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Interstellar Space Missions: Ultra-Reliability Requirements and Engineering Issues

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ABSTRACT

Although no interstellar space mission has been designated as yet by NASA, it and a number of other organizations such at the British Interplanetary Society (BIS) have long considered the possibility of a mission to interstellar space (for example, the NASA Interstellar Probe Mission proposed in 1999[1]) or to a nearby star (see the BIS's 1973-1978 Daedalus Project study[2]). Indeed, a number of conferences, papers, and books have addressed various aspects of such missions (e.g., Mallove and Matloff , 1989[3]; McElyea and Brin, 2003[4]; Kondo, 2003[5]; Frisbee, 2003[6]; Frisbee, 2004[7]; Gilster, 2004[8]). With the extended operation time of such missions in mind (typically 25-50 years), revolutionary reliability strategies need to be developed in the early design stages of these missions so that the vehicles may be maintained and, if necessary, easily reconfigured inflight. In addition, new design-for-reliability features will need to be invented to enhance the lifetime and improve the reliability of these vehicles. This study will provide an overview of the key potential reliability areas that will need to be considered in planning such truly long life missions. Specifically, the talk will:

1) Review current studies of long life missions and their requirements
2) Summarize key reliability requirements of representative long life missions
3) Recommend steps to address perceived shortfalls in current, long life reliability methods for interstellar space missions.

INTRODUCTION

An on-going theme in space research is the desire to actually travel to another solar system. This paper will briefly review previous studies of the feasibility of such a venture and the requirements that such a mission places on our current capabilities. Given the profound sociological and physiological problems that would need to be considered for a human mission, the study will concentrate on a robotic mission. Further, while it is unlikely in the next few decades that humanity will be able to execute a true interstellar mission, the possibility of a mission along the lines of the proposed Interstellar Probe (ISP) would be a possibility (indeed, the New Hoirzons Pluto-Kuiper Belt Mission or the continuing Voyager 1 and 2 missions could be considered pre-cursors for the ISP). Realistic concerns (aside from the key problem of selecting a propulsion system) for such missions will be their duration and the long term effects of exposure to the interstellar environment. These two issues will be the primary concerns of the study. Following a brief overview of current proposals for such long lived missions, possible constraints and requirements imposed by the issues will be addressed. By addressing these concerns, it is intended that this study will provide another step in our continuing journey to the stars.

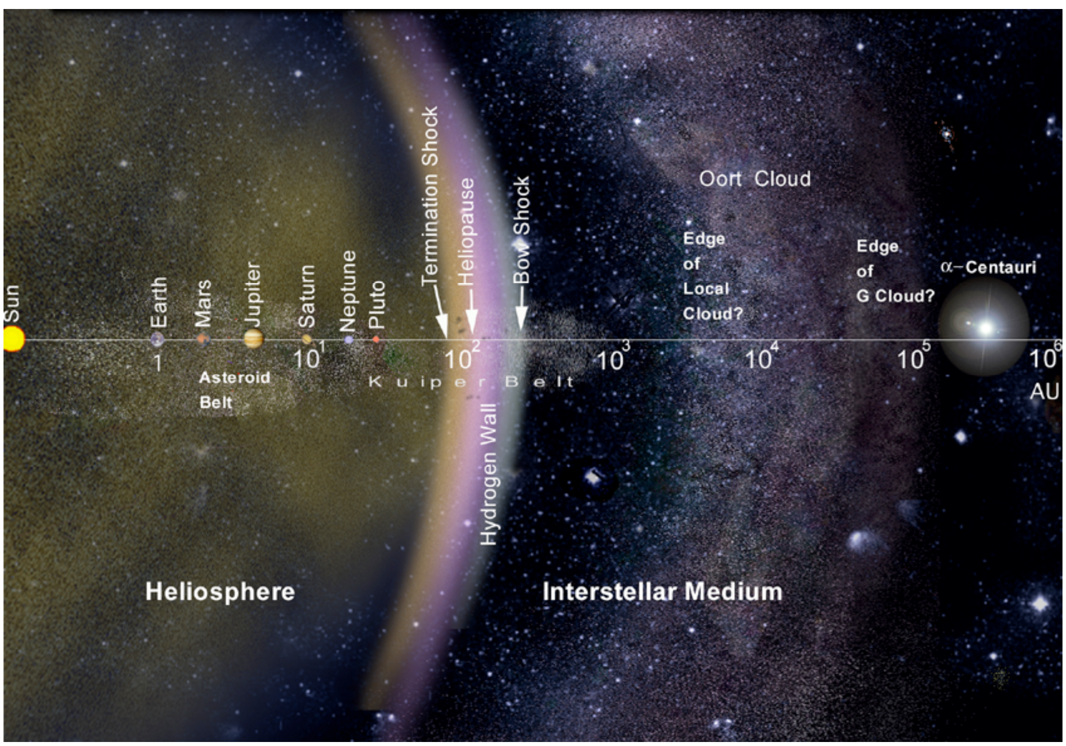

Figure 1. Exploring the Nearby Interstellar Medium and its Interaction with the Solar System (courtesy “Interstellar Probe Mission Review”, Sarah Gavit and Paulett Liewer, October 12, 1999[1]).

