Interstellar Mission to Gliese 581

A Senior Project

presented to

the Faculty of the Aerospace Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by

Brock Schmalzel and Brian Tsoi

June, 2012

Interstellar Mission to Gliese 581

Brock Schmalzel and Brian Tsoi
California Polytechnic State University, San Luis Obispo, California, 93407

This report details a conceptual design for a one-way, interstellar mission, based upon assumed technological advances over the next few hundred years. It addresses the unique challenges associated with an interstellar mission, looking at both developed and theoretical technologies. This report looks specifically at propulsion systems required to reach an exoplanet. In addition, the power, communication, and orbital trajectories are analyzed to see the differences and technological advancements necessary for future missions and the proposed interstellar mission. The destination for the interstellar mission in Gliese 581, which is a star system that lies about 20.3 light years away and has 5 known planets and an unconfirmed 6th planet. There is one known planet that lies in the habitable zone, an area around a star most likely to harbor water or other forms of life, and another known planet on the edge of the habitable zone. The unconfirmed 6th planet is thought to be in the middle of the zone and makes Gliese 581 an appealing destination. Nuclear fusion using a ^{2}H + ^{3}He reaction is used for both supplying power and the propulsion system with an estimated transit time around two hundred years with two stages of acceleration and one stage of deceleration. The communications system makes use of the sun focal point in order to increase the gain of the transmit antenna and uses two 50 meter dishes on the spacecraft to talk to Earth.

Nomenclature

a	=	acceleration (m/s^2)
c	=	speed of light
d_1	=	distance from Earth to laser-cutoff point
d_2	=	distance from laser-cutoff point to Gliese 581
D	=	effective diameter (m)
e	=	available fusion energy (J/kg)
f	=	antenna frequency (Hz)
g	=	gravitational force at Earth (9.81 m/s)
ISP	=	specific impulse (seconds)
m	=	spacecraft mass (kg)
n	=	antenna efficiency
P	=	Power (W)
We	=	watt energy
λ	=	wavelength (m)
r	=	sail reflectivity
r_{sch}	=	Schwarzschild radius (m)
ρ	=	abundance of Hydrogen in interstellar medium (kg/m^3)
T	=	mission duration (s)

Subscripts

L	=	beam laser
S	=	solar sail
C	=	communications dish

I. Introduction

Humankind has fostered a romance of space travel for many years, exemplified in the works of science fiction by the likes of Isaac Asimov, Frank Herbert, Robert Silverberg, and Gene Roddenberry. Planets and stars have become more than points of light in the night sky—they have become destinations. Considering the planetary conquests of NASA and other space agencies—conquests once thought to be impossible—we can contemplate the placement of interstellar travel in the eyepiece of the futurist's telescope. As the technology of space travel has steadily improved, voyages to distant stars have become a distant reality not unlike the Spacing Guild of Herbert's *Dune* and Roddenberry's United Federation of Planets in *Star Trek*. The arguments in support of such voyages have remained rather unchanged for decades: scientific discovery, economic competitiveness, geopolitics, and the survival of the species are all strong rationales for investing research into interstellar travel[1]. And recent advances in the field of observational astronomy have established a new incentive for interstellar missions: habitable-zone exoplanets.

Exoplanets are planets located outside our solar system and were first confirmed twenty years ago by Wolszcan and Frail[2]. Several methods of detecting exoplanets have been developed and over 750 planets have been discovered thus far[3]. A 2011 Astrophysical Journal article analyzed the data from 156,453 stars observed during the first four months of the Kepler mission—of those stars a total of 1235 planetary candidates were detected[4]. Most exoplanets have been discovered with the use of two primary techniques: radial-velocity and photometric transit. The radial-velocity method utilizes spectroscopy to measure the Doppler shift produced by the "wobble" of a star due to the orbit of a planet. Photometric transit method detects the event of an exoplanet crossing between Earth and its host star. Such an event partially eclipses the star and produces a measurable dip in the star's brightness. Less productive methods include, but are not limited to, astrometry, pulsar timing, and gravitational microlensing[2]. The orbital parameters produced by these methods have allowed exoplanetologists to determine whether or not a given exoplanet is located within its star's habitable zone, also known colloquially as the "goldilocks zone"[5]. This exciting new field has provided additional insight into the possibility of extraterrestrial life—a fact these authors believe to be a fascinating reason for interstellar exploration. In an attempt to gauge public opinion, a survey was posed on the topic of travel to exoplanets. The survey was opened on the social networks Reddit and Facebook and gathered 162 participants, including approximately thirty students from the 2012 Aerospace Engineering Space Design class at Cal Poly State University, SLO. Of the participants, 65±7.3% (95% confidence level) were "familiar with the terms exoplanet, or extrasolar planets" prior to the survey.

This survey, referred to as the Interstellar Mission Survey, also questioned users about their support for, and understanding of, an interstellar mission to visit an exoplanet. Two main questions and the associated results are shown in Table 1. Response options can be seen in greater detail in Appendix A, along with the rest of the survey process. Participants were divided into the following, non-independent groups: F=Those who considered themselves to be familiar with the fields of Aerospace Engineering, Astronomy, and General Physics (NF=Not familiar), I=Those interested in the fields of space exploration and future technology (NI=Not interested), A= Aerospace Engineers, NA=Non-Aerospace Engineers, E=All Engineers, NE=Non-Engineers, LE=Lower Education (High School, Some College, 2 year degree), HE=Higher Education (4 year degree, postgraduate degrees).

Table 1. Results from the Interstellar Mission Survey. Participants were divided into one or more of the following groups explained above. Confidence intervals calculated with confidence level of 95%.

Question 1: Do you agree that an interstellar mission would be worthwhile? (0=Do Not Agree 3=Completely Agree)			
Group F	2.32 ± 0.20	Group NF	2.11 ± 0.21
Group I	2.54 ± 0.15	Group NI	1.63 ± 0.25
Question 2: When do you think an interstellar mission will be most likely to occur? (Years)			
Group A	104 ± 20	Group NA	85 ± 9
Group E	96 ± 13	Group NE	83.5 ± 11
Group LE	90 ± 10	Group UE	89.5 ± 14

The results suggest that an interest and familiarity with the fields described in Table 1 increases the likelihood of support for an interstellar mission. And while a person's area of study has a noticeable effect on their mission prediction (Aerospace Engineers predict an interstellar mission to occur 25% further into the future than Non-Engineers), there is no distinct difference in terms of education level. The authors tentatively conclude from these results that, for an interstellar mission to gather widespread public support, two methods can be enacted: increased focus on astronomy, engineering, and physics in any form of general education, and improved public accessibility to

research in the fields of space exploration technology. In light of these conclusions, this report aims to engage readers of all backgrounds.

This paper seeks to produce a basic conceptual design of an interstellar spacecraft and will focus on some of the most important considerations: propulsion, power, and communications subsystems, along with the selection of a destination in relatively close proximity to Earth[1]. In addition, rudimentary orbital analysis will be performed. Over the past few decades, several concepts have been developed for interstellar missions. These concepts include both manned and unmanned vehicles that utilize propulsion methods of variable speed. J.D. Bernal's idea for an interstellar spacecraft sacrificed speed for increased comfort and habitability. Such a "worldship" would sustain tens of thousands of passengers to endure for multiple generations[6]. An opposite approach would be that of the thirty-year-old Daedalus project and the ongoing Icarus project authored by members of the British Interplanetary Society and the Tau Zero Foundation. These two concepts dismiss the worldship idea in favor of an unmanned probe that would utilize more powerful propulsion systems[7]. Because of difficulties associated with designing a manned spacecraft, this paper will consider options that favor the approach of the Daedalus and Icarus teams.

II. Research

A. Propulsion

The large distances associated with interstellar travel place the propulsion system of the spacecraft is one of the most important aspect of the design process. With mission durations on the scale of hundreds of years, the slight advantages between different systems are amplified. And because there is no established timeframe for the launch of an interstellar mission, both present and future technologies should be considered. This section will briefly introduce the multiple engines and propulsions methods that will be considered in this paper, along with performance parameters for future analysis. These different methods will also be classified in the following method: present (application proven or tested), near future (system, prototype, or component proof), distant future (physics proof or scientific concept) and far-distant future (speculation). These terms are defined by K.F. Long in *Deep Space Propulsion*[8].

i. Liquid Bipropellant

Bipropellant system uses a fuel and oxidizer to combust spontaneously after coming into contact with an ignition source. For liquid propellant, the liquid breaks up into droplets, vaporizes and only then mixes with the other propellant. Bipropellant systems provide a higher ISP (~270-460 sec) then monopropellant or solid rocket fuels at the cost of a heavier system mass[9].

ii. Dual-Stage 4-Grid Ion Thruster

Gridded ion thrusters produce thrust by the acceleration of ions through an electric potential difference between the source of the ion stream and an ion-permeable grid[10]. A 4-grid concept has been tested as a small-scale, low-power experimental model[11].

iii. TM-50 double-stage Hall thruster

Hall-Effect thrusters operate by accelerating an ionized propellant through electrostatic forces—similar to the gridded ion thruster. The TM-50 (TsNIIMASH) thruster utilizes xenon propellant and is currently under development[10].

iv. VASIMR VX-200

The Variable Specific Impulse Magnetoplasma Rocket is under development by Ad-Astra and generates thrust by the magnetic acceleration of heated plasma particles[12]. Michio Kaku hypothesizes such a system could reach ISP levels as high as 30,000 seconds[13].

v. Rubbia's engine (optional: superconductive MPD rocket)

This engine utilizes nuclear fission to heat a working propellant, effectively converting nuclear potential energy into fission fragment kinetic energy—it has also been theorized that the heat generated by the engine could be used to power a superconductive MPD rocket coupled with the Rubbia's engine. This coupling would drastically increase the system's ISP from 2500 to 56000 seconds[10].

vi. Solar Sail

The solar sail is a relatively simple concept. A solar sail directly utilizes the power output of the sun in the same way a sailboat utilizes the wind. As solar wind strikes a reflective sail surface, momentum is imparted into the sail system. A spacecraft equipped with a solar sail would have no need to carry fuel and would receive power inversely proportional to the square of the distance from the sun[9].

vii. Beamed Solar Sail

A beamed solar sail builds upon the previous concept. Instead of relying upon the sun as a source of power, a beamed solar sail utilizes the focused power of a ground-based laser[8]. An additional method could utilize a mirror system to focus the light from the sun. But this method would require an equal but opposite force to stabilize the mirror platform[14].

iix. Nuclear Fusion

Given the possibility of controlled nuclear fusion, a spacecraft could be propelled with various methods including pulsed micro-explosion (used by Project Daedalus and Project Longshot) and external nuclear pulse detonation (Project Orion). This propulsion method could use either Deuterium-Tritium or Deuterium-Helium-3 as its main fuel [9]. Nuclear fusion is discussed further in the power system section.

ix. Interstellar Hydrogen Ramjet

Similar to an atmospheric ramjet, an interstellar ramjet would utilize reusable fluid. But instead of air it would utilize the trace amounts of hydrogen present in interstellar space. Upon collection the hydrogen would be refined for use in a nuclear fusion reaction. However, the collection area necessary for such a system would vary from 10,000 to 10 million kilometers squared[9].

x. Antimatter

The final option to be assessed in this report is an antimatter propulsion system. Such a system would utilize the thrust generated by matter-antimatter annihilation. While this method can produce phenomenal ISP performance, the amount of antimatter necessary would far exceed the current production rate of the world[9].

