might have completely different accommodation requirements for the science payload. A fission-pulse system would need to support a large and massive pusher plate that would drive the system design. More advanced systems, like fusion and antimatter rockets, would be completely driven the requirements for radiation shielding, magnetic plasma drive coils, and huge radiators.

Drawing from past work on interstellar mission studies over more than half a century by many agencies, universities, and countries, a number of system options were considered in this study. Key system trades are shown in Table 1.

The most plausible vehicle approaches for a system that could be built in the next 50 years would be nuclear electric propulsion (NEP) and beamed sails. An example of an NEP interstellar vehicle design is depicted in Fig. 1. An example of a beamed energy sail vehicle design is shown in Fig. 2.

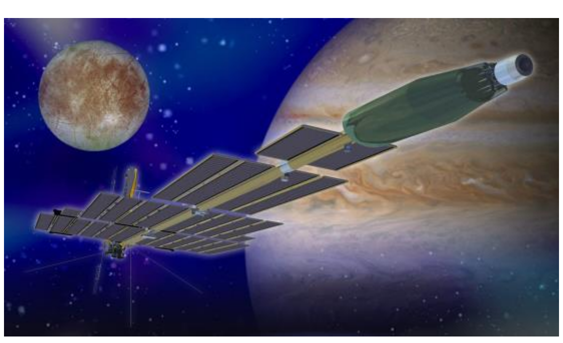

Figure 1. Nuclear Electric Propulsion Vehicle Concept

An interstellar vehicle would be an unprecedentedly difficult undertaking, and descope options would need to be defined in order to address and mitigate development risk. Some

Figure 2. Beamed Energy Sail Vehicle Concept

The biggest system challenge for an interstellar vehicle is propulsion, and the degree of the challenge is a function of flight time and ΔV. A mission that requires slowing down, stopping, going into orbit, or landing on an extra-solar world more than doubles the propulsive requirements. The second biggest challenge is telecommunications. The optimum communications system is probably one that minimizes the requirements on the interstellar vehicle at the expense of a large Earth or near-Earth based infrastructure to receive that data from the spacecraft. For missions with flight times greater than 50 years, new technologies would need to be developed to ensure system reliability over the design life.

Table 1. Key System Trades

	Flight Time	TRL	Development Risk	Payload Mass	Pros	Cons	Comments
Mission design							
Fast flyby	Possibly <100 y	2	lower		Minimum ΔV requirement	Encounter time is too short	
Braking at target	>100 y	0	high		Adequate encounter time	Twice the ΔV of flyby	
Propulsion							
NEP	~1,000 y	2	lower	large	Might fit on a single SLS		Requires very high I_{SP}
Beamed energy sail	Possibly 50 y	2	lower	very small		May require vast infrastructure	Ref. Starshot
Fission pulse	Possibly 200 y	2	high	large			Ref. Dyson Orion proj.
Beamed power EP	>500 y	1	high	large	Might fit on a single SLS	May require vast infrastructure	
Fusion pulse	Possibly 50 y	0	very high	large			Ref. BIS Daedelus
Bussard ramjet	Possibly 25 y	0	extreme	large	Minimal propellant required	No credible concepts	
Antimatter rocket	Possibly 25 y	0	extreme	large		No credible concepts for storing antimatter or directing thrust	
Telecom							
Optical com		4	lower				
Large aperture μ-wave		3	moderate		Might integrate with a sail	Difficult to maintain shape	
Power							
Radioisotope		6	low				
Fission		4	moderate				
Beamed		1	high				
Antimatter		0	extreme				

examples of potential descopes would be:

- Increasing flight time
- Descoping some of the payload
- Switching to a nearer target
- Switching to fallback technologies

Starting up a serious effort for an interstellar program would require a systematic assessment of available technologies, possible but realistic near-term advancements, programmatic risk assessment, cost and schedule estimates, developing feasible system design concepts, and identifying implementable fallback options.

2. KEY MISSION REQUIREMENTS AND ASSUMPTIONS

A number of key mission requirements and assumptions were drafted early in the study and modified as the study unfolded. These notional requirements, assumptions and their rationale are listed below.

Mission Duration: The threshold data shall come back within 70 yrs from launch.

- Rationale: The threshold data must come back within the professional lifetime of someone born around launch; this person can grow up learning about the mission and become inspired by it, eventually joining the team and working to be ready to interpret the data when it comes back.

If the spacecraft is travelling at a low fraction of the speed of light (0.1 – 0.3c), the exoplanet target must be no greater than 15 LY of Earth (50 yr travel time and ~20 years to collect and send the threshold data back to Earth). Note that this means the first bit of data collected at the exoplanet will make it back to Earth 15 years after exoplanet arrival.

Science Collection Enroute: Science data shall be collected en route to the exoplanet.

- Rationale: There should be a mission conducted during the flight to the exoplanet to keep the science community engaged.

Meaningful science return at least every decade, with fields and particles data being collected continuously and relayed to Earth on a regular basis, would significantly contribute to modeling and understanding the interstellar medium.

Launch Date: The launch date shall be no later than July 16, 2069.