PROPOSED LONG LIFE MISSIONS

Consider the nearby interstellar environment as illustrated in Figure 1. Since 1957, we have been in the process of exploring our local interplanetary environment. Indeed, we currently have spacecraft that have been operational since the early 1970's that are still transmitting data (e.g., IMP-8 (IMP-J) was launched by NASA on October 26, 1973, to study the Earth's magnetosphere and the interplanetary environment and is still returning useful data). The Voyager spacecraft, launched in the 1970's, are still operating and are on the verge of exiting our local neighborhood and passing into the interstellar medium (Voyager 1 reached 100 AU on 15 August 2006). To illustrate the long term value of these missions, Fig. 2 compares over 25 years of solar wind data from the Voyager and IMP-8 spacecraft—we thus have empirical evidence that missions in excess of 30 years are possible and that we can reach beyond the Solar System!

Aside from humanity's obvious need to explore and to seek life elsewhere, what is the value of long life, long range space exploration? Practical goals for long lived interstellar missions based on a study in support of ISP (Gavit and Liewer, 1999[1]) are listed in Table 1. Objectives for a mission to a nearby star would be very similar with the added interest of studying the properties of another solar system and star(s) up close.

Table 1. ISP Science Objectives (Gavit and Liewer, 1999[1])

1. Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our Galaxy and Universe.
2. Explore the outer solar system in search of clues to its origin and to the nature of other planetary systems.
3. Explore the influence of the interstellar medium on the solar system.
4. Explore the interaction between the interstellar medium and the solar system as an example of how a star interacts with its local galactic environment.

Given that there are sufficient reasons and the will to go to a nearby star, which one would that be? Within ~20 light-years (Ly) of the Sun there are approximately 75 stellar systems. The closest of these are shown in Fig. 3. Barring the discovery of a nearby Earth-like planet, these 10 are the most likely candidates for a mission at this time. In the 1970s, an extensive analysis was carried out of a potential mission to one of these stars under the auspices of the British Interplanetary Society. Called Project Daedalus, this study postulated and then carried out detailed analyses of many of the issues associated with an interstellar mission including a study of several nearby stars from the standpoint of their merits for exploration. The rankings (A. R. Martin, 1978[2]), based on their potential scientific merit, are listed in Table 2.

Table 2. Stellar rankings for nearby target stars (Martin, 1978[2]). R1 is based on stellar evolution. R2 is based on likelihood of inorganic materials. R3 is based on the possibility of organic life. I is the cumulative importance value derived from these rankings.

STAR	DIST (Ly)	Spectral Class	R1	R2	R3	I	RANK
Proxima	4.25	M5e	2	0	2	94.12	6
α Centauri A/B	4.3	G2/K6	7	10.7	10	644.19	1
Barnard's Star	5.9	M5	2	0	6	135.59	3
Wolf 359	7.6	dM8e	7	0	-1	78.98	8
Lalande 21185	8.1	M2	2	0.1	3	62.96	11
Sirius A/B	8.6	A1/wdA	12	0	-6	69.77	10

Luytens 726-8 A/B	8.9	dM6e/dM6e	12	0	-4	89.89	7
Ross 154	9.4	dM5e	2	0	2	42.55	12
Ross 248	10.3	dM6e	5	0	-1	38.83	13
ε Eridani	10.7	K2	2	3.3	9	133.64	4
61 Cygni A/B	11.2	K5/K7	6	0.1	10	143.75	2
ε Indi	11.2	K5	2	0.1	6	72.32	9
τ Ceti	11.9	G8p	6	3.6	6	131.09	5