Table 2. Performance Specifications for listed Propulsion Methods (subject to change). If a range of specifications is given, the lower value has been proven to some degree while the higher value is theoretical.

	ISP (s)	Necessary Power (kW)	Efficiency (%)	Classification
i	<500	n/a	n/a	Present
ii	15000-19300	40-250	70	Present/Near Future
iii	7000	50	70	Present/Near Future
iv	3000-30000	200	40-72	Present/Near Future
v	2500-56000	n/a	n/a	Near Future
vi	n/a	n/a	n/a	Present/Near Future
vii	n/a	Analysis-dependent	n/a	Distant Future
iix	Analysis-dependent	n/a	n/a	Distant Future
ix	Analysis-dependent	n/a	n/a	Far-Distant Future
x	10000000	n/a	n/a	Far-Distant Future

B. Power System

Power is an integral portion of all space missions. Large amounts of power are even more essential for supplying energy to advanced propulsion engines such as electrical or fusion propulsion. The most common type of propulsion for Earth orbiting spacecraft is photovoltaic power systems. Technological advancements on solar cells for generating photovoltaic power usually has centered on developing more efficient solar cells. Solar cell efficiency has been raised from approximately 10% to over 27% today. Although there has been discussion on being able to capture starlight for spacecraft moving between stars, the required solar array would need to be unrealistically large even with 100% efficient solar cells. A solar array would have to be 1500 times as large as it would be at Earth in order to provide the same amount of power that a spacecraft could collect at Earth. In addition, after around 223 K, solar cells start becoming less efficient because of the cold temperatures. Since the solar flux decreases with the inverse square law, solar power in an unreasonable power source[15,16].

The other source of commonly used power is chemical energy storage systems. These are primarily used to provide backup power in case the primary power source shuts down and to provide extra "burst power" for short periods of time. Batteries are the most common type of chemical energy storage and come in two types: primary and secondary. Primary are single discharge and are used only on missions that need a single use of electrical power. Secondary batteries are rechargeable and are used mostly for load leveling and providing power during eclipse periods for Earth orbiting spacecraft. Modern secondary batteries are made up of nickel-hydrogen or lithium[15,16, 17].

Since missions to other stars and planets will need to be independent of the sun, nuclear powered systems are the most likely candidates for a power source. There are three different types of nuclear power: radioisotope, fusion, and antimatter. Each of these is either researched, being developed, or speculation. Radioisotope power sources have been used for the cold, radiation intensive and poorly lit environments of space. This includes both distant interplanetary missions and missions close to the sun. Advances in radioisotope thermoelectric generators (RTG) are to increase power conversion efficiency in order to decrease the amount of nuclear material. The heat-producing radioisotope of the RTG is plutionium-238 for U.S.-based RTGs. The thermal power from nuclear material is transmitted to thermoelectric elements. These thermoelectric elements convert the thermal power into electoral power before sending it to the spacecraft. Advancements to RTGs are advanced Stirling radioisotope generators (ASRG) to be much more efficient using the Stirling conversion system that will reduce the amount of plutonium-238 required. ASRGs could provide 7 We/kg compared to around 2.7 We/kg for RTGs. This is important because the U.S. no longer produces plutonium-238. Another type of radioisotope power sources is the radioisotope electric propulsion (REP) which would use the radioisotope to power electric propulsion thrusters. This could be used to help get an interstellar spacecraft out of the solar system. However, one drawback is the degradation of these radioisotopes. ASRGs are the most advanced type of RTG but still only have a half-life of 87 years. Since the purposed mission for this paper is to Gliese 581, over 20 light years away, the transit time alone will be on the order of hundreds of years. This makes RTGs infeasible in their current state. A new material with a half life on the order of thousands of years would need to be incorporated as the heart of the RTG system in order for them to be a viable power source for interstellar travel to Gliese 581[15,18].

Nuclear fusion power is another type of nuclear power. Nuclear fusion has the potential of powering interplanetary and possibly interstellar missions. Light nuclides have a relatively small binding energy per nucleon compared to heavier nuclei like uranium and plutonium. The fusion of light nuclei such as deuterons and tritons results in the release of large amount of energy per nucleon. The most difficult aspect of nuclear fusion is harnessing enough energy to overcome the electrostatic repulsion of the positive charges to start the reaction. In addition, the plasma has to be confined long enough for the reactions to occur. Energy release per atomic mass unit for nuclear fusion is almost 4.75 times greater than that of provided from nuclear fission with a uranium core. Theoretically, nuclear fusion can reach 3.8MeV/amu. There are two different approaches to nuclear fusion, inertial confinement fusion and magnetic confinement fusion. Inertial confinement fusion uses a high power source, such as lasers, to compress a pellet of fusion fuel to the ignition conditions required to achieve fusion. Magnetic confinement fusion utilizes strong magnetic fields to confine the fusion plasma. Both are thought to provide about the same performance, however, using magnetic confinement may weigh more due to the large magnets that must be present. Nuclear fusion technology seems like the most likely technology to power a spacecraft on an interstellar mission in the future due to its higher power output[15].

The final, more speculative, nuclear technology is antimatter power. Antimatter annihilation by combining it with matter offers the greatest specific energy of any known reaction. The specific energy of antimatter annihilation is 9E16 J/kg which is larger than fusion 3E14 J/kg, fission (RTGs) 8E13 J/kg and chemical 1E7 J/kg. In addition, it is theorized that antimatter annihilation can be created without the need of a complex reactor subsystem like that of nuclear fusion. It should be noted that no antimatter power sources exist. It is also not known how efficient the conversion from the antimatter conversion to Watt energy would be. Antimatter is thought to be the best source of power[15].

C. Communications

Every spacecraft and satellite that has left the Earth has possessed some sort of dedicated communications subsystem and an interstellar probe will be no exception. In order to transmit and receive data over a distance of twenty light years will demand one of the most powerful system ever conceived. If the distance to Gliese 581 was equivalent to the distance between Los Angeles and New York City, the moon would be located a pencil's width away on the same scale. Considering that radio waves encounter space propagation loss proportional to the square of the transmitter-receiver separation distance, the vast distances associated with interstellar travel will be a difficult

problem to overcome[17]. Additional problems associated with this subsystem include the necessity of protecting any antennas from dust damage and providing the necessary transmit power. Mauldin estimates that a 100-m antenna dish will require 1 MW of power to establish minimum detection at 10 LY[14].

One method of improving communications involves the use of the sun as a naturally occurring focusing lens. As Einstein predicted in 1936, light that passes near a significant gravity field will bend towards the gravitational source. Light that passes the edge of the sun is bent to a focal point at approximately 550 AU. This focal point can be exploited as a gravitational lens to increase the effective antenna gain and improve the communications link[19]. A relay station established at 550 AU from the sun in the opposite direction of Gliese 581 could enable this method.

D. Orbital Trajectory

There are hundreds of different possible planets to visit beyond our solar system. In selecting possible destinations for the interstellar mission, the factors considered were proximity to Earth, possibility of life and scientific interest. Most detected exoplanets are giant (Jupiter sized) planets. One possibility is Eps Eridani b, which is the closest planet to our solar system at 3.2 pc (1 pc is 3.08568025e13 km), or around 10 light years away. Eps Eridani b is thought to have an orbital period around 2500 days with a semi major axis of around 3.39 AU. In addition, there is another unconfirmed planet in the eps Eridani system thought to be quite small[20]. However, the closest habitable planet lies in the Gliese 581 system. Gliese 581 d is thought to be a "super Earth" with a mass 8.3 times larger than that of Earth's. The Gliese 581 system is around 6.27 pc, which is around 20 light years away [21,22]. Another scientifically interesting planet is that of HD 209458b. Hubble picked up traces of methane, water vapor and carbon dioxide from this planet using near-infrared spectrometry. HD 209458b was the first planet with a detected atmosphere and is about 69% the mass of Jupiter. However, this planet is around 48 pc away (150 light years). In addition, it is the only detected planet in its system [23,24]. Because the Gliese 581 system meets all of the parameters in discussing possible destinations it has been chosen as the destination of this mission. The system has multiple planets for scientific observation as opposed to star systems with just one planet; this would allow scientists to gather significantly more data and makes a long duration mission outside of the solar system more worthwhile. In addition, the presence of a super Earth in the habitable zone makes it an even more intriguing option and it is not thought to be a completely unfeasible distance away for the purposes of this report. Figure 1 shows the location and distance of Gliese 581 relative to the solar system and the galactic center.

The Gliese 581 system is the 89th closest star to the Solar system and has a red dwarf star at its center which has a mass around 1/3 of the sun with at least five planets and possibly a sixth. In addition to Gliese 581 d, which lies in the habitable zone, it has three other confirmed planets and 1 unconfirmed planet in the system. An artist's representation of the Gliese system and the habitable zone is shown below,

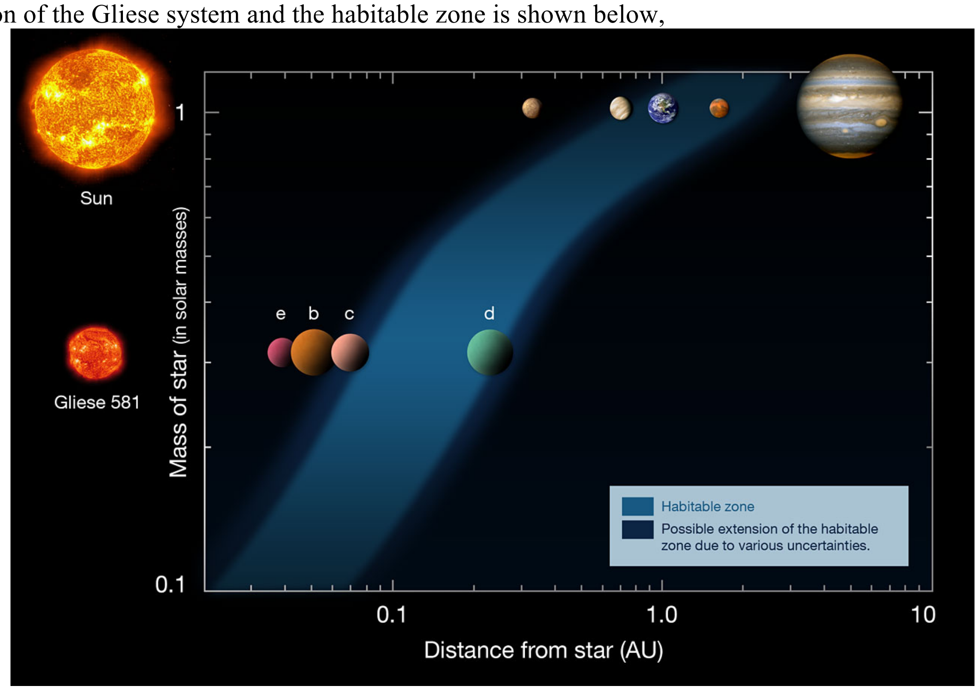

Figure 1. Artist's representation of the Gliese 581 system showing the habitable zone.