- Rationale: U. S. Congressional language introduced by Representative John Culberson. [9]

This target in general allows five decades of exoplanet characterization to feed the target selection process, technology development and verification, and maturation of scientific techniques and instrumentation, particularly in the area of life detection and characterization.

Confirm and Characterize Life: The mission shall seek to confirm and characterize life.

- Rationale: Per NASA's strategic objectives: "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars." [9]

The expenditure to develop infrastructure and technology to explore an exoplanet would be significant. Proposed near-Earth telescopes and/or a mission to the Solar Gravity Lens should be able to collect spectra that would achieve most of the exoplanet characterization objectives that a typical reconnaissance space science mission can achieve today [10,11,12]. Information from atmospheric composition (perhaps a next-generation LUVOIR or HabEx) to 1000 x 1000 pixel imaging of the world (via a Solar Gravity Lens mission [13]) may be available (as an aside, space-based interferometers would have integration times of thousands of years and thus are not practical). Thus, in order to have a compelling case to procure and spend the resources, a science objective is required that far exceeds our anticipated near-Earth remote sensing capabilities over the next century. Moreover, a key lesson learned from the Viking lander experience [14,15,16] is to use multiple, unambiguous investigations to confirm life; today, the only way to do that is via in-situ sampling.

Key Assumptions:

- We can't be constrained to today's technology

An example is the use of 3-D printing technology in space to build new parts for that spacecraft that have worn out during the long journey.

- The exoplanet target has been previously observed such that we have a strong case for life

The target exoplanet should have already been characterized via spectroscopy and/or imaging and either resolved to 1000x1000 pixels or to 1 pixel with promising bio-signature spectra. While the threshold for making a strong case for life is expected to mature in the future with continued research, the suggested threshold is a start.

3. SCIENCE OBJECTIVES AND REQUIREMENTS

Many science objectives can be envisioned for a mission to an exoplanet, and eventually it will fall to the Decadal Survey process and NASA to decide upon them. For this study, five main categories of science objectives were considered: Heliosphere Boundaries, the Interstellar Medium (ISM) and other Science En Route, Astrosphere of the Target Star, The Solar System of the Target Exoplanet, and the Target Exoplanet.

Of note to the first three categories, Voyager data appears to show that ISM's influence reaches further than previously believed; the Voyagers are still being influenced by the Sun. It is thought that a spacecraft probably needs to travel to 500 AU from the Sun before escaping the Sun's influence [17]. This belief has implications for the study of the Sun's heliosphere boundaries as well as the target star's astrosphere boundaries. Travelling at 0.1c offers almost 30 years of valuable scientific data collection inside of 500 AU. Realistically, key ISM and heliospheric objectives need to be achieved on precursor missions to an exoplanet mission; for spacecraft health and safety purposes, it is necessary to understand the environment that the spacecraft would encounter in order to fold that into the design to achieve high confidence of success. However, it is still valuable, and it is a key baseline mission requirement, to conduct meaningful ISM investigations during a mission to an exoplanet, such as understanding the small scale structure of the local ISM and how that compares to the Sun/ Solar nebula, the ISM composition, imaging rouge planets, and measuring galactic cosmic rays and short path-length emissions. In addition, other investigations could take place en route involving the extragalactic/ reionization background, extragalactic parallaxes at nanoarcseconds, and tests of general relativity, but these can be performed on precursor missions as well.

Science objectives involving the solar system of the target star are numerous and involve the typical basic reconnaissance/ characterization objectives that missions in the solar system have had – composition and mapping, atmospheres, moons, rings, dust, asteroids/ comets, refinements of size and mass, spin rates, etc. However, given that the mission's main objective is study of one exoplanet in the star's system, and there is a requirement to return mission data within 70 years from launch, it is not clear how many other exoplanets can be well-characterized given orbital mechanics and the mission duration.

Science objectives involving the target exoplanet can include many of the basic categories listed above; an orbiting mission can resolve rivers, forest, deserts, and oceans. A key mission requirement is to confirm and characterize life. Returning to the question of what could be deduced via future near-Earth telescopes or a mission to the Solar Gravity Lens vs. a mission to an exoplanet: at a minimum, biosignatures of life must have been detected at this exoplanet before choosing it as a target. Since this data will have been collected via remote sensing from long distances, these biosignatures would be spectral (disequilibrium components in the atmosphere such as O_2, photosynthesis – red edge of vegetation), spatially-resolved images (structures, cities, lights turning on and off, large-scale land modification*), or electromagnetic (radio or optical signals).

Because these biosignatures are neither confirmation of life nor characterization of life, a mission to the exoplanet would be required to confirm and characterize its life. While a Solar Gravity Lens mission ***may*** be able to confirm existence of life (e.g. lights turning on and off, informational radio signals), it would not be able to characterize that life. Detection of atmospheric disequilibrium does not necessarily equate to a biomarker [18]. Atmospheric spectroscopy from afar can identify potential biosignatures better than imaging, but a mission must go to the exoplanet to unambiguously confirm life with in-situ sampling, ideally with multiple, independent investigations. A Solar Gravity Lens mission with 10 km imaging resolution could plausibly detect artificial illumination on the exoplanet, if present. However, the exoplanet may be a world where there is not yet advanced intelligent life to produce electric light. Intelligent life capable of producing lights, radio signals, structures, etc. only recently appeared on the Earth and so there is a low chance of finding life in that state. Those technologies have only existed on Earth for about 100 years, and the atmosphere has only had sufficient free oxygen (a potential biosignature) for less than a billion years. So for the Earth, advanced intelligent life has only been detectable for a world with a measurable bio-signature for ~100 parts in 1 billion (~$1x10^{-7}$). Thus, as a proxy for other exo-worlds, there is a very small likelihood of finding advanced life, and there is a very small number of candidate exo-worlds available within 15 LY.