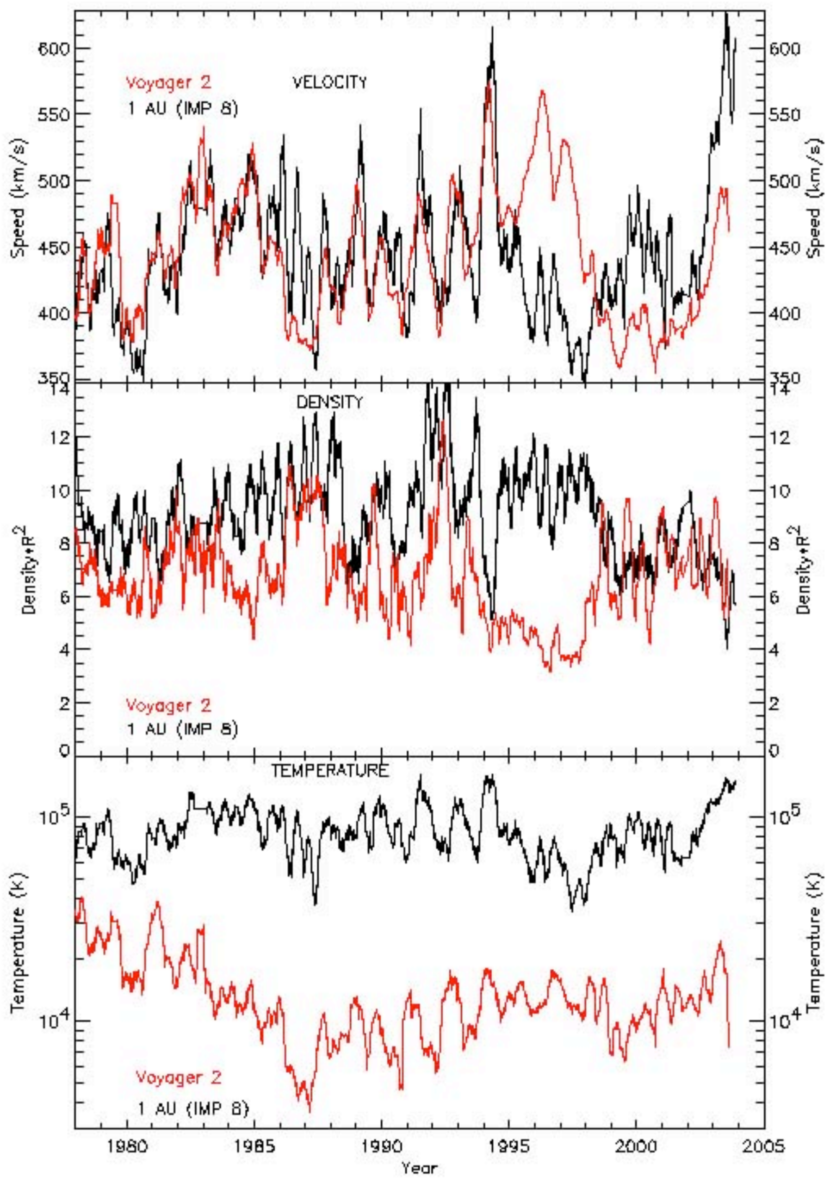

Figure 2. *Solar wind plasma from IMP-8 in Earth orbit (black line) versus Voyager 2 as it approached 72 AU (red line). The data are 50-day running averages (Voyager 2 data are time-shifted to 1 AU and densities are normalized to 1 AU.*[9]

KEY	NAME	LIGHT YEARS	CLASS
1	Proxima Centauri	4.2	G2
2	Alpha Centauri A/B	4.3	G0/K5
3	Barnard	5.9	M5
4	Wolf 359	7.6	M6e
5	Lalande 21185	8.1	M2
6	Sirius A/B	8.7	A0/WH DW
7	Luyten 726-8 A/B	8.9	M6e/M6e
8	Ross 154	9.4	M5e
9	Ross 248	10.3	M6e
10	Epsilon Eridani	10.6	K2
11	Gliese 876 *	15.4	M4

* Closest star with planet (1.9 x Jupiter's mass)

Sun = Class G2

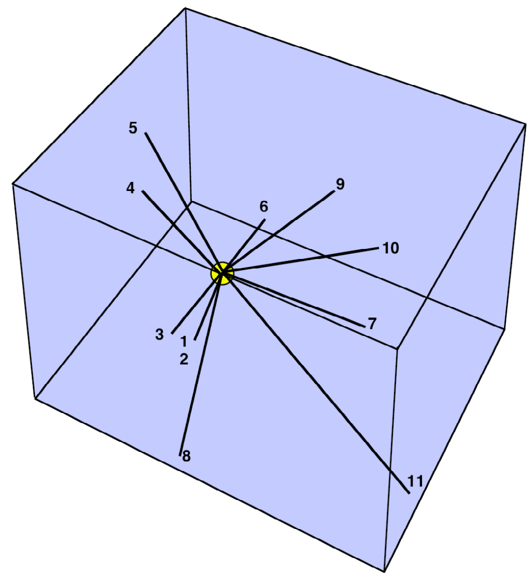

Figure 3 Our interstellar neighbors (courtesy R. H. Frisbee, 2003[6])

As discussed by Martin, the results demonstrate that α Centauri A/B is by far the highest ranked target. The next four, however, are of nearly identical ranking. Note that distance was not the primary ranking criteria as Proxima would then get the highest ranking.

Based on the preceding, it is clear that a mission to a star within ~10 Ly makes logical sense. How we get there, however, is still somewhat unclear. A number of different forms of propulsion have been suggested as possible candidates for such a mission and will be discussed briefly later in this paper. Given that propulsion technologies exist, the issue of how long it will take to reach possible targets arises. Table 3 lists the potential arrival times of our current interstellar missions—travel times measured in tens of thousands of years or more. The proposed ISP mission on the other hand would take a much more reasonable ~15 years to reach ~200 AU at 70 km/s (Gavit and Liewer, 1999[1]). 15 years is thus a convenient and would appear to be an upper limit on any potential interstellar precursor mission—time enough for a complete mission within a researcher's normal career. What about a mission to α Centauri at 4.3 Ly? Given that recent NASA studies have indicated that any such mission would have to go into orbit to be viable (a flyby is too short…), it will be necessary to accelerate and then decelerate. Therefore consider a simple estimate assuming a constant acceleration to the halfway point followed by a constant deceleration for the second half plus the time it takes to communicate back to the Earth. This shows that at an acceleration of .01 G would take 20 years to reach the halfway point (at which time it would be going ~20% the speed of light), 20 years to decelerate, and 4.3 year to communicate back to the Earth—a roughly 50 year mission (c.f., Forward, 2003[6]). 50 years is probably the maximum "one researcher lifetime" mission that would be viable so these two scenarios bound the practical time period (15-50 years) for ultra-long life interstellar missions and set the acceleration criteria.