As can be seen in the figure above, because Gliese 581 is so much smaller than the Solar, Gliese 581's habitable zone is much closer to it than the Sun's habitable zone. The habitable zone extends out to about where Mercury is in the Solar system. Gliese 581 c is on the edge of the habitable zone and could be another "super Earth" (having about 5 times the mass of Earth). However, it is expected that Gliese 581 c has a great greenhouse gas effect and could not be habitable like that of Venus, which is on the edge of the habitable zone in the Solar system. Another planet Gliese 581 g 's existence is not yet confirmed by thought to exist in the middle of the habitable zone orbiting between Gliese 581 d and Gliese 581 c and has the greatest chance of having water. The possible existence of Gliese 581 g is another large reason for visiting the system because of the chance of two planets in the habitable zone.

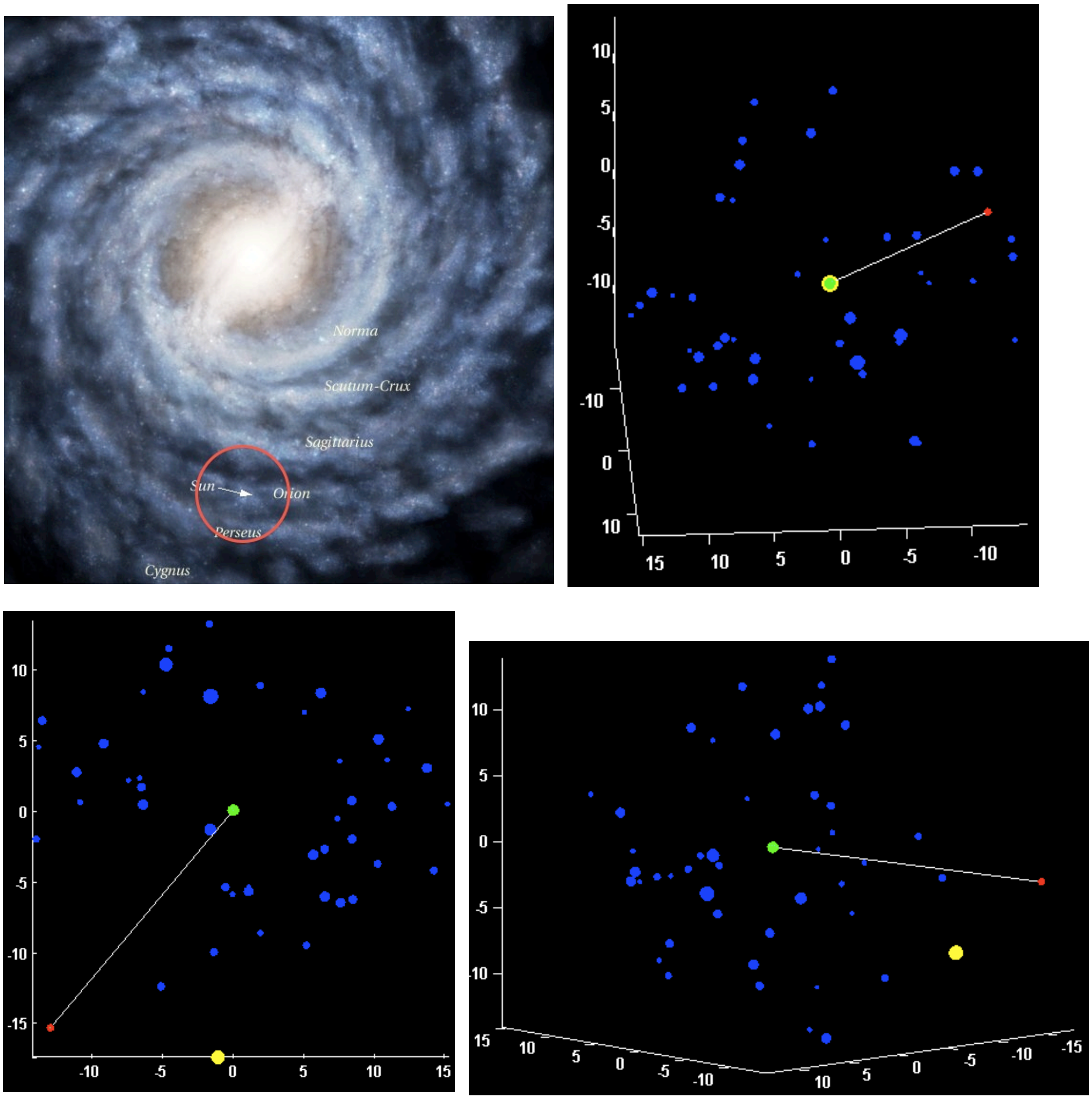

Figure 2. Top-left: The Milky Way Galaxy[25]—the red circle has a radius of 10,000 LY. The other three images occupy about 0.000001% the space within the circle (10 units out of a billion). Top-right: The center green object designates Earth, the red object represents Gliese 581; blue objects designate the closest 50 stars to the Sun. The relative size of each object is proportional to the star's sphere of influence and the direction of the Galactic center is straight into the page. Scale is in LY. Bottom-left/Bottom-right: Alternate orientations of the top-right image. Galactic center is represented in yellow.

There are two types of missions for interstellar travel. The first type is considered a “short” mission but is still well beyond the lifetime of any spacecraft that has been launched. The short mission duration uses high exhaust velocity to achieve a mission lifetime around 50 years in order to complete the mission within the lifetime of designers. Type II missions involve 100 to 1000 year mission lifetimes using lower exhaust velocity engines. The two different types of mission are showed visually in the figure below. Type II missions require seeing the mission through multiple generations of scientists and engineers. It is thought that a Type I mission would only be feasible with a large technology jump, while a Type II mission is possible with only a more moderate jump. Missions beyond Type II are not considered because of the undertaking required in committing to a mission over 1000 years is unreasonable. Because of the velocity requirements to reach Gliese 581 during a Type I trajectory, a Type II trajectory is chosen to have a less technologically advanced design. It should be noted that these types of missions are considered for closer stars than Gliese 581 and therefore a slightly larger technology jump would be required before the orbital trajectory would be possible[8].

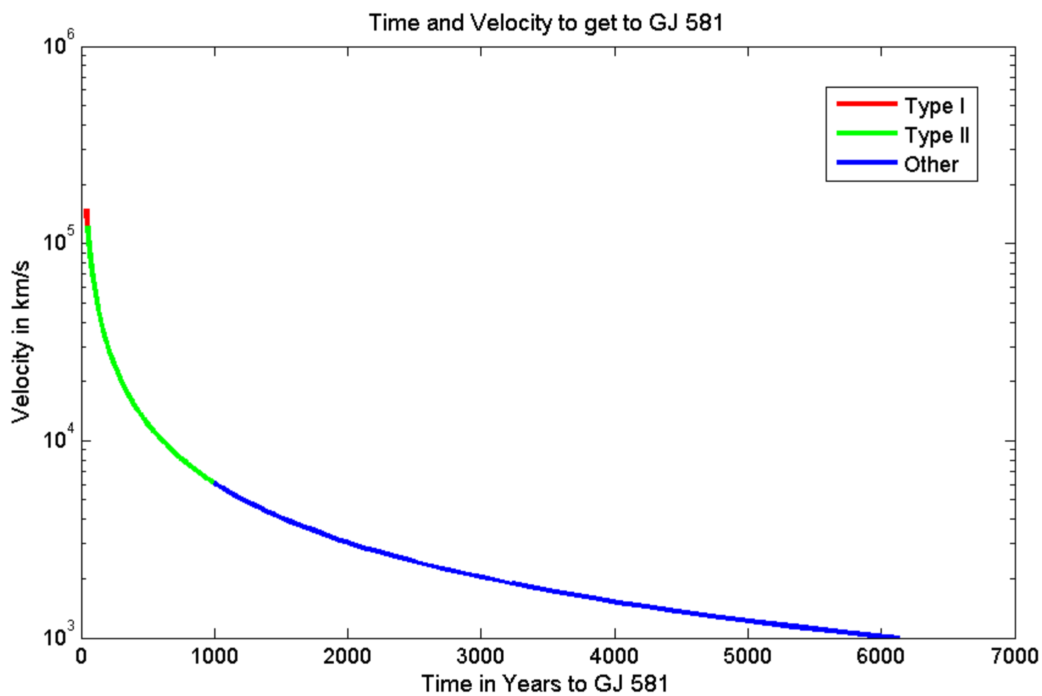

Figure 3. Velocity vs Time to reach Gliese 581. Trajectory type: red Type I, green Type II, blue > Type II

III. Analysis

A. Propulsion

Because of the variation in possible propulsion techniques, analysis will be accomplished with separate benchmarks for each set of techniques. Initial plans were to conduct trade studies based upon the ISP performance, necessary power for electrical systems, and projected system size and mass, however these plans were changed due to several reasons. Power, size, and mass considerations were removed when it became evident that those parameters of other subsystems (thermal, communications, and the fuel tanks themselves) would exceed those of the engines, thus nullifying the necessity of including them in the analysis. The inclusion of non-ISP propulsion methods, such as the solar sails or ramjet, will also necessitate a separate benchmark of size and implementation difficulty. For this analysis the spacecraft dry mass was selected to be 200,000 kg.

i. Present/Near Future Methods

As discussed in the orbital analysis section, the fuel mass estimates for ruled out all of the present and near future ISP options. The options with the best ISP of 30000 (theoretical VASIMR and the Rubbia w/MPD rocket) could not complete a 100-year mission, and needed 2.24E184 kg of fuel for a 200-year mission. It was plain to see

that more powerful propulsion methods would be required. The solar sail method was also ruled out, as the escape velocity achieved by a 16,000 km sail would propel the spacecraft to Gliese 581 in approximately 38400 years.

ii. Distant Future Methods

These methods were found to be much more reasonable than those available with current technology and are included in the final trade study.

a. Beamed Solar Sail

Due to the multiple variables involved in the design of a beamed solar sail—namely lens and sail size—additional analysis was devoted to this method. A laser wavelength of 1 mm was chosen along with a very optimistic sail loading value of 0.000001 kg/m^3 and reflectivity of 0.9. The acceleration, a, necessary to propel the probe in a given time frame was found with the following relationship,

$$a = \frac{(d_2 - d_1)}{\left(T\sqrt{2d_1}\right)^2} \quad (1)$$

where d1 is the distance from Earth to the laser turn-off point, d2 is the remaining distance to Gliese 581, and T is the transfer time. Laser turn-off point refers to the Earth-probe separation distance at which the Sun-based laser will cease firing, thus ending the acceleration of the probe. Sail diameter, D_S is then calculated with the equation,

$$D_S = \frac{2.4 d_1 \lambda_L}{D_L} \quad (2)$$

where λ_L is the wavelength of the laser and D_L is the diameter of the laser lens. The laser power, P_L, necessary to push the spacecraft with the aforementioned acceleration would be,

$$P_L = \frac{mca}{2r} \quad (3)$$

with spacecraft mass, m, speed of light, c, and sail reflectivity, r. The inverse nature of the laser lens size and sail size is demonstrated in Fig. 4. Because the difficulty of constructing a lens of this size in the far future is unknown, the ratio of lens to sail size was arbitrarily chosen to be 1:10. This ratio produced the following parameters for the system: 152 km lens, 1520 km sail, 7.44E6 kg mass, and 5.4E10 W laser power for a 100-year mission (1.3E10 W for 200-year). Because Fig. 4 demonstrated that the distance from laser turnoff had minimal effect upon the lens and sail size, the laser turn-off point was chosen to be at the distance halfway to Gliese 581. A visual reference to the size of this system can be seen in Fig. 5.