Another example of a pitfall of relying solely on remote spectra: the potentially habitable planet Proxima Centauri b [6] is close to its star, and it could have been (or still is) subject to a massive solar wind and left with a thick O_2 atmosphere and yet no possibility of life [19]. In fact, there are at least three mechanisms for abiotic production of O_2 on planets with different geological histories [20,21]. Thus, spectral signatues alone are inadequate, and the mission should orbit and preferably land instrumentation to sample exoplanet material to confirm life. A fast flyby mission of an exoplanet may not offer a compelling science return compared to near-Earth telescopes providing spectra and possibly imaging that could be achieved over the next decades. Flying by the target at 0.1c only gives ~100 hours in the target solar system, or ~1/2 of a planetary diameter per second. Even if quality data were to be captured on a such a fast flyby, sending the data back when travelling at 17 AU/ day makes the problem far more challenging. **This a key finding of the study: to make a mission to an exoplanet scientifically compelling, we need to, at a minimum, slow down – a fast flyby (0.1 c) is not scientifically compelling.** This finding had enormous ramifications on the propulsion design.

4. TARGET CHARACTERIZATION AND SELECTION

Currently, 53 stars and nine brown dwarfs are known within 15 LY of the Sun. It is remarkable that three brown dwarfs have been discovered within 8 LY just within the past few years using the WISE infrared sky survey [22,23]. Of these, only nine are FGK-type stars that could be roughly considered "Sun-like." In the quest for optimizing observations for detecting biosignatures from potential life on small rock-dominated exoplanets with surface liquid water, astronomers have calculated theoretical limits of maximum and minimum stellar flux for stars of varying luminosity and/or effective temperature appropriate for planets similar to Earth in size and atmosphere (the so-called "habitable zone"). NASA is currently interested in studying icy moons of Jupiter (Europa) and Saturn (Enceladus) due to their potential for harboring life in liquid oceans under the ice. These types of worlds should not be excluded from exoplanet mission target consideration in the future if the ability to put together a strong case for life is developed.

Today there is also a limitation on detecting and characterizing exoplanets that can be seen from Earth – either due to the techniques currently in use which can improve in the future or due to the basic viewing geometry, period, and radius of the planet which cannot be improved. For example, the transit method which has yielded thousands of planets on close-in orbits around stars is only sensitive to finding ~0.5% of planets orbiting in the habitable zones (~1 au) of G stars due to the random orientation of orbits among target stars, and hence this particular method is likely to yield few such planets among the nearest Sun-like stars. The study considered what future near-Earth missions could do to find targets for a future mission to go to another star. Precision radial velocity methods are currently challenged at the ~0.5-1 m/s level due to stellar noise sources, and progress is being made to improve the method to the ~10s cm/s level needed for detecting Earth's around Sun-like stars . Microarcsecond astrometry with proposed large space telescopes like LUVOIR or HabEx may be able to survey nearby Sun-like stars for ~Earth-mass planets on ~1 AU orbits. The key technology elements for the LUVOIR High Definition imager to enable this level of astrometry is part of the baseline LUVOIR instrument design [23]. Since G-like stars offer the best prospects for finding life given the current understanding of how to detect it, and there are very few candidates within 10 LY of Earth, the mission requirements had to be pushed out to 15 LY. If Habitable Zone planets around Alpha Centauri A or B are detected in the future and meet the selection criteria at the time, they could make great candidate targets and are only ~4 LY from Earth, but the team did not feel it prudent to count on the existence of those planets today.

In addition, the study considered what these future missions could reveal concerning apriori knowledge. LUVOIR should be able to pin down the location of the exoplanet to with a few exoplanet radii, and the Solar Gravity Lens mission should be able to pin it down to < 10 km. Either one of these techniques should be good enough to plan a mission around.

Target Selection Criteria

It is understood that exoplanet characterization techniques and the understanding of what constitutes a biomarker will expand and improve in the future, and therefore the target selection criteria will adapt and change in the future. In fact, multiple papers are in work/ recently published describing biosignatures [24]. However, based on limited knowledge today, the target selection criteria are:

- Exoplanets that are in their star's Habitable Zone
- Exoplanets with masses > the mass of Mars (this would indicate rocky planets with a decent chance for the existence of an atmosphere)
- Exoplanets that experience roughly the same solar radiation as Earth
- Detection of a biosignature from the exoplanet plus at least 1 pixel image of the exoplanet (ideally 1000 x 1000 pixel image)
- The current age and estimated lifetime of the star should be such that life will have had a chance to form
    - The current thinking is that the star should be at least > 1 billion years old (and preferable older)
- The exoplanet's star should be close to a G2V Class (the Sun)

For instance, if Alpha Centauri A, which is estimated to be a six billion year old type G2V star, had a rocky planet in its habitable zone, it would be a very good candidate to make it through all the target selection criteria.