Table 3. Travel times for current "interstellar missions" to reach nearby stars (Sheffield, 2003[10])

Spacecraft:	Pioneer 10	Pioneer 11	Voyager 1	Voyager 2
Launch Date:	3-Mar-72	3-Apr-73	20-Aug-77	5-Sep-77
Star:	Ross 248	AC+79 3888	AC+79 3888	Sirius
Travel Time:	32,600 yr	42,400 yr	40,300 yr	497,700 yr

RELIABILITY REQUIREMENTS

In the previous section, the criteria for long life interstellar missions have been established—a 15 year to 200 AU for a current technology-based, precursor mission and ~50 years at ~.01 G to α Centauri at 4.3 Ly. This section will summarize some of the initial reliability issues that these two missions will raise. In particular, we have broken the issues into the following reliability areas:

1. Environmental Exposure
2. Propulsion Systems
3. Electronic Systems
4. Mechanical Systems
5. Materials
6. Thermal Control
7. Infrastructure
8. Mission Assurance
9. Software
10. Integrated Systems Health Management
11. Navigation and Attitude Control
12. Planetary Protection
13. Political Matters

In this short paper, we will not attempt to treat these areas in detail but rather indicate the state of the art and where we will need to go for some of them. Fortunately, as noted earlier, a number of existing missions have had extended mission lifetimes such as Voyager 1 and 2, Galileo, and Cassini. Extensive studies have already been carried out on the reliability issues to date for these missions (Green et al., 2005[11]) that are applicable to the current study.

Environmental Exposure

Reliability issues associated with the space environment can be divided into two categories—those that would result from normal exposure to the space environment over an extended time period and those that would be unique to a hypervelocity mission. In the former category fall the normal issues associated with total ionizing dose and single event upsets. Since the bulk of the mission would be in the interplanetary medium outside the heliosphere, the main concern would be the interstellar cosmic ray environment. Figure 4 and Table 4 illustrate the expected background radiation environment in interstellar space—Figure 4a is a graph of the expected flux of cosmic rays and Figure 4b is the 20 year (halfway point) total dose for various levels of shielding. Although several orders of magnitude above the interplanetary environment at energies below 10 MeV/nucleon, it by and large is relatively benign except for the extended exposure. While dose would be a minimal concern (provided that no “super flares” were encountered in transit….), the long term displacement damage and accumulated SEEs (if not corrected—this is, however, common procedure for most space systems) might be of concern. These estimates clearly show that the major natural radiation environment would actually be that in the inner solar system during departure or arrival (that is, solar proton events and planetary trapped radiation belts in the two star systems might be the most severe ambient radiation environments—environments we deal with regularly). The primary in-situ radiation environment will probably be from whatever propulsion/power sources are selected. Depending on the actual configuration, neutron and gamma rays will likely be the major radiation issues in the latter case.

Whereas spacecraft charging (unless some form of plasma propulsion is used) will likely be minimal in interstellar space, the dust and micrometeoroid environments and their resulting hypervelocity impacts could be a serious issue for even the precursor mission at its relatively low 70 km/s velocity. For a mission at 20% the speed of light, a 1 g particle encounter would likely be catastrophic. Several studies have concentrated on the effects of these microparticle and atomic impacts at near-light speed on exposed surfaces. These were summarized by Martin (1978)[2] as part of the BIS Project Daedalus. The impact problem arises as interstellar space is not completely empty but populated by interstellar gas and dust grains. Table 5 lists some of those properties.