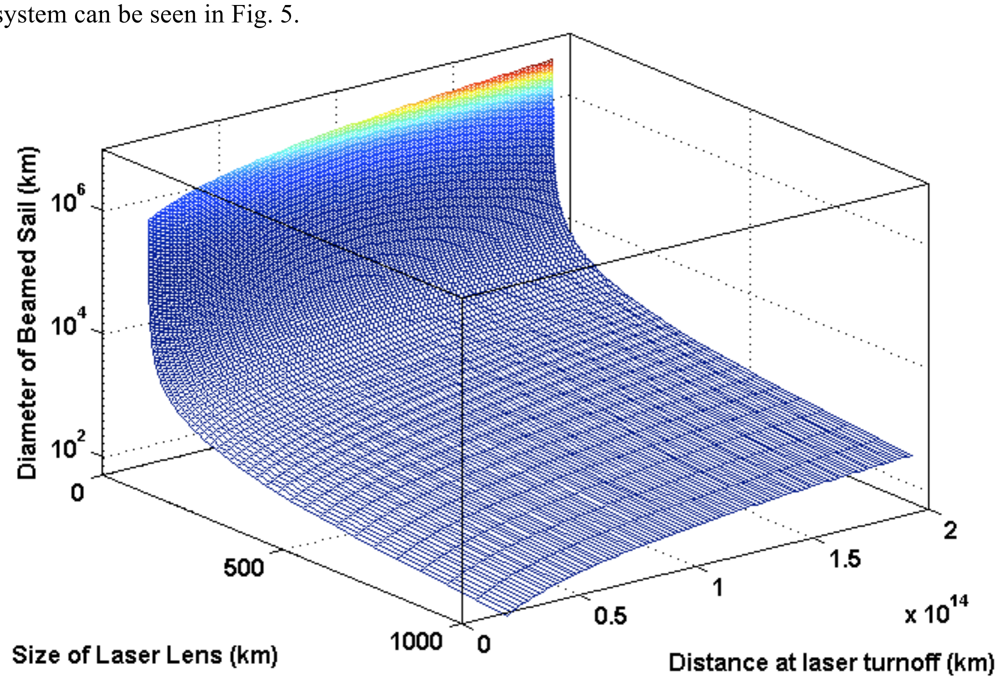

Figure 4. Possible combinations of lens and sail sizes, dependent on distance from Earth at laser turnoff.

b. Nuclear Fusion

The high ISP of the internal fusion method (2.65E6 s) guaranteed it as a top contender for propulsion. Unlike the impossible fuel masses of the lower ISP's, nuclear fusion enabled a much more doable system—Table 3 lists the calculated fuel mass and fuel tank diameter. Volume was determined from mass and density with the assumptions that the fuel was held in a spherical tank and had a density of 89.1 kg/m^3 (converted from a fuel pellet listed value for a Deuterium + Helium-3 reaction) [8].

Table 3. Fuel mass and volume of a three-stage internal nuclear fusion spacecraft—100-year and 200-year mission.

Mission Transfer Time	Stage 1		Stage 2		Stage 3		Total Mass (kg)
	Mass (kg)	Diameter (m)	Mass (kg)	Diameter (m)	Mass (kg)	Diameter (m)	
100-year	1.82E7	157	2.19E6	77	1.92E6	74	2.23E7
200-year	1.19E6	63	2.76E5	39	4.51E5	46	1.92E6

Visual approximations of the interstellar probe with the nuclear fusion propulsion system can be found in Section IV of this report. It is evident that a main factor for choosing between a 100-year and 200-year mission will be the necessary fuel mass, as the shorter mission requires a 1061% increase in mass.

iii. Far-Distant Future

a. Interstellar Hydrogen Ramjet

Another exciting possibility for propulsion, the interstellar ramjet was analyzed with the following assumptions: the abundance of hydrogen in interstellar space is a conservative 1E-21 kg/m^3, fusion energy of the Deuterium+ Tritium product is 3.37E14 J/kg, and the presence of hydrogen is uniform in the interstellar medium[8]. The area of the collection scoop necessary to provide the necessary acceleration was calculated by the following relationship,

$$A = \frac{am}{\rho e} \tag{4}$$

where ρ is the hydrogen density of space and e is the available fusion energy. For a 100-year mission, the required size of the collection scoop would be 275 km in diameter—a 200-year mission would require a 137 km diameter scoop. A visual reference to the size of these systems can be seen in Fig. 5. With a scoop loading ten times greater than that of the beamed sail (0.0001 kg/m^2), the mass of the ramjet system was approximately 2E5 kg for the 200-year mission and 7E5 kg for the 100-year mission.

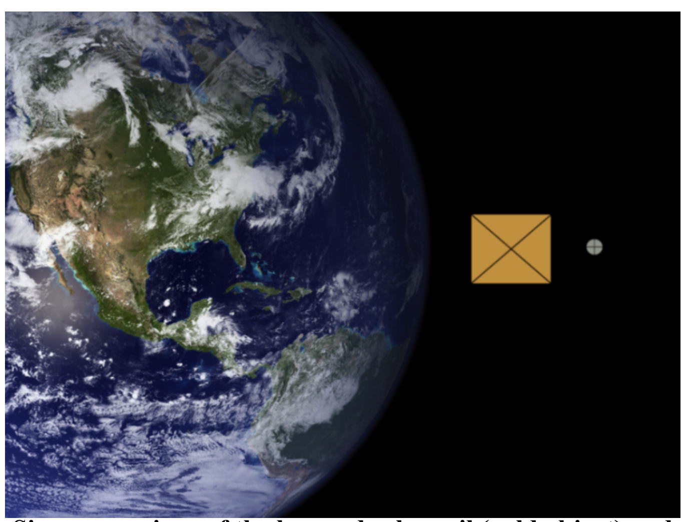

Figure 5. Approximate Size comparison of the beamed solar sail (gold object) and the ramjet propulsion (gray object) systems with the Earth.

b. Antimatter

Arguably, Gene Roddenberry's top choice for space exploration is an engine that utilizes the energy of matter-antimatter annihilation was the final possibility. With the highest ISP of all the considerations, the antimatter propulsion system enjoys a low mass of 4.97E5 kg for the 100-year mission, and 1.73E5 kg for the 200-year mission. However, the distant-future status of the technology necessary for this option severely reduces its likelihood for selection. The current price of antimatter generation is approximately $100 billion/mg—an astonishing figure that, even if greatly reduced in the future, will be an imposing impediment to the implementation of this propulsion method[8].

iv. Trade Study and Method Selection

Due to the decrease in possible propulsion methods, parameters of the trade study were reduced to mass and implementation difficulty, or rather, technology availability. Points for implementation difficulty were taken away for the following reasons: excessive necessary energy source (beamed sail -2), undeveloped technology (fusion, ramjet, antimatter -1), excessive size (sail, ramjet -1), and very expensive fuel source (antimatter -2). This trade study concluded that nuclear fusion was the best option for both the 100-year and 200-year missions (although the ramjet is shown to have the same score as fusion, its mass value is less well known and is likely more than what was estimated).

Table 4. Trade Study of propulsion methods—higher numbers indicate optimal choices (w= weight). Ratings are given in following format: 100-year/200-year.

	Beamed Sail	**Fusion**	Ramjet	Antimatter
Mass (kg, w=1)	2/2	**1/3**	4/5	4/5
Implementation Difficulty (w=3)	2	**4**	3	2
Total	10/10	**13/15**	13/14	10/11

B. Power System

The projected future goals of each energy type of power are 1000 We/kg for Photovoltaic at 1 AU from the sun, 10 We/kg for radioisotope, and 1000 We/kg for nuclear fusion while antimatter is thought to be orders of magnitude above that of fusion. These projected results for the future of powering a spacecraft show that eventually, nuclear fusion would be the most likely candidate (assuming antimatter technology is too far away) to power an interstellar mission a few hundred years from now.[15]

There are many different types of nuclear fusion reactions to choose from when considering powering a spacecraft. Some of these options are shown in the table below,

Table 5. Fusion Reactions

Reaction	Total Energy release (MeV)	Energy/mass release (MeV/amu)
$^1H + ^2H \rightarrow ^3He + \gamma$	5.5	1.8
$^2H + ^2H \rightarrow ^3H + ^1H$	4.0	1.0
$^2H + ^3H \rightarrow ^4He + n$	17.6	3.5
$^2H + ^3He \rightarrow ^4He + ^1H$	18.4	3.8
$^2H + ^6Li \rightarrow ^4He + ^4He$	22.4	2.8
$^3H + ^3H \rightarrow ^4He + n + n$	11.3	1.9
$^3He + ^3He \rightarrow ^4He + ^1H + ^1H$	12.9	2.1

For such a long duration mission, ^3H (Tritium) is not feasible to use as the basis of the reaction for nuclear fusion. This is because Tritium has a half-life of just less than 13 years making it unusable for the proposed length of this mission. ^2H, ^3He and ^6Li are all stable elements and can be used for a long duration mission without worrying about decay. Because of the high energy to mass ratio, the reaction of ^2H (Deuterium) and ^3He (Tralphium) is chosen as the sources of nuclear fusion power. There has also been analysis done already on the $^2H + ^3He$ reaction. This reaction will provide around 493 MW-h per 3 g of Deuterium and Tralphium used in the reaction. The main driver of the power requirement is heating the spacecraft consistently for a few hundred years. A simple thermal analysis was performed in order to obtain a rough estimate of how much power is required to heat the spacecraft. To

perform this analysis, Patran running SINDA-G and SINDA-RAD model was used for steady state analysis of a simplified version of the spacecraft. The model is shown below,

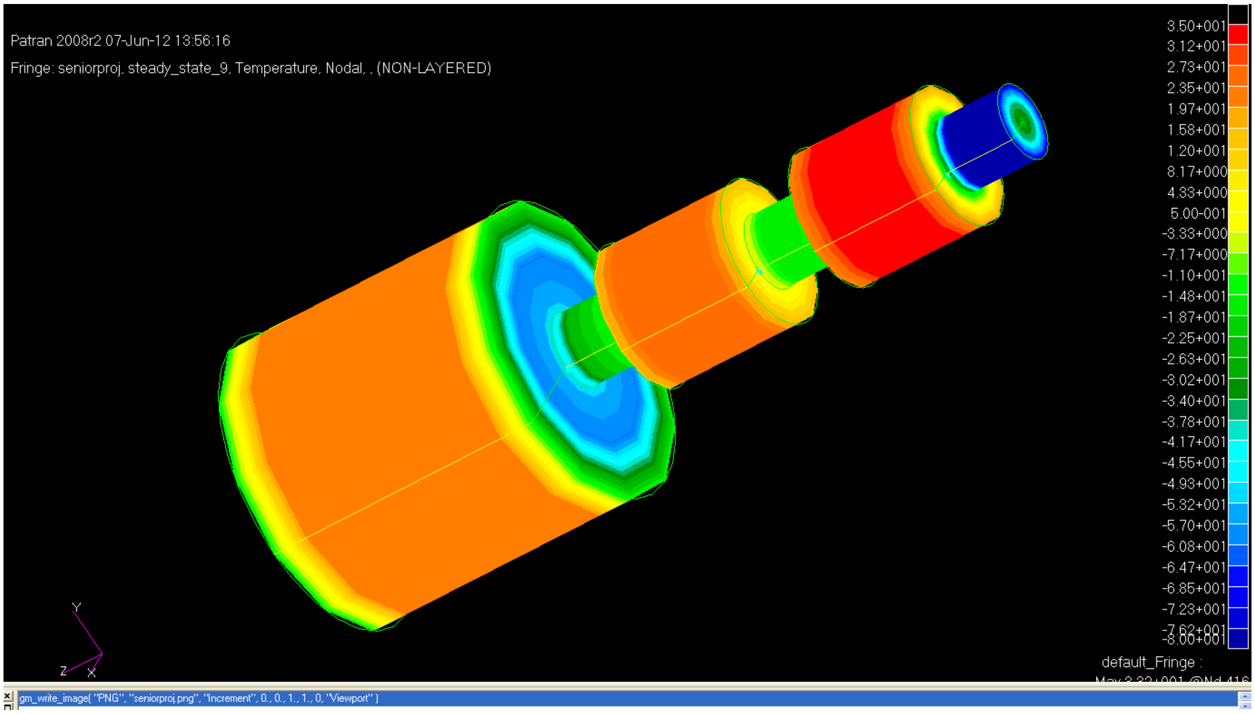

Figure 6. Rough Patran model of the spacecraft.