5. INSTRUMENTATION

The instrumentation required for this mission would follow the science and mission requirements set. In general, through, the instrumentation requirements for the heliosphere boundaries, astrosphere boundaries, and the ISM would be very similar and likely include magnetometers, plasma detectors, cosmic ray detectors, Lyman alpha detectors, radio detectors (for plasma density), dust detectors, and ion/ electron direction and velocity detectors. For short path length emissions, ultra-violet and X-ray spectrometers would be needed. An IR imager would be useful for rogue planets. Finally, imaging the spacecraft shield would be useful to monitor damage over time from dust and debris impacts. Simply monitoring the velocity over time through the ISM would yield data about the changes in progress due to the ISM.

Inside the target star's solar system, a variety of cameras ranging from narrow angle to wide angle with various resolutions would be desirable to look at distant planets and Moons; the narrow angle camera could also be used to navigate closer in (see Section 9). Infrared and ultraviolet cameras and spectrometers with a variety of spectral ranges, in addition to visible and mass spectrometers, would be useful for thermal characterization and compositional characterization. In addition, at the exoplanet itself, having one or more landers or probes with life detection experiments, a metrology station (wind, temperature, atmospheric density and composition), and a suite of cameras and spectrometers as described above, would be required.

The technology exists today, in limited scale, to use onboard autonomy to allow instruments to detect targets of opportunity (for example, dust devils on Mars, or a hurricane forming in the ocean on Earth). It is expected that future version of this technology will be running onboard the spacecraft with a priority scheme in order to increase the scientific return from the mission.

6. COMMUNICATION

The power required to transmit data increases as R^4 (where R = distance from the spacecraft to the Earth) for radio and R^2 for light, so laser-based communication (lasercomm) is the better choice of technology from an energy standpoint. The OPALS lasercomm system was recently tested aboard the International Space Station and demonstrated significant increases in transmit time and data volume [25]. However, a key mission consideration is the energy required onboard the spacecraft, and it was shown that current technology - an OPALS-like system with 40 m light bucket receivers on Earth – would require over 100 kW of power to operate. A different approach was chosen assuming large aperture diameter transmitters and collectors to increase net gain of the link.

For ground-based receiving of optical signals losses due to atmospheric transmission of the Doppler shifted laser wavelength and irrecoverable atmospheric turbulence induced aberration losses can be severe. On the other hand, space based receivers will be free from atmospheric transmission and turbulence losses but they will need to be equipped with autonomy to search for and acquire the laser link. In this study we aggressively choose a 100-m diameter receiving aperture. For any laser wavelength increasing transmitter diameter results in higher far-field gain but also results in a narrower laser angular beam-width needing tight pointing control. For this study, a telescope with Hubble Space Telescope (HST) like aperture and pointing control was adopted. The pointing accuracy of the Hubble telescope is approximately 35 nanoradians (nrad) [26]. Assuming a laser beam-width of 10× the pointing accuracy, as a rule of thumb, a 350 nrad beam can be transmitted. Given the HST-class aperture diameter of 2.4-m, a transmitted laser wavelength of 840 nm results in the beam-width that can be accurately controlled.

Table 2 summarizes a notional link design for a 840 nm laser with 4000 W average power transmitted from a 240-cm diameter telescope. From interstellar ranges the sun is used as a pointing reference to point the laser back at the Earth receiver. The Earth receiver is a 100-m diameter space-based collecting aperture with photon counting detectors. The laser is pulsed with low duty cycle.

Provided additive noise can be suppressed using spectral filtering and the 100 m aperture can pointing is stable, 100's of bits/second of data-rate can be received based on a 1-2

Table 2. Notional Link Design for Interstellar Lasercomm

Average Laser Power	36.02	dB-W	4000	W	4 kilowatt average power 840 nm laser
Transmitter Gain	138.17	dB	240	cm	HST equivalent aperture diameter
Transmitter Efficiency	-6.21	dB			Opticaltransmission and pointing losses
Space Loss	-486.54	dB	15	Ly	Free-space loss from 15 lightyears
Receiver Gain	171.28	dB	100	m	100m collecting aperture in space
Receiver Efficiency	-10.56	dB			Optical and implementation loss w/3-dB margin
Received Power	-157.84	dB-W			
Photon Flux	28.42	dB-ph	695	ph/s	Received photon flux in photons per second

bits/photon link capacity. If he above link design were scaled to 4.37 Ly (Alpha Centauri) the photon flux would increase to ~ 8000 photons/sec supporting a few kilobits of data-rate. While this indicates the viability of laser links from interstellar distances, developing lasers that can survive the 50-70 year journey and operate reliably poses a formidable challenge. 100-m apertures in space would also be non-trivial. The possibility of using gravitational lensing was explored and can offer huge gains except for the fact that the receiver would be nearly 550 AU from the sun and aligning the transmitter, gravitational lens and receiver poses a problem.