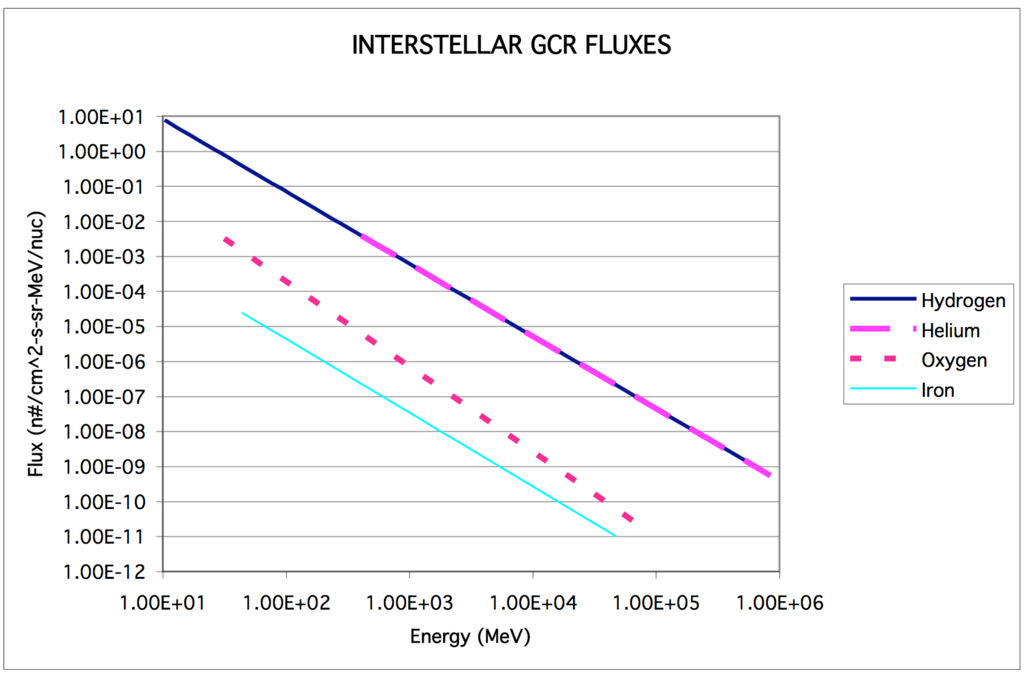

Figure 4a. Background Galactic Cosmic Ray environment in interstellar space.

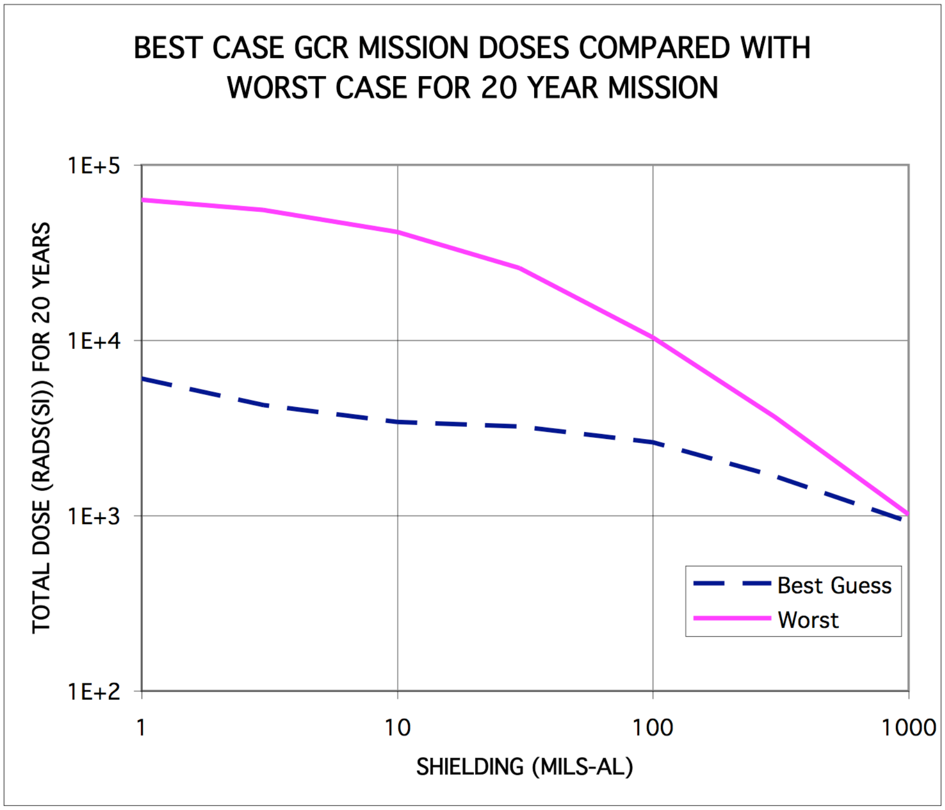

Figure 4b. Total Ionizing Dose from Galactic Cosmic Rays as a Function of Aluminum Shielding Thickness*. rad (Si) vs. mils (Al)

Table 4. Total Ionizing Dose (Rads(Si)) from Galactic Cosmic Rays as a Function of Aluminum Shielding Thickness*

Area Density (g/cm^2)	**Shielding** (mils)	**TID (rad)** Best Guess	Worst
6.86E-03	1.00E+00	6.04E+03	6.30E+04
2.06E-02	3.00E+00	4.27E+03	5.54E+04
6.86E-02	1.00E+01	3.41E+03	4.13E+04
2.06E-01	3.00E+01	3.22E+03	2.58E+04
6.86E-01	1.00E+02	2.62E+03	1.04E+04
2.06E+00	3.00E+02	1.68E+03	3.66E+03
6.86E+00	1.00E+03	9.23E+02	1.01E+03

*Calculations are for a 4π steradian view factor and for a solid sphere. The “Worst” case is for 20 years at the ISP fluence levels.