The model shows the spacecraft with three tanks for staging that will be discussed further in the report. For simplicity, the tanks are modeled as cylinders. For the thermal model, the entire spacecraft was assumed to be covered in multi-layer insulation (MLI) with an emissivity* value of .04 while the largest tank is assumed an emissivity* value of .03. A total of 1.88 MW is needed to maintain the spacecraft at temperatures of 22^{o}C for the large tank, 27^{o}C for the middle tank, and 33^{o}C for the final tank. The electronics sections of the spacecraft are kept at around -18^{o}C. The largest tank requires 1 MW to keep heated, however, because of the staging of the spacecraft, this tank will be jettisoned after the first burn is completed. In order to keep the spacecraft at a reasonable temperature, the first order analysis indicates that less than 1 MW of nominal power must be used throughout the mission for thermal purposes. Since this is drastically more power than the power requirements for anything else on the spacecraft it is conservatively assumed that 1 MW nominal power is sufficient for the mission for all devices in the spacecraft including power for thermal. Using 1 MW for 200 years is roughly 1.7532e12 W-h. This equates to a best guess estimate mass of 1185 kg of mass for the fuel of the power system. This would be just a small portion of the nearly 200000 kg payload delivered mass to Gliese 581. This high nominal power requirement drives wanting the best energy to mass ratio for the nuclear fusion reaction and the choice of a ^{2}H and ^{3}He reaction for the power subsystem.

One problem with using this is, while there is ^{2}H on Earth, there is a very scarce amount of ^{3}He here on Earth. There is enough that tests could be conducted in order to verify the fusion reaction and converting it into useable power or thrust, but there is not enough to use for a Type II interstellar mission. However, there is ample amounts that can be harvested from the moon from a lunar mine type facility or even the gas giants such as Jupiter, Saturn, and Uranus. ^{3}He is thought to be brought by solar winds, deposited into the lunar surface over the past few billion years, and spread a few meters deep by meteorite bombardments. There is thought to be on the order of 10^{9} kg of ^{3}He on the Lunar surface which would provide more than enough fuel for this type of mission. Therefore, an additional assumption that has to be made is there will be a technology leap and lunar harvesting of ^{3}He in the next few hundred years which must take place before this mission. There should be ample incentive to harvest ^{3}He from the moon as it can also be used in terrestrial applications as an energy source. In addition, beyond the lunar resources of ^{3}He, there are enormous quantities of both ^{3}He and ^{2}H in the gas giants that could also be reasonably obtained in the next few hundred years.[26]

C. Communications

All communications analysis was performed with the use of standard link equations outlined in SMAD[17]. The MATLAB codes *ZELDA.m* and *ZELDAII.m* were utilized throughout the analysis and the following section details the process of *communications_analysis.m*. The primary goal of the communications subsystem is to achieve a data rate of at least 10 kb/s, with secondary goals to decrease system implementation difficulty (cost and size).

i. Ground Station Selection

The first step in the analysis was selection of a ground station. A trade study was conducted by comparing the gain advantages and implementation difficulty of multiple ground station types. The following parabolic antenna setup options were considered: 1) 70 m, 2) four arrayed 34 m, 3) eight arrayed 34 m, 4) 140 m orbiting, and 5) 17 arrayed 34 m. For the options with arrayed antennas, gain was calculated for a single antenna with an effective area equal to that of the combined array. Gain was calculated with the equation,

$$gain = -159.59 + 20\log(D_C) + 20\log(f) + 10\log(n) \tag{5}$$

where D_C is effective diameter, f is frequency, and n is antenna efficiency. For the entirety of the analysis, frequency was assumed to be Ka-Band 32.3 GHz and efficiency was assumed to be 0.55. Table 6 shows the results of the trade study for ground station selection: Option 4. It is conclusive that a single, large orbiting antenna will be the optimal selection for a ground station. Not considered in the trade study is the fact that an orbiting antenna can have the additional benefit of increased visibility with the interstellar probe, as it will not be susceptible to blackouts caused by the Earth's rotation.

Table 6. Ground Station Trade Study—higher numbers indicate optimal selection. (w=weight)

	Option 1	Option 2	Option 3	**Option 4**	Option 5
Gain (w=3)	1	1	2	**5**	5
Implementation Difficulty (w=1)	5	5	4	**2**	1
Total	8	8	10	**17**	16

ii Link Method Selection

In addition to the frequency and efficiency values mentioned earlier, the following assumptions were made for link analysis: signal to noise ratio of 10 dB, pointing receive of 0.001° (this value was changed for some portions of the analysis), and system noise temperature of 15K. It was initially planned to analyze four potential communication methods of downlinking from the interstellar probe to Earth. The first method was the most basic of the four ideas: direct link between the probe and Earth.

a. Direct Link

The estimated data rate was calculated for a path length of 1.9205E14 km with the receive antenna equal to 140 meters with no atmospheric loss (the results of the ground trade study). Figure 7 shows the calculated bit rate for a variety of transmit antenna diameters and transmit powers.

It is apparent from Fig. 7 that a direct link would be unfeasible—the extreme case of 10 kW transmit power with a 200 m dish could barely achieve emergency data rate levels.

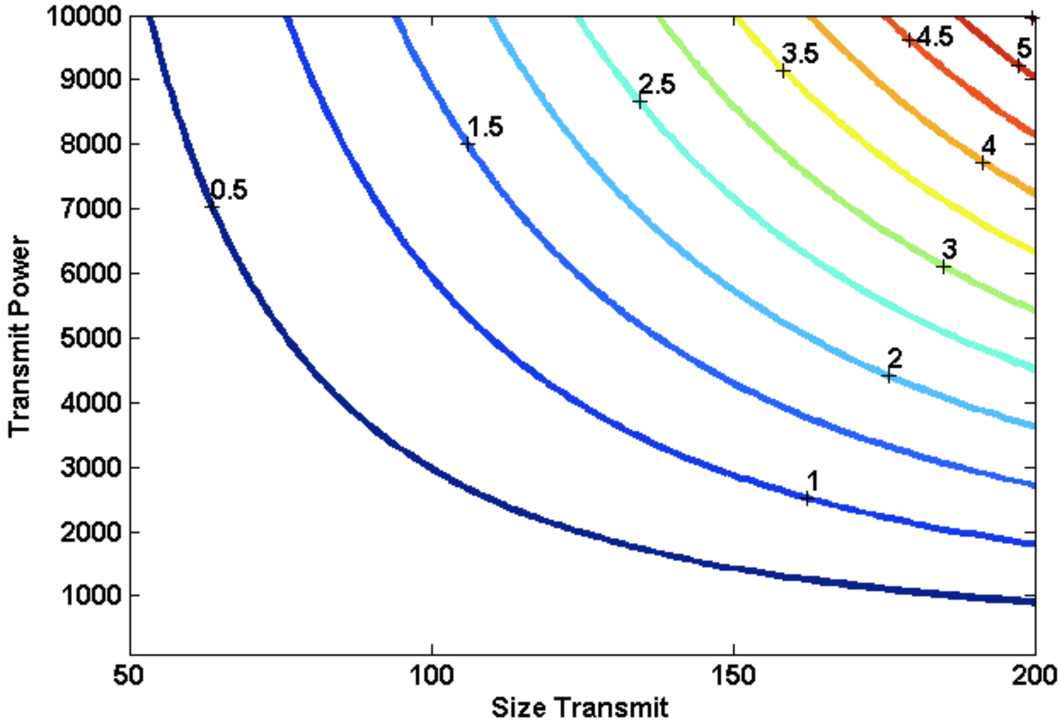

Figure 7. Transmit Power (W) vs. Transmit Antenna Diameter (m) for direct link between interstellar probe and Earth, contour lines are calculated bit rate (bps).

b. Additional Gain from Sun Gravitational Focus Lens

With the gravitational lens method employed, the additional gain would be equal to,

$$Gain\_sun = \frac{4\pi^2 r_{sch}}{\lambda} \tag{6}$$

where r_{sch} is the Schwazschild radius and λ is wavelength. For a frequency of 32.3 GHz (highest frequency supported by the Deep Space Network), the additional gain would be 71 dB. This additional gain greatly improved the calculated data rates. Due to increased data rate levels (5 to 8 orders of magnitude greater than the direct link), it was decided that further analysis could use the lower limit of transmit antenna size of 50 m. And because the link would be relayed at a station at 550 AU, a lower range of receive antenna sizes will be considered. Figures 8 and 9 show the calculated data rates for a 200 m (0.001° pointing accuracy) and 50 m (0.01° pointing accuracy) transmit antenna, respectively.

The results shown in Fig. 8 and 9 indicate that it is plausible to design a high science rate downlink, however it was decided that the range of receive sizes would be reduced once again. This allowed for a decrease in pointing accuracy. The authors theorize that this reduction in antenna size and pointing accuracy, while not in fact necessary, would likely decrease mission cost and implementation difficulty of a the attitude determination and control system. Figure 10 shows the performance values for the final iteration of the communications system, with a pointing accuracy of 0.01° for both transmit and receive (all of the previous figures used a receive accuracy of 0.001°).