It should also be noted that all of these options are constrained by the speed of light, and the first bit of data returned from the exoplanet will still take 15 years to travel back to Earth from 15 LY.

7. ENVIRONMENTS

Understanding the space environment is key to spacecraft design. Concerns are radiation damage from trapped electrons, protons, and solar protons; surface charging from plasma electrons and ions, internal charging from high-energy trapped electrons, single event upsets from trapped protons, solar protons, or galactic cosmic rays, structure damage and/or electrostatic discharge from dust or micrometeorites, and material degradation from atomic oxygen and UV. Of all of these, the items that are most concerning for a mission to an exoplanet are dust and galactic cosmic rays. Models by Weingartner and Drain [27] and Hoang [28] show there could be up to 0.5 mm erosion at velocities of 0.2c; this is an important consideration for design and especially or concepts involving ultra-thin light sails. A few mitigation approaches have been suggested, such as electric deflection or radiation pressure deflection [28]. In the ISM, interstellar galactic cosmic rays dominate the radiation concerns. However, a big unknown is the environment in the target star system, especially for high-energy radiation that is important for spacecraft design. X-ray observations of the target host start could be used as a proxy for high-energy particle environment estimate although it will not be direct measurement of energy spectra [29].

8. PROPULSION

Since there is currently no existing propulsion technology that can achieve 0.1c, the team reviewed various propulsion options in order to determine which candidates were the most promising for technology readiness in the next five decades, assuming a robust and focused technology development. Options considered for this study included matter/ antimatter annihilation [30,21,32], beamed momentum [33,34], the Bussard ramjet [35], Daedalus-style fusion [36], and fission fragment [37,38]. The requirement for confirmation/ characterization of life resulting in the need to orbit and land on the exoplanet is a huge challenge in the propulsion arena.

From a propellant energy density standpoint, matter/ antimatter is the top choice (Fig. 3) [39]. However, it is not a very efficient system, decaying or radiating its energy before thermalization [40,41,42] and thus it does not compare favorably with fusion or fission. In addition, only ~10 ng/ year of antimatter is produced vs. the millions of metric tons required for a rendezvous mission that meets the stated requirements, and it is unlikely that such large-scale production will be achievable in the next five decades [42]. Despite the special handling considerations (magnetic levitation in ultra-high vacuum in a system that can never fail), a single cosmic ray impact could destroy the mission.

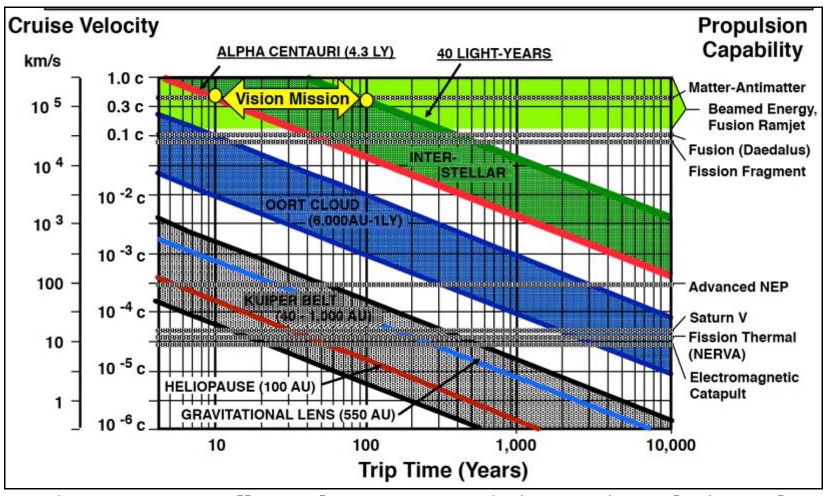

Figure 3. Interstellar and Precusrsor Mission Cruise Velocity and Propulsion Requirements [44]

The Bussard fusion ramjet was considered and discarded because of its large number of technological issues. These include the design of the electromagnet scoop, the need to collect interstellar deuterium for fusion (since pure hydrogen fusion may never be achieved by humans), significant energy losses in the fusion reaction, and need for a “drag free” scoop, fusion reactor, and electromagnetic nozzle [45]. Some of the issues may have solutions, but others may remain intractable. For example, energy losses from the reactor this issue could be overcome by laser power-beaming, but then a laser sail may just as well be used without the mass overhead.

The three top choices for a potentially successful propulsion system development in the next five decades were a two-stage laser sail, fission fragment, and fusion-thermal (Daedalus). All three of these proposed technologies have challenging development problems associated with it, but the team felt that the laser sail had the highest potential to be ready in five decades and also had the most potential payoff for the infrastructure investment involved. The small (roughly 14-m square) Japanese Ikaros solar sail has flown in space [46,47], and the development challenges for this technology include deployment and control of ultra-large sails (> 100’s of meters in diameter), developing ultra-lightweight sail material, and the laser itself. The technology roadmap from today’s laser technology to what would be needed for a mission to an exoplanet is daunting, but so are the development paths for the other two potential propulsion candidates. In addition, there are political ramifications concerning lasers of that power as well as space-based nuclear systems. It is expected that serious study be given all three options before committing to any single one. Advantages of a laser sail is that the propulsion source does not have to be carried onboard, which allows the system to be less massive and require less power to operate. Another nice feature is that laser technology could continue to improve over the course of the mission and those upgrades could be used by the mission in flight. Like building the launch pads for early NASA rockets, a series of large (> terrawatts) lasers could also be used in conjunction with laser-electric propulsion to enable missions such as achieving Pluto orbit in under four years, a mission to the Solar Gravity Lens in under 15 years, or sending 100 metric tons of cargo to Jupiter’s orbit in a year [48].