Table 5. The particle environment in interstellar environment (after Martin, 1978[2]).

Number Density of Interstellar gas:	
- Clouds	10^{7}-10^{9} m^{-3}
- Intercloud Regions	2-3x10^{5} m^{-3}
- Solar Neighborhood	10^{6} m^{-3}
Density of Gas:	1.67x10^{-21} kg m^{-3}
Mass Density of Interstellar Grains:	
- Mean	1.4x10^{-23} kg m^{-3}
- Intercloud Regions	(?)10^{-25} kg m^{-3}
- Solar Neighborhood	(?)10^{-24} kg m^{-3}
Mean Mass of Grains:	10^{-16} kg

Martin has also estimated the erosion rates for two different density particles for a 6 Lyr Daedalus mission for various light speeds (Table 6). These worst case estimates show that erosion rates could reach as high as 30 kg m^{-2}—a very sizable shield will thus be required (note: Martin (1978)[2] points out a number of problems with the estimates that will need to be re-evaluated). Although we will not pursue the issue here, the other aspect of the problem is the nuclear and other radiation effects induced by these extreme impacts. These effects, radiation and erosion, are a potentially serious environmental concern and need to be evaluated for each design (note: it is often assumed that the damage due to dust and grains on sails will be minimal because the impacts will result in a simple "cookie cutter" or punch-through, again this assumption will need to be re-evaluated based on the actual sail design).

Table 6. Erosion rates for particle impacts in the interstellar environment (after Martin, 1978[2]). Where β= V/c and ρ= particle density.

	m/A_o (kg m^{-2})	
β	**$\rho=10^{-23}$ kg m^{-3}**	**$\rho=10^{-24}$ kg m^{-3}**
0.05	1.8	0.18
0.10	7.32	0.73
0.15	16.68	1.67
0.20	30.27	3.03
0.25	48.72	4.87

Propulsion Systems

We note that the propulsion system will have a potentially major role in determining the induced environment for the mission depending on whether is it is nuclear, laser/electromagnetic, or plasma based. Each of these systems has its own unique effects that can impact the long term behavior of the electronic and mechanical systems. Table 7 is a short list of some of the most likely or popular choices (see Mills (2004)[12] for a number of additional ideas). Figure 5 shows cartoons of some of these systems. Numerous studies have been performed over the years with Frisbee and Leifer giving a comprehensive evaluation of the main propulsion methods in 1998 (Frisbee and Leifer, 1998[13]). Since then several new concepts have been introduced and the existing ones developed further. These propulsion studies include solar sails (Matloff (1984)[14], Herbeck, et al, (2003)[15], and Bazan (2004)[16]), laser or particle beams (Forward (1982)[17], Salama et al, (2000)[18], Kare (2000)[19], and Frisbee (2004)[7]), antimatter (Forward (1984)[20], Frisbee (2004)[6], and Howe and Jackson (2005)[21]), nuclear fusion and fission (Orth et al (1987)[22], Kammash (1999)[23], Cassenti (2000)[24], and, Prashant et al (2004)[25]), and plasmas (Zubechen et al (2001)[26], Gorelenkov et al (2001)[27], and Gorelenkov and Zakharov (2003)[28]), as well as forms of ion propulsion (Fearn (2000)[29], Rawlin et al (2002)[30], and Fearn(2004)[31]). Each of these systems has advantages and disadvantages as outlined by the various authors. Reliability specifically, was not addressed in most of the proposals. Clearly, there will be reliability issues with each of them. There is not enough space to go into a detailed reliability review for each of them, however, a few highlights can be noted. Solar or beamed powered structures are susceptible to particle or meteoroid damage. Ion thrusters have wear issues that will be difficult to overcome for a fifty year lifetime. For nuclear missions, the reactor would need to be self-sustaining for fifty years without the maintenance procedures that are currently typical of such systems.

Table 7. Examples of possible interstellar propulsion sources

Propulsion Concept	Mission or Type	Source
- Traditional	Pioneer 10,11	NASA
	Voyager 1,2	NASA
	Pluto-Kuiper Belt	NASA
- Sail	Interstellar Probe	NASA
	Beamed Power	Forward
	Solar	
- Electric Propulsion	Solar Electric	NASA/ESA
	Ion Thruster	
	Hall Effect Thruster	
	Magneto-Plasma Dynamic Thruster	
- Fission/Fusion	Anti-matter	Frisbee
	Nuclear Fission - Electric	NASA
	Fusion Bomb	(Daedalus)
	Plasma	
- Beamed power	Laser	Forward
	Particles	Forward
	Microwave	Forward
- Brussard Fusion Ramjet		Brussard
- Plasma	Laser Accelerated	Kammash
	Torroidal	Gorelenkov