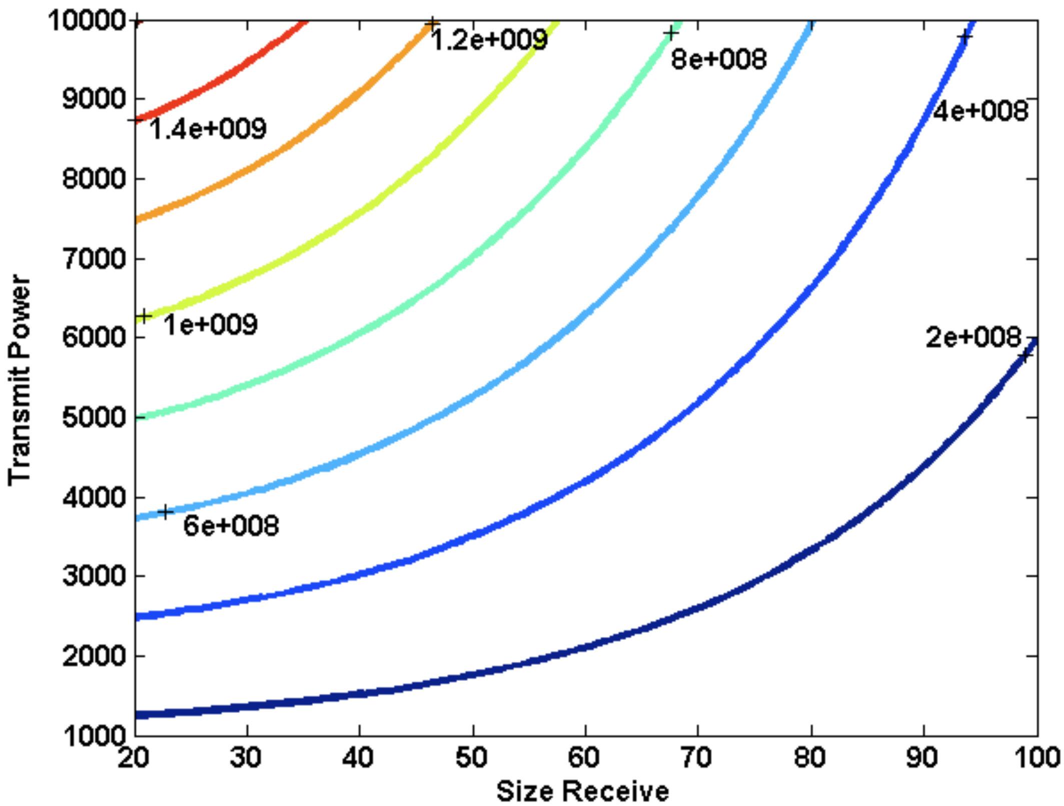

Figure 8. Transmit Power (W) vs. Receive Antenna Diameter (m), 200 m transmit antenna for link between interstellar probe and 550 AU relay station, contour lines are calculated bit rate (bps).

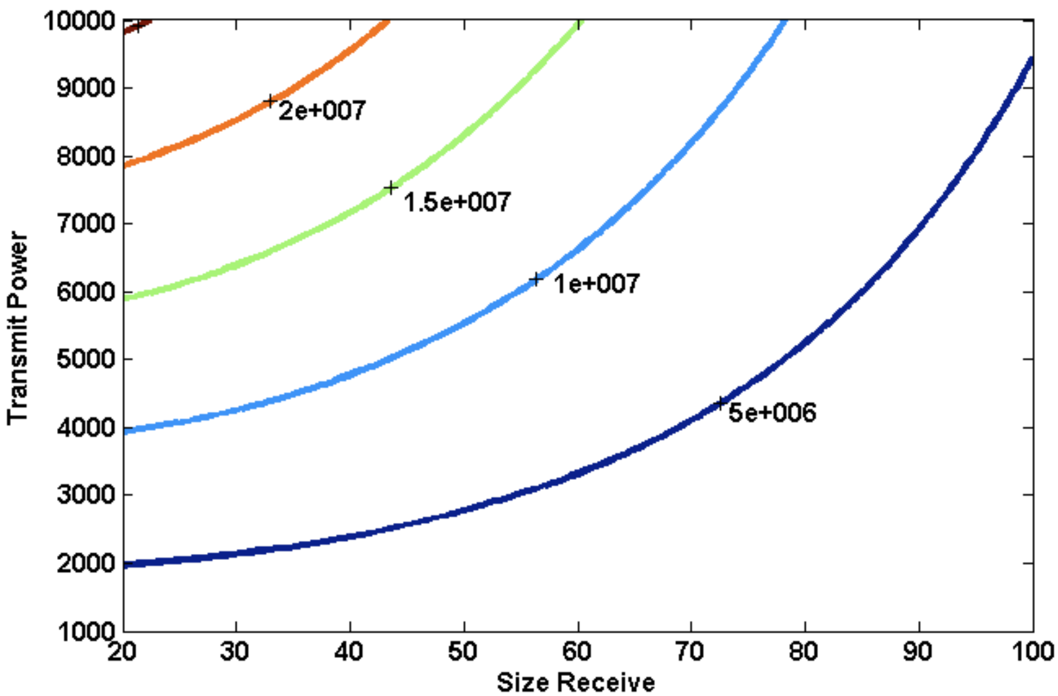

Figure 9. Transmit Power (W) vs. Receive Antenna Diameter (m), 50 m transmit antenna, for link between interstellar probe and 550 AU relay station, contour lines are calculated bit rate (bps).

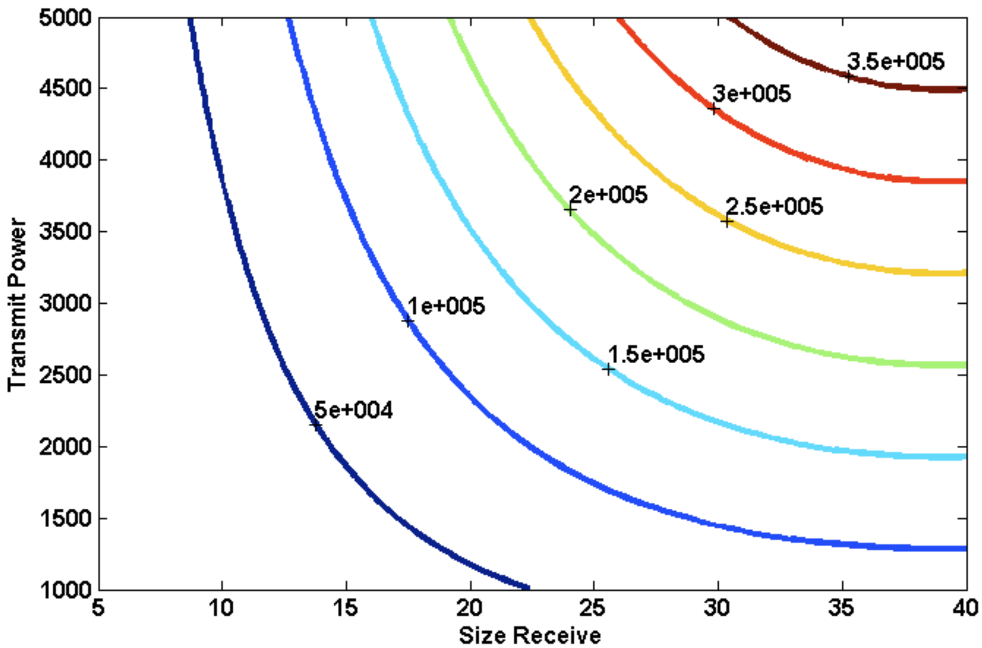

Figure 10. Transmit Power (W) vs. Receive Antenna Diameter (m), 50 m transmit antenna, for link between interstellar probe and 550 AU relay station, contour lines are calculated bit rate (bps).

iii. Additional Methods

Because the goal of 10 kb/s was exceeded with the implementation of the Sun focal lens effect, analysis of additional methods were not analyzed. The next possibility for communication dealt with the possibility of relay stations incrementally placed between Earth and Gliese 581. Based upon the data rates achieved by the direct method, this method would likely need dozens of relay stations. Such a scenario would greatly increase the mass of the spacecraft and necessary fuel.

Another possibility includes the use of laser communication. A significant increase in frequency has the potential to improve the expected data rates of the system. However, laser communication for deep space operations has yet to be tested and significant research and development remain before the field becomes a possibility[17].

iii. Final Subsystem Parameters and Link Budget

The communications subsystem chosen for this mission consists of: two 50 m transmit antennas on the interstellar probe (one for redundancy purposes or an increase in data rate), 22.5 m receive antenna at the sun focal point at 550 AU, and an orbiting antenna at Earth of an undetermined size (the initial size of 140 m, meant for a direct link, may be excessive). The associated link budget is shown in Table 7.

Table 7. Link Budget for communications downlink from Gliese 581 to Sun Focal relay station.

Parameter	Value
Frequency (GHz)	32.3
Path Length (km)	1.9205E14
Transmit Antenna Diameter (m)	50
Receive Antenna Diameter (m)	22.5
Transmit Antenna Gain (dB)	82
Receive Antenna Gain (+ Focal Gain) (dB)	75+71=146
Transmit Power RF (W)	1000
Transmit Antenna Pointing Offset (°)	0.01
Receive Antenna Pointing Offset (°)	0.01
Data Rate (bps)	50000

D. Orbital Trajectory

The first step in an interstellar mission is to escape the gravitational pull of the sun. The necessary escape velocity from the solar system is calculated to be 618 km/s. However, from the reference frame of Earth, the required escape velocity is only 42.1 km/s. Using the basic, linear, first order kinematic equations, the required average velocity can be computed along with the transit duration time the mission would require. Relativistic effects have been neglected for the purpose of this initial analysis. It should be noted that the effective mission time would be longer than the stated transit time not just because of the science collection that would need to occur at Gliese 581, but also because of the communication time. Gliese 581 is around 20 light years away; data being sent back would require the additional 20 years in order to be received by engineers and scientists on Earth. Only a one dimensional analysis is performed because of the lack of curvature in an orbit between two stars so close together which are both relatively far from the galactic center. When propagating the orbit around the galactic center for 100 years to Gliese 581, the angle difference between the beginning and end vectors was found to be 8.065e-5 degrees. This was done using an Enke's method of propagation taking one day time steps for the one hundred years. Because of the extremely low difference in direction of the vector at the beginning and end, it was determined that a one dimensional analysis was sufficient for relatively close, Type II interstellar missions.

As Table 8 shows, in order to reach a transit time on the order of hundreds of years, an average velocity over 10,000 km/s is required. Assuming this average velocity this only provides a small window if a flyby of the scientific objectives were to occur. The assumption is made that scientific data can be collected within ± 2 AU and then the amount of time able to gather scientific data can be calculated.

Table 8. Linear Velocity to Gliese 581

Average Velocity (km/s)	% Light Speed	Transit Time (years)
1	0.0003	6130000
10	0.003	613000
100	0.03	61300
1000	.3	6130
10000	3	613
25000	8	245
61170	20.39	100
100000	33	61.3
300000	100	20.44

$$Time = \frac{4(149598000km)}{10000\frac{km}{s}} \quad (7)$$

This gives an answer of 59839 seconds or a little over 16.6 hours. 16.6 hours is not enough of a payoff for a transit time on the order of over 100 years. If a mission transit length of only 100 years were desired, this would correspond to only 2.7 hours to collect data. This analysis shows that a deceleration phase must occur in order to have enough time to make the mission worthwhile.

Based on the needed acceleration and deceleration phase, kinematic equations of 1D motion were used in order to determine the length of acceleration and deceleration phase for different mission lengths. The assumption is made that the acceleration is exactly equal to the deceleration in both time and amount of acceleration.