9. NAVIGATION

Navigation for a mission to an exoplanet has to be autonomous and on-board by nature in order to be useful since one-way light times are 4 – 15 years. Any ground-based navigation would be purely forensic after about 500 AU. On-board, autonomous navigation was successfully used on Deep Impact to hit the comet [49]. What has not yet been demonstrated is a fully autonomous on-board mission replanning system. To elaborate, upon arrival at the exoplanet, the approach trajectory and target orbit parameters will need to be adjusted based on new knowledge gained either about the exoplanet’s dynamics or the current performance capabilities of the spacecraft. In addition, landing site selection would be based on data gathered and interpreted completely on-board the spacecraft rather than via teams of scientists on the ground.

It was determined that today's target knowledge is sufficient to perform that mission. However, expected improvements with LUVOIR and/or a mission to the Solar Gravity Lens would certainly help. An extremely accurate time reference will be required, and the Deep Space Atomic Clock [50] appears sufficient for this type of mission. A consideration is determining, from on-board optical navigation, how close one is to the exoplanet; this can be achieved by observing the planet's motion over time. This can be done by slowing down within the system or by coming in fast and using a very good telescope.

10. POWER

Electrical power is arguably the most important subsystem on any spacecraft because almost every other subsystem requires electrical power. The basic elements of a spacecraft electric power subsystem (EPS) are shown in Figure 4. Essentially a power source (e.g., nuclear or solar or power beaming) provides the electrical power, which is conditioned through the power management and distribution (PMAD) subsystem and other power processors to the "loads" (e.g., spacecraft instruments, computers, etc.). Energy storage is a way to save unused electrical power for times when the spacecraft needs more power than the power source can provide. For the proposed concept, the requirement is to provide 5 kilowatts (kWe) for 70 years, which was based on 4 kWe for the lasercomm system and 1 kWe for all other spacecraft power needs.

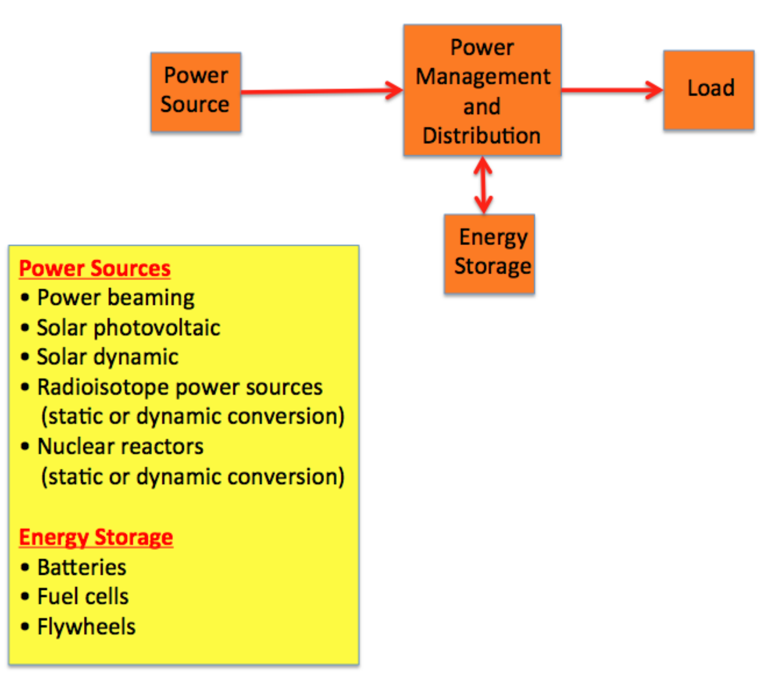

Figure 4. The basic elements of a spacecraft electric power subsystem (EPS)

As shown in Figure 4, there are five basic types of power sources currently available or having near-term availability. Power beaming offers the potential of having a low-mass electrical power subsystem because most of the mass from which the power would be beamed would be on Earth or in space. The two principal types of power beaming are lasers and microwave. If the spacecraft were already using lasers for communication and navigation, power beaming would be a nice addition. However, the spacecraft would need very good energy storage for times when the laser was down or the spacecraft fell off the beam.

Solar power has been used on most of the spacecraft that have been launched since the beginning of the space age. While the solar power has come from photovoltaic (i.e., "static") conversion, solar power could also involve the use of "dynamic" power conversion (e.g., turbine-alternators or linear alternators), which offers the potential for higher thermal-to-electric conversion efficiencies. The 5-kWe requirement is not an issue for spacecraft operating in the inner Solar System; for example, the International Space Station (ISS) was designed for 110 kWe of solar power. However, the major issue facing solar power subsystems is operating far from the Sun. With the solar flux falling off as the reciprocal of the square of the distance from the Sun (see Figure 5) the solar array size would grow proportionately (see Figure 6).

