A Program for Interstellar Exploration

A 15 year period of mission definition and development of key technologies results in an automated interstellar probe design. This is followed by a 20 year development of man rated interstellar propulsion systems that results in the launch of a manned exploration starship to Alpha Centauri.

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Abstract

A program for interstellar exploration is proposed. The program starts with a fifteen year period of mission definition studies, automated probe payload definition studies and development efforts on critical technology areas. The funding required during this initial phase of the program would be a few million dollars a year. As the automated probe design is finalized, work on the design and feasibility testing of ultra-high velocity propulsion systems would be initiated.

Five possibilities for interstellar propulsion systems are discussed that are based on 10-30 year projections of present day technology development programs in controlled nuclear fusion, elementary particle physics, high power lasers, and thermonuclear explosives. Annual funding for this phase of the program would climb to the multi-billion dollar level to peak around 2000 AD with the launch of a number of automated interstellar probes to carry out an initial exploration of the nearest stellar systems.

Development of man-rated propulsion systems would continue for 20 years while awaiting the return of the automated probe data. Assuming positive returns from the probes, a manned exploration starship would be launched in 2025 AD, arriving at Alpha Centauri 10-20 years later.

1. Apologia

In July 1975, the Subcommittee on Space Science and Applications of the United States House of Representatives solicited proposals and held hearings on new ideas for future United States space programs[1]. This paper is a shortened version of one of the many proposals that they received[2]. The paper concentrates specifically on just one possible aspect of future space programs — interstellar exploration. Because of the highly political and non-technical nature of the soliciting body, the long-range, broad-brush purposes of the hearings, and the speculative thrust of the proposed program, the paper is more lyrical than technical, as well as being optimistic in the extreme. However, I believe that interstellar exploration will happen sooner than we think, and will very likely follow along the general directions outlined in the paper.

Now it is likely than any program for interstellar exploration will be a cooperative international program and will use intelligent robots rather than fragile man. However, the program proposed here assumes that there is such a strong United States commitment to a goal of interstellar exploration that there will be the same strong financial support and rapid progress that we experienced in the United States lunar exploration program. If this commitment did occur, (unfortunately it is unlikely) then the United States would proceed on its own and an interstellar transport would be ready in 2025 AD. We then would probably have to utilize the best of the intelligent robots available at that time, even if they were made of meat and bone with ionic circuitry. For if progress were that rapid, the more rugged and quicker models made of plastic and steel with electronic circuitry would probably still be children in the teaching laboratories and would not yet be ready to take over the important task of spreading intelligent life throughout the Universe.

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2. Prologue

Imagine that this is the year 1935. It has been over thirty years since the discovery of radium by the Curies, the first transatlantic radio signal by Marconi, and the first manned, heavier-than-air flight by the Wright brothers. In the past decades, the pace of scientific and engineering development has been increasing rapidly. The newspapers contain stories about transcontinental telephone calls, television, transatlantic flights in aircraft, and around-the-world flights in the Graf Zeppelin. (Almost unnoticed were Dr. Goddard's first rocket flights nine years ago.)

Suppose that in 1935, a farsighted House of Representatives had formed a Subcommittee on Aeronautical Science and Applications to hold hearings on future national aeronautics programs. The Subcommittee would receive many worthwhile proposals for future programs. Programs to develop more effective propulsion systems (which would have led to jet engines). Programs to develop larger aircraft designs capable of hauling significant payloads cheaply and rapidly (which would have led to commercial aviation). Programs to develop radio aided air traffic control (which would have led to radar).

Suppose that during those hearings in 1935, a national program for interplanetary exploration was proposed. The proposed program would have an initial goal of sending an automated probe to the Moon within 25 years, followed by the landing of a man on the Moon within 50 years, with further steps leading to manned exploration of the planets. The program would plan to use advanced aircraft construction techniques to produce rockets containing thousands of tons of fuel, with only a few tons of payload. These expensive vehicles would only be used once, the various parts to be dropped into the ocean or left in orbit or on the Moon. The power generated by the rocket engines during launch would equal the total installed electrical generation capability of the U.S. in 1935 (20,000 MW). The program cost over the 50-year period would equal the Federal appropriations for 1935 ($7,500 million). Yet the proposer would assure Congress that all this was possible with only predictable 10-30 year projections of 1935 technology.