Table 9. Linear Acceleration Analysis to Gliese 581

Acceleration/Deceleration Phase	Cruise Phase	Transit Mission Time
.01 g for 1 year.	.0103c for 1980 years	1982 years
.01g for 5 years	.0516c for 391 years	401 years
.01g for 10 years	0.103c for 188 years	208 years
.1g for 1 years	.103c for 197 years	199 years
.1g for 5 years	.516c for 34.6 years	44.6 years
.5g for 1 year	.516c for 17.8 years	19.8 years
.5g for 2 years	~1c for 19 years	24 years

This table shows some basic analysis for the requirements of the acceleration needed from the propulsion system and for how long they would need to burn for. Realistically, there will be different sections of acceleration and deceleration and would not happen solely at the beginning and end of the transit phase of the mission. Accelerations that provide a speed of greater then 1c would not influence the mission because of limit on the speed of light. In addition, another consideration on the velocity of the spacecraft during this mission is any particles encountered during the transit phase would bombard the spacecraft at speeds on the order of .1c-.5c. This would present a significant technical obstacle to the survivability with no critical failures of the spacecraft on such a long duration mission. It is assumed that enough technological advances will have been made to shield against such particles[8].

Next, different mission lengths along with different propulsion types discussed above were analyzed in order to determine a propulsion fuel mass. It was discovered that any ISP under 300,000 seconds required more mass then that of the Earth for a one hundred year mission to both speed up and slow down and capture at Gliese 581. Because of this, only nuclear fusion is considered a viable propulsion system for a mission as far out as Gliese 581. The ^{2}H + ^{3}He reaction produces an ISP of 2.65E6 seconds. Using this ISP value different fuel masses were found.

Table 10. Fuel Masses for Various Types of Engines/ISPs

ISP, seconds	100 year transit (No Staging) kg	100 year transit (With staging) kg	200 year transit (No Staging) kg	200 year transit (With staging) kg
30,000 (VASMIR, Rubbia)	Infinite	1.67E186	2.24E184	3.87E95
2.65E6 (Fusion)	9.57E7	2.21E7	2.45E6	1.904E6
1.0E7 (Anti-Matter)	5.35E5	4.97E5	1.77E5	1.73E5

As can be seen in Table 10, there is a significant benefit to staging the spacecraft's acceleration into three parts. The spacecraft will have three stages, the first is stage will occur for 250 days at .1 g (.981 m/s), while the second stage will occur for 110 days at .1 g. The final stage will be the deceleration stage that will occur over the last year of the mission at .1 g. The table above also shows that the 30,000 ISP VASMIR or Rubbia Engines are not powerful enough to accomplish the mission in the desired time frame being over 150 order of magnitude higher than the mass of the Earth. Only nuclear fusion or anti-matter engines can obtain a more achievable future goal of fuel mass. Going to a two hundred year long mission with staging and a nuclear fusion engine using the ^{2}H and ^{3}He reaction, decreases the amount of fuel required from one hundred years by a full order of magnitude. A cap of two hundred years for the mission duration was arbitrarily chosen. In addition, because anti-matter technology is considered much further away then second generation fusion technology, the nuclear fusion engine was chosen.

IV. Spacecraft Models

Models of the fusion spacecraft concepts were made based upon approximate sizing of the propulsion and communications subsystem. These models were created with Pro/Engineer Creo Elements Pro 5 and are made to scale. The spacecraft are shown alongside recognizable objects for scale comparison: the Space Shuttle Enterprise and the Empire State Building. The large, spherical portions of the spacecraft are based upon the calculated volume of necessary fuel, and the cylindrical bodies were arbitrarily sized to accommodate additional spacecraft subsystems and payload. Each of the cylindrical bodies is a separate stage—thrusters for the later stages not shown. It should be noted that the number and size of the thrusters are chosen arbitrarily.

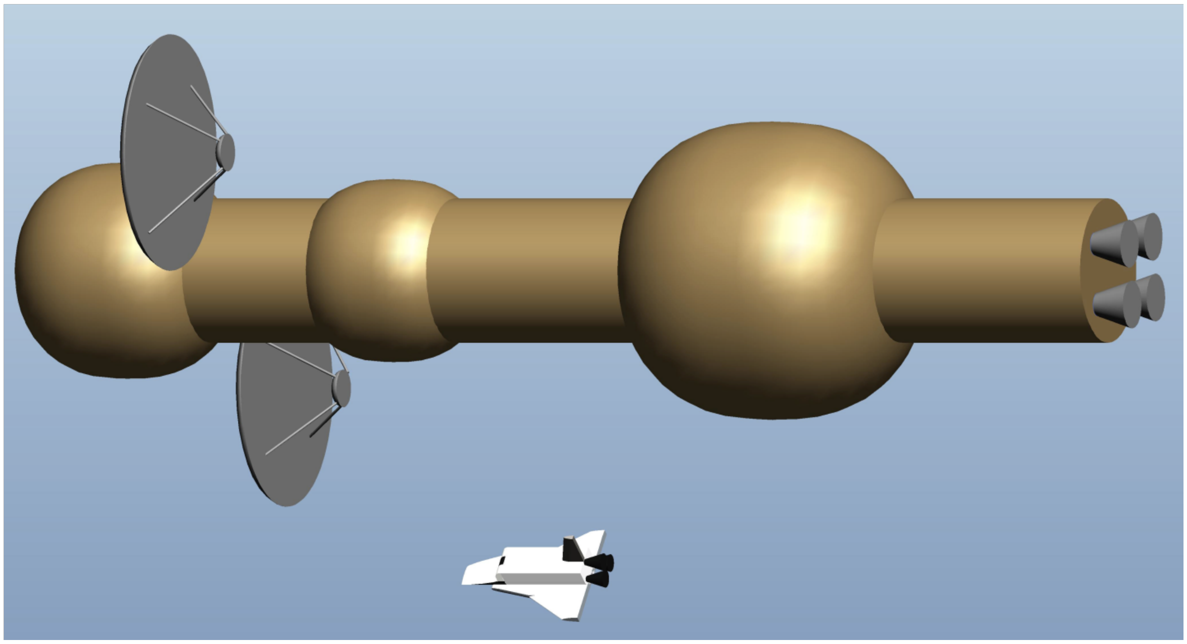
Figure 11. 200 Year Fusion Spacecraft scale comparison to Space Shuttle Enterprise.

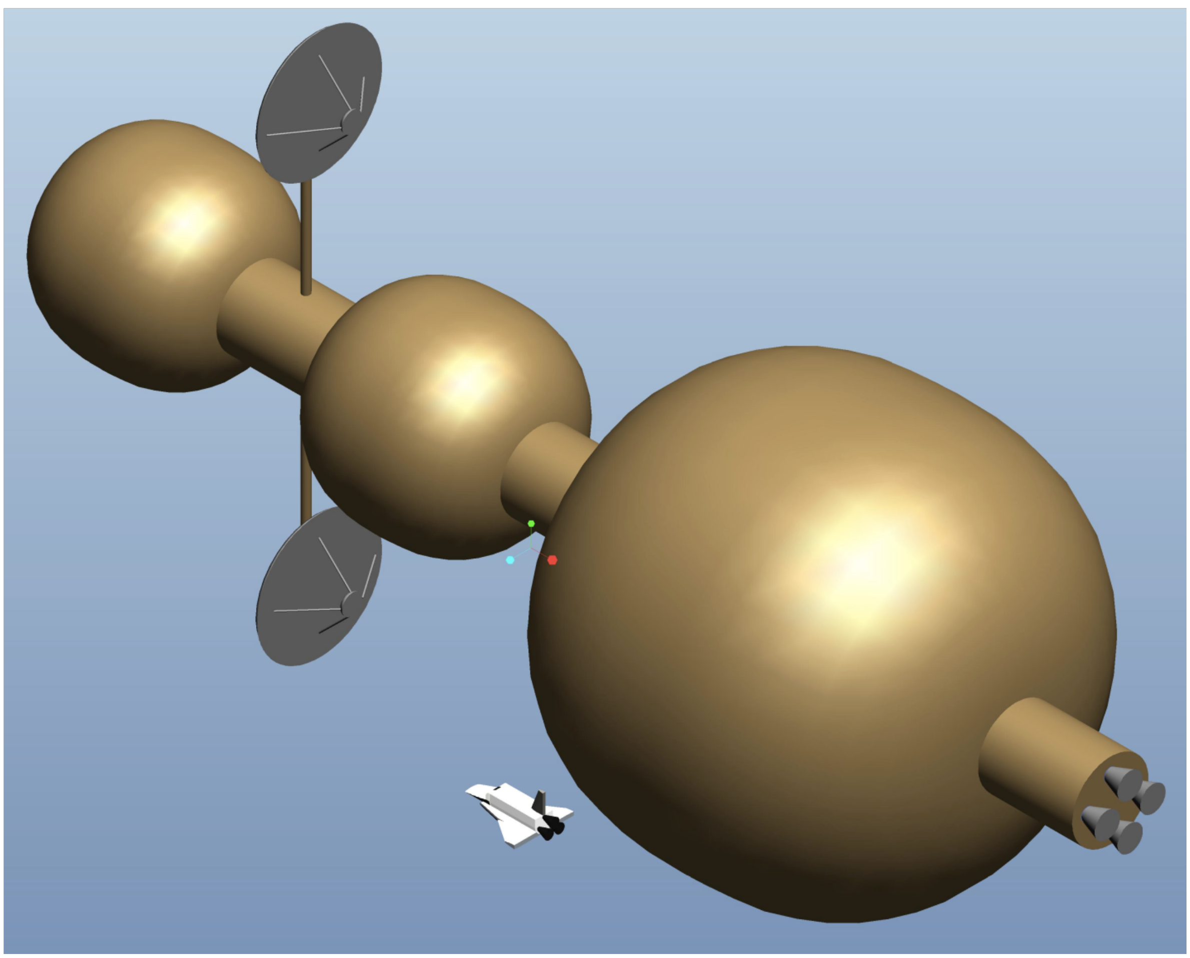
Figure 12. 100 Year Fusion Spacecraft scale comparison to Space Shuttle Enterprise.