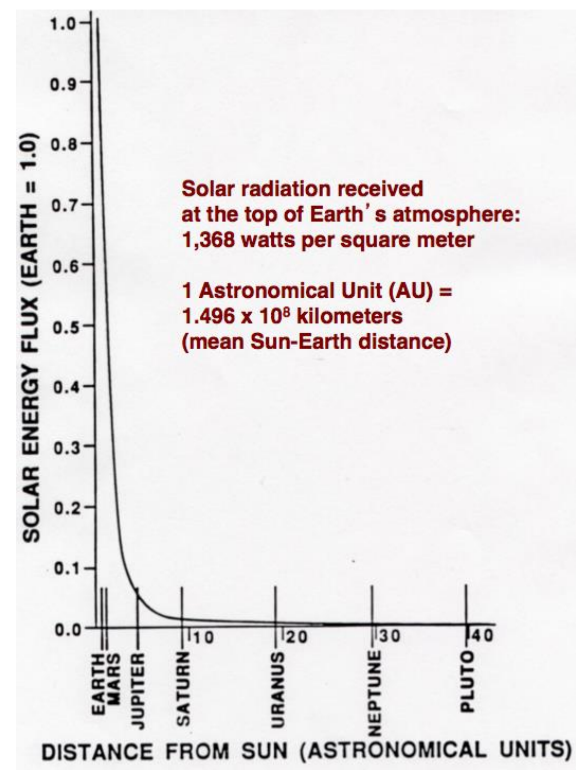

Figure 5. Relative solar energy flux as a distance from the Sun

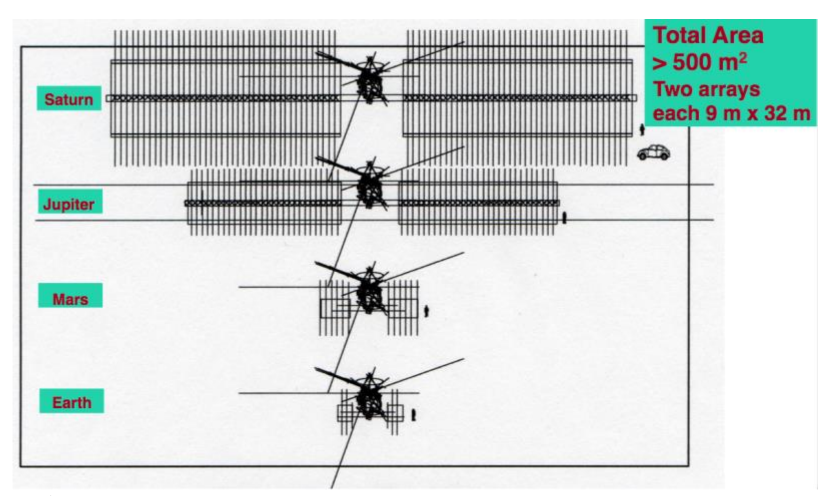

Figure 6. Relative solar array sizes as a function of distance from the Sun

Currently there are two practical nuclear power sources: radioisotope and nuclear fission (at some future point, nuclear fusion may become an option for interstellar missions). A radioisotope power system (RPS) converts the heat from the natural decay of a radioisotope (e.g., plutonium-238 on U.S. space missions) to useful electrical power. To date, all of the RPS that have been flown by the United States have used thermoelectric elements for the thermal-to-electrical conversion, although research has been conducted on using other conversion systems (e.g., turbine-alternators and linear alternators). An RPS that uses thermoelectric conversion is called a radioisotope thermoelectric generator (RTG).

The highest-power RTG flown by the U.S. is the General Purpose Heat Source-Radioisotope Thermoelectric Generator (GPHS-RTG), which provided 300 We at beginning of life (BOL) at about 6.8% conversion efficiency. Thus, almost 17 GPHS-RTGs would be needed to provide 5 kWe at BOL. However, the natural decay of the plutonium-238 (87.7-year half-life) leads to a drop in power of at least 1.6% per year (plutonium-238 decay plus thermoelectric decay), which means essentially all the electrical power would be "gone" after 70 years. Note that the RTGs on the Voyager spacecraft have operated for over 40 years. If thermal control could be employed to keep the thermoelectric elements operating at the ideal temperature, it would theoretically be possible to have an RTG-powered mission if one started with about twice the number of BOL RTGs (about 34). A radioisotope decays away below detectable levels in about 10 to 15 half-lives;

fortunately, a 70-year mission would be less than one half-life of Pu-238.

Fortunately, there are higher-powered RPS concepts that could help reduce the mass needed to achieve 5 kWe. The U.S. has sponsored work on kilowatt-class dynamic RPS using various power conversion technologies (Brayton, Rankine and Stirling), which offer the potential of achieving up to 30% conversion efficiencies. Thus, if one started with about a 10-kWe dynamic RPS, it would be possible to have about 5 kWe available after 70 years (assuming no losses in the dynamic conversion system). As an aside, it is worth noting that the Swan Falls dam in Idaho has turbines that have operated for 90 years.