I doubt that Congress in 1935 would have strongly recommended supporting such a program. "A man on the Moon in 50 years! Ridiculous!"

But ahead of us in 1935 would lie further advances in the aeronautical technologies - mixed up with, and influenced by, scientific breakthroughs and the swirls of politics. Some could have been foreseen, others could not. In the decade following 1935, we would have seen the release of nuclear energy (both for weapons and peaceful purposes), radar and long distance radio, jet aircraft approaching the speed of sound, and the surprise descent of the V-2 rocket through the skies of Britain. However, it would take 22 years before the appearance of high quality communication through the transatlantic telephone cable and fast, comfortable travel on commercial jets even though these technological results were predictable and planned in 1935.

However, the same 22 years would also usher in the space age, unforeseen and unplanned. It would start with Sputnik in 1957, followed by manned orbital flight, automated lunar and interplanetary probes, communications satellites, and just 34 years from 1935, on 20 July 1969, a United States astronaut walking on the Moon.

It is important to recognize that the start of interplanetary space flight did not wait for the full and complete development of all the potentials of earth bound aeronautics. We did not plan the space age, but it came anyway. It came because it was technologically possible, and was politically needed. Would things have been different if there had been some preliminary planning during the years 1935 to 1960? If there had been a plan, would the space program still have cost so much? If there had been a plan, would it still have resulted in a disruptive rapid expansion and contraction of the NASA organization and its associated contractors? If there had been a plan, would we still have developed a manned space program with capacity only for lunar exploration and no potential for interplanetary work? If there had been a plan, would we still have a four-year gap from 1975 to 1979 without a United States astronaut in space?

3. Introduction

It is now 1975. It has been over thirty years since the first controlled release of nuclear energy, the discovery of the quantum mechanical principles that led to the laser, the discovery of anti-matter, and the first demonstration of controlled long-range rocketry by Wernher von Braun and co-workers. In the past decades, the pace of scientific and engineering development has been increasing rapidly. The newspapers contain stories about man's exploration of the Moon, sophisticated semi-automated landing probes being sent to Mars, space probes passing by Jupiter with enough energy to go sailing off into interstellar space — never to return to the solar system, designs for laser AICBM weapons capable of beaming megawatts of power out into the fringes of space and the development of magnetic bottles and short pulse lasers for controlled fusion (with its promise of almost unlimited amounts of energy).

A farsighted House of Representatives has formed a Subcommittee on Space Science and Applications to explore future national space programs. The subcommittee will receive many worthwhile proposals for future space programs. Programs to utilize the capability of the shuttle for earth applications programs. Programs for space-borne observations of the planets, nearby stars, and the deeper reaches of the galaxy and universe. Programs for the colonization of space. Programs for automated and manned exploration of the moon, asteroids, comets and planets. Programs to initiate interstellar communication with those advanced technologies capable of (and interested in) communicating with us.

I would like to propose for the committee's consideration a future national space program for interstellar exploration. It is a fifty year program to send man to the stars. The initial goal is to launch sophisticated autonomous probes to the nearest stellar systems before the century is out (twenty-five years from now). The interstellar probes would use advanced computer micro-miniaturisation techniques to achieve unrivaled orbital surveillance capability combined with almost human intelligence in a few kilograms of payload. The power generated

by the interstellar probe launch vehicle as it leaves the solar system will approach the total installed electrical generator capacity of the United States today. The cost of the proposed program over the next 50 years will probably equal the Federal appropriations for 1975, with the peak in the development expenditures occurring in the decades around the year 2000. However, success of the program does not depend upon exotic break-