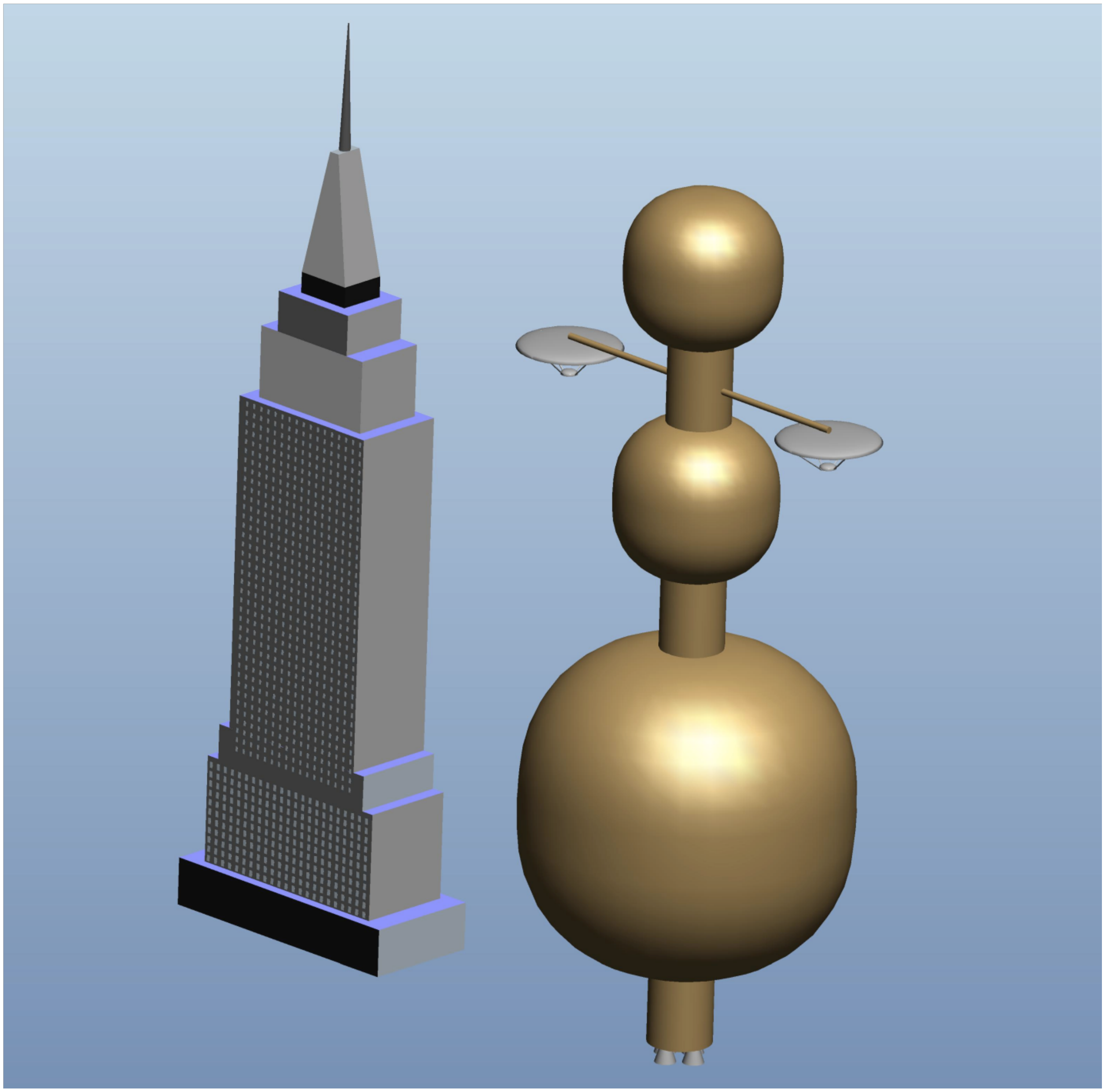

Figure 13. 100 Year Fusion Spacecraft scale comparison to the Empire State Building.

Figures 11 through 13 demonstrate that the size of these spacecraft will likely necessitate that construction must take place in orbit. It is clear that even the 200-year spacecraft (even single components such as the main bodies or the parabolic antennas) would be unable to fit in any modern launch vehicle fairing.

V. Conclusion

Gliese 581 has been chosen as the destination of the interstellar mission because of its similarity to the Solar system. It is the closest start with a planet in the habitable zone, a zone specified by a distance away from its star based on the stars mass where there are conditions to support life. The planet in the habitable zone is considered a super Earth and is approximately 8.3 times larger than Earth. In addition, the Gliese 581 system has five other known planets and one additional unconfirmed planet that could reside in the center of the habitable zone. Because it is a system with so many planets and the possibility of life, it is considered the best destination. However, in order to reach a system 20.3 light years away, a few technological leaps need to be made.

There are a few major obstacles to an interstellar mission to Gliese 581 that we feel can be met in the next few hundred years. The first is harvesting enough ^3He isotopes to function as both the power supply and fuel for nuclear fusion reactions. This can be accomplished all through lunar mining, since the moon is thought to possess enough ^3He for this mission, but might also require harvesting the gas giants in the Solar system. In addition the nuclear fusion process of ^3He + ^2H needs to be perfected more before a mission of this magnitude is flown. Secondly, a communications relay station must be built at 550 AU from the sun in order to benefit from the sun gravitational lens effect. At the focus of the lens effect, additional gain is provided to the link to enable transmit of data over the distance of 20 light years. In addition, because of the size of the spacecraft, it will have to be constructed in space. Large projects such as the ISS have been completed and over the next few hundred years a large-scale spacecraft of this magnitude should be possible to build. The difficulty of constructing large objects in space will also inhibit the implementation of other possible propulsion methods, such as the beamed solar sail or the interstellar hydrogen ramjet.

For future work, the reliability/survivability, ADCS and thermal systems need to be addressed. Because of the long duration mission, relying on components for one to two hundred years is a difficult undertaking. In addition, because of the size of the spacecraft, an ADCS system would likely require a large amount of resources and likely technology that has not yet been invented yet. Only a very basic, first order analysis of thermal from a rough power estimate was done in this report and more detailed analysis must be performed. More research could also be devoted to developing a method for sizing the scientific payload.

As the scientific interest in interstellar missions grows, public and private investment in interstellar research will likely increase as well. In late May 2012, the Defense Advanced Research Projects Agency chose to invest in the Dorothy Jemison Foundation for Excellence (led by former astronaut Mae Jemison) as part of the 100-Year Starship project[27]. No matter the source of investment, the engineering principles demonstrated in this project will remain an invaluable tool throughout conceptual and critical design. With exciting discoveries in exoplanetology and the rise of private space ventures, these authors firmly believe that an interstellar mission will launch within the next quarter millennium. An interstellar starship will shatter distance and speed records, set new precedents for scientific exploration, and likely transcend national borders as a worldwide effort.

Acknowledgements

The authors would like to acknowledge their advisor Dr. Kira Abercromby for her support and Joe Palomares for his help with Patran analysis.

Contact

For questions, comments, or requests for MATLAB support codes, please contact the authors at bschmalzel@gmail.com.

References

[1]Launius, R.D., McCurdy, H.E., *Robots in Space: Technology, Evolution, and Interplanetary Travel*, John Hopkins University Press, Baltimore, 2008.

[2]Santos, N.C., "Extra-solar planets: Detection methods and results," *New Astronomy Reviews*, Vol. 52, 2008, pp. 154-166.

[3]Schneider, J., "Interactive Extra-solar Planets Catalog," The Extrasolar Planets Encylopaedia, 2012. [http://exoplanet.eu/catalog.php. Accessed 3/15/12.]

[4]Borucki, J.W., Koch, D.G., Basri, G., Batalha, N., Brown, T.M, "Characteristics of planetary candidates observed by *Kepler*, II: Analysis of the first four months of data," *The Astrophysical Journal*, Vol. 736, No. 1, 2011.

[5]Greenfieldboyce, N., "Found: Earth-Like Planet That Might Be Right For Life," National Public Radio, December 2011. [http://libraries.uc.edu/libraries/ceas/instruction/classes/aero/cite.html. Accessed 3/14/12.]

[6]Harrison, A.A., *Spacefaring, The Human Dimension*, University of California Press, Berkeley, 2001.

[7]Long, K.F., Obousy, R.K., Tziolas, A.C., Mann, A., Osborne, R., Presby, A., Fogg, M., "PROJECT ICARUS: Son od Daedalus Flying Closer to Another Star," *Daedalus after 30 years symposium*, British Interplanetary Society,

[8]Long, K.F., *Deep Space Propulsion: A Roadmap to Interstellar Flight*, Springer, New York, 2012.

[9] Wertz, James Richard., David F. Everett, and Jeffery John. Puschell. *Space Mission Engineering: The New SMAD*. Hawthorne, CA: Microcosm, 2011. Print.

[10]Bruno, C., Accettura, A.G., Lu, F.K., "Advanced Propulsion Systems and Technologies, Today to 2020", *Progress in Astronautics and Aeronautics,* Vol. 223, AIAA, Reston, Virginia, 2008.

[11]Bramanti, C., Walker, R., Sutherland, O., Boswell, R., Charles, C., Fearn, D., Gonzalez Del Amo, J., Orlandi, M., "The Innovative Dual-Stage 4-Grid Ion Thruster Concept—Theory and Experimental Results," *IAC-06-C4.4.7.*

[12]Bering, E.A., "Performance Measurements and Technology Demonstration of the VASIMR VX-200," *Space 2010 Conference and Exposition,* AIAA, Anaheim, 2010.

[13]Kaku, M., *Physics of the Impossible:* A Scientific Exploration into the World of Phasers, Force Fields, Teleportation, and Time Travel, Anchor Books, New York, 2008.

[14]Mauldin, J.H., "Prospects for Interstellar Travel," *Science and Technology Series*, American Astronautical Society, Vol. 80, San Diego, 1992.

[15] Millis, Marc G., and Eric W. Davis. *Frontiers of Propulsion Science*. Reston, VA: American Institute of Aeronautics and Astronautics, 2009. Print.

[16]Surampudi S., Rapp, D., Cutts, J., and Khanna, S., *Assessment of Power Conversion and Energy Storage Techniques for Future Space Science Missions*. JPL, Space Power Workshop. April 2005. http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/38069/1/05-1006.pdf

[17] Wertz, James Richard. *Space Mission Analysis and Design*. El Segundo: Microcosm, 2003. Print.

[18]Lavery, D., *Final Programmatic Environmental Impact Statement for the Development of Advanced Radioisotope Power Systems*. NASA and U.S. Department of Energy. Washington D.C. September 2006.

[19]Maccone, C., "Interstellar radio links enhanced by exploiting the Sun as a Gravitational Lens," *Acta Astronautica* (2010), doi:10.1016/j.actaastro.2010.06.039.

[20]Extrasolar Planets Encyclopedia Star: eps Eridani. Accessed 3/16/2012. http://exoplanet.eu/star.php?st=eps+Eridani

[21] Bloh, W., Bounama, C., Cuntz, M., and Franck, S., "The habitability of Super-Earths in Gliese 581". *Astronomy and Astorphysics*. Vol 7939, February 2008.

[22]NASA Exoplanet Archive Gliese 581. Accessed 3/12/2012 http://exoplanetarchive.ipac.caltech.edu/cgi-bin/Sieve/nph-sieve?mission=ExoData&currentForm=Result&objectSearch&stripped=+&id=74995&aliases=/work/TMP_ZCQQNj_14674/ExoData/default/aliases_74995

[23] NASA Exoplanet Archive HD 209458. Accessed 3/12/2012 http://exoplanetarchive.ipac.caltech.edu/cgi-bin/Sieve/nph-sieve?mission=ExoData&currentForm=Result&objectSearch&dump&stripped=+&obj=HIP+108859&id=108859&MNAME=multi_tpfsim_uniqueid&aliases=/work/TMP_ZCQQNj_14674/ExoData/default/aliases_108859

[24] Swain, M., et al., "Water, Methane, and Carbon Dioxide Present in the Dayside Spectrum of Exoplanet HD 209458b". *Astrophysical Journal*. August 2009.

[25][http://www.atlasoftheuniverse.com/milkyway.html. Accessed 3/15/12.]

[26]Santarius, John F. "Lunar 3He, Fusion Propulsion, and Space Development." *NASA Astrophysics Data System* (1993).

[27]O'Neill, Ian, "Uniting the Planet for a Journey to Another Star", Discovery News, May 2012. [http://news.discovery.com/space/mae-jemison-darpa-100yss-interstellar-120529.html. Accessed 6/7/12].