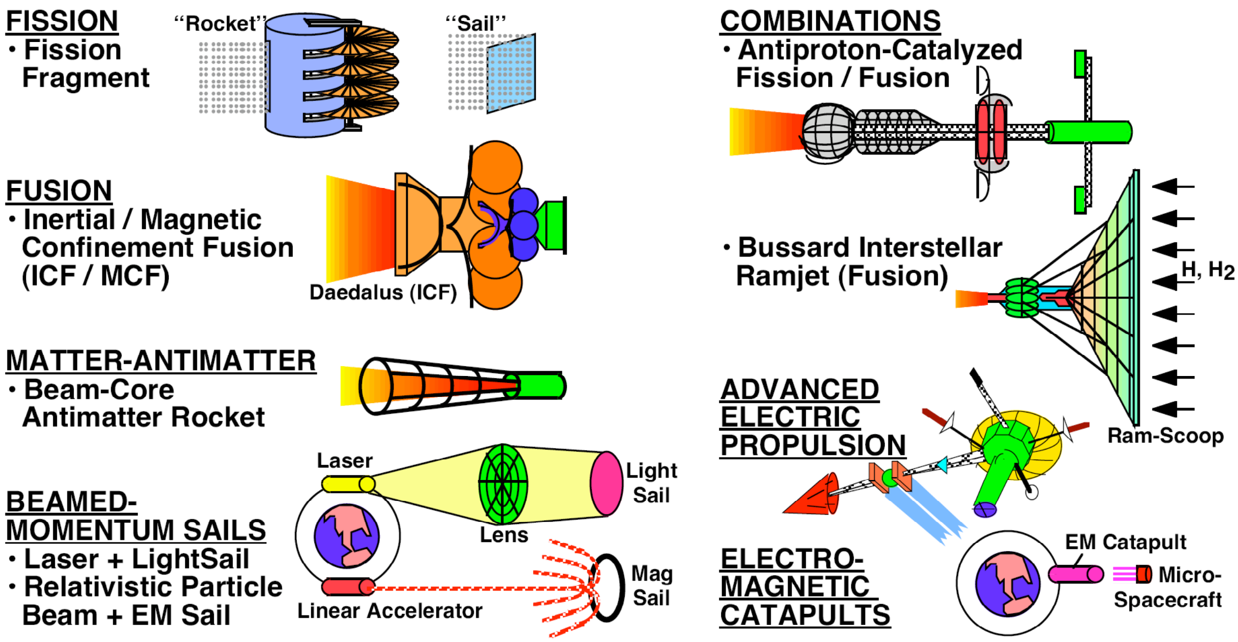

Figure 5. Cartoon of the various types of interstellar propulsion being considered (courtesy Frisbee, 2003[6]).

Electronic Systems, Mechanical Systems, and Materials

In future studies, we will address the reliability issues associated with the electronic systems, materials, and the mechanical systems in more detail based on a point design. A general consideration for electronics is that virtually none of the electronics that we use today are designed to work for more than ten years. Electronics will have to be custom designed and/or packaged for extended lifetimes. Because of the nature of an extended mission, extensive autonomy will be needed. Additionally, strategies of reconfigurability of electronic systems will also be a likely option. With these two items, a substantial increase of the sophistication of on-board electronics will be needed and with this the reliability issues become more complex. New methods for handling the degradation of electrical hardware will also be needed. The software will also be extensively integrated with the electrical hardware making the two inseparable. It is clear that, due to the complexities mentioned, that the software and hardware will need to be co-developed as an integrated part of the spacecraft. These will tie in to the IVHM and overall reliability of the spacecraft discussed later in this paper.

Aside from standard issues with long term aging of mechanical systems and materials, propulsion-specific effects due to say neutron and gamma radiation will need to be considered. It should be noted that the propulsion system will have a significant role in determining the environment for the mission, whether it is nuclear, laser, electromagnetic, or plasma. Each of these systems has its unique effects that can impact the behavior of the electronics, materials, and mechanical systems.

Data and communication systems will also need to be more sophisticated than in current mission designs. Because of the difficulty of communicating over the exceptionally long distances envisioned (light years), signal divergence and strength need to be accounted for.

Some concepts involve dropping communications relay satellites along the way. Optical communications is another option, although significant work would need to be done on laser beam divergence for such long distances and on pointing control.

Thermal Control, Navigation and Attitude Control

Current expertise in thermal, navigation, and attitude control will likely be adequate for most interstellar missions based on existing experience. This should be especially true for any coast phase although some issues will arise due to the long distances involved. Small corrections will need to be made autonomously and the initial trajectories will need to be exceptionally accurate. The accuracy requirements will be constrained even more by the need for precise antenna positioning for science data and telemetry transmission and reception across such long distances. Possible exceptions would be in the area of thermal control for some of the propulsion-induced environments and for autonomous navigation during orbit insertion and exploration at the α Centauri system. Attitude control will likely be a major concern for the "beam rider" class of systems so that the spacecraft can maintain its orientation and location in a laser or particle beam.