There are, of course, radioisotopes with longer half-lives than plutonium-238 [e.g., samarium-151 (96.6 years); nickel-63 (100.1 years); silicon-32 (170 years); americium-241 (432.2 years), etc.] that could be investigated to determine if they would alleviate the radioisotope fuel decay issue, recognizing that the longer the half-life, the lower the specific thermal power (watts thermal per gram of radioisotope fuel).

A nuclear reactor can provide steady power through the appropriate application of the control system (e.g., control rods or control drums). By removing the neutron-absorbing material in the control system, the power can be maintained at a steady level as long as sufficient fuel (e.g., uranium-235) is available to fission. Significant tests would need to be run to ensure that a space-based reactor could operate for 70 years. The only reactor flown by the U.S. to date (SNAP-10A launched in 1965) used uranium-235 as the fissile material ("fuel"); it functioned for 43 days before an unrelated failure ended reactor operations.

Currently, NASA and DOE are investigating a reactor concept that could provide 1 kWe to 10 kWe for missions up to 16+ years (see Figure 7). In the past, the U.S. has studied a range of nuclear reactor concepts, from the kilowatt level to the multi-megawatt level.

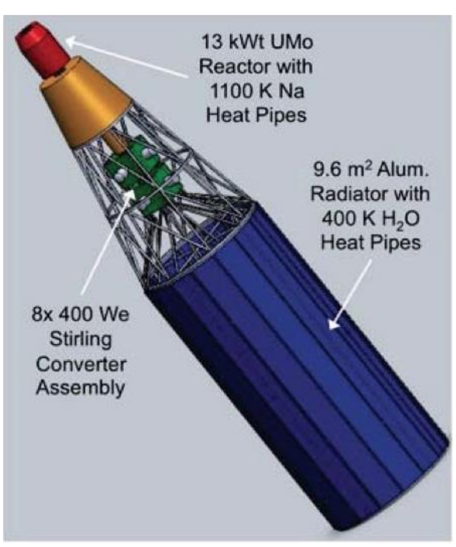

Figure 7. Artist's Concept of a Nuclear Reactor Using Eight 400-We Stirling Convertors

With today's technology, the most reliable source of electrical power for an interstellar spacecraft requiring 5 kWe of continuous onboard power for 70 years would be an RTG. However, it is recognized that with current conversion efficiencies, this could require over 30 RTGs on the spacecraft. However, with advances in space nuclear electric power technology, a nuclear reactor power system could become the lowest-mass nuclear power source with the fewest thermal and structural issues.

11. CONCLUSIONS

A science-driven mission concept to an exoplanet has been studied by a multi-center team of experienced engineers and scientists. Using a mission concept approach to the design, rather than focusing on just the key technology developments, resulted in findings and requirements that were not obvious at the beginning of the study. A prime example is the need to confirm and characterize life, which was not one of the original objectives. Given anticipated advances in near-Earth telescopes and/or a mission to the Solar Gravity Lens Focus in the next 50 years, it is expected that a considerable knowledge base on the exoplanet would be amassed. The only compelling science objective left that warrants the enormous investment in developing this mission would be to confirm and characterize life.

Large space-based telescopes, some of which are currently under study by NASA, will be required to characterize potential targets. Much work is still needed in the area of unambiguous life detection, particularly via remote sensing. Precursor ISM missions and/ or investigations are required to characterize the environment the spacecraft would travel through and test out required technologies, such as propulsion and long-duration on-board autonomous operations.

The single largest open trade is the propulsion technology and associated sizing of that system. It is strongly recommended that a comprehensive trade study on propulsions technologies in the context of a mission concept be aggressively pursued, as interstellar propulsion is bound to be a long-lead development effort. Just as the Solar Gravity Lens mission concept, based upon known physics applied in a novel way, has been recently proposed as a method to resolve an exoplanet, it is highly desirable for a new, enabling propulsion technology to be proposed based on a novel application of known physical laws. While this mission was sized for targets within 15 LY from Earth, the extensibility of the system concept for distances beyond 15 LY was out of scope for this study. Since many more targets for extrasolar life exist beyond this distance, extending the range to the target should be considered for future work.

Space power is an enabling technology and the technology must be pursued aggressively. To power an interstellar spacecraft for 70 years at 5 kWe, the following technologies should be pursued:

- improved conversion efficiencies (both for static and dynamic conversion systems), including in-flight refreshing
- advanced radioisotope power systems (both RTGs and dynamic RPS using Brayton or Rankine or Stirling conversion cycles)
- long-lived, autonomous nuclear reactor power systems
- improved heat rejection radiators

It would be important to maintain the supply of enriched uranium for future use in space reactors.

Significant work remains in on-board autonomous operations, including mission planning and system self-repair.

The sizing of the lasercomm system is another area where open trades exist, including system sizing, laser frequency, laser reliability over long durations, and receiver locations.

Finally, it is acknowledged that many, many more mission concepts should be examined before the one that is ultimately adopter for implementation is selected. Significant work remains to be done on a science-driven mission concept to an exoplanet, and the authors would like to encourage this work to continue.

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TABLES

FIGURES