Mission Assurance, Software and Integrated Systems Health Management

Mission assurance, software reliability, and integrated systems health management are all interrelated concerns. Given the very high level of autonomy required by interstellar missions, this will likely be the overriding practical concern for actually executing an interstellar mission when the spacecraft is performing its science functions —at best, there will be a 9 year turn around on any help request/fix from the home planet! The ability to execute a complete scientific exploration and data return sequence after arriving in the system will require real time, in-situ decisions that would tax existing real-time capabilities here on Earth. Mission assurance will also have to consider the issues of self-repair and extensive system redundancy and fault tolerance. Particular care will have to be given to flight spare versus functional redundancy. As proposed in the original Daedalus study, we will have to develop robots capable of in-flight repairs—the ultimate integrated health management system. A common set of replacement parts will have to be developed that can be used, if necessary, to repair systems by the robots—otherwise we will have to develop some means of actively regenerating some types of systems in-flight. Techniques for reconfiguring and reprogramming electronic systems in real time are now available for example that have not been considered in previous interstellar studies (i.e., field programmable gate arrays) that open up a whole new range of possibilities.

Software reliability will be a key component to the success of the interstellar mission. Currently, initial studies indicate that 50% of the reliability issues for long and short duration missions are software related.[32] Considering the ISHM and autonomy demands, the software role will be substantially increased for interstellar missions.

Infrastructure

A final, unique concern for long term interstellar missions will be the home planet infrastructure and how it will be maintained to provide continuing support to the mission. Today, even a mission of ~15 years duration can see substantial changes in the operative hardware, software, and support personnel. Maintaining the communications equipment and keeping the frequency band clear for 40-50 years may be the most severe long term challenge for an interstellar mission. Indeed, as technology is more and more rapidly evolving, it is clear that the time between radical changes (for example, the time period between vacuum tubes to transistors to integrated circuits) is markedly decreasing. Aside from the issues of keeping the human institutions alive and capable of receiving a signal from a Centauri 50 years after launch, the likelihood that the technology to receive the signal will also be available is also debatable. Special steps will need to be taken to both have the mission provide useful data throughout its cruise phase (thereby warranting the maintenance of a permanent caretaker staff) and to maintain the capability to interpret the vast amount of data expected from such a mission.

It is likely that a new field of engineering will need to be created. This field would be the study of "ancient" engineering and technologies including "hands-on" training. The role of data interpretation may require concerted international cooperation. Further, advances in programming techniques, information transfer algorithms, etc. may make possible continuing enhancements in the mission capabilities if the spacecraft systems are open to in-flight reconfiguration. Indeed, much like the Voyagers no longer resemble in many particulars the spacecraft we originally launched through re-programming and changes in operation techniques, so our future explorers may be very different when they arrive from what we start with. This indeed may be a major key to their long term survival.

Planetary Protection

One of the issues that will need to be addressed is planetary protection. If any part of the probe is to be sent to a planet, if found, then the probe will need to be decontaminated to ensure that we do not bring any life forms from earth that could contaminate the planet. The decontamination process will likely impact the reliability of electronics and possibly some mechanical systems due to the required exposure at high temperatures or chemical sterilization agents. The impact of the decontamination process will need to be evaluated with respect to the lifetime of the various systems over fifty years.

Political Matters

The impact of politics is generally not thought of as a mission design parameter, but in this particular case, it is incredibly important due to the extended nature of the mission. The fluctuation in administrations both in the government and in NASA will lead to difficulty in supporting an ongoing mission for fifty years. Sustained funding will be needed to maintain a staff for operations, maintain antennas worldwide, analyze data as it comes back, and integrate new technologies on the ground as existing ones become obsolete. Sustained funding for an extended mission is at many levels foremost a political matter and probably can only be achieved through international agreements with many countries participating in the effort. Additionally, the initial cost of such a mission would likely be substantial and would necessarily need to be specifically funded.

CONCLUSIONS

To summarize, in this study we have attempted to identify the longevity requirements for a typical interstellar precursor or interstellar orbiter mission. Based on previous analyses, it appears that lifetimes of 15 years for a precursor mission to interstellar space (an Interstellar Probe) are well within current capabilities and, with the crossing of the heliopause of Voyager 1 at 100 AU, a straightforward extension of existing reliability practices. Several studies have indicated that α Centauri at 4.3 Ly is a likely candidate for the first true interstellar mission. A 40 to 50 year mission terminating in orbit insertion and follow-on investigations is the best case scenario at this time. A mission longer then this challenges the normal range of human interest and would likely offer a serious infrastructure problem. An orbiter has been chosen as a flyby mission at near the speed of light offers little long term return on investment—we must be able to truly exploit any interstellar mission given the societal costs involved. These mission requirements, in particular the acceleration required, place significant constraints on the propulsion system—an issue that is not part of this study (suffice it to say that some concepts utilizing current technologies may be feasible). The constraints also allow us to begin the process of defining the key environmental and reliability concerns that we need to address now. In particular, hypervelocity impacts with interstellar flotsam, completely autonomous operations and self-repair, the ability to perhaps completely reconfigure our systems, and the establishment of institutions and techniques for managing a single mission over many decades surface as key reliability issues. Even so, as has been said by our predecessors:

"Ad Astra!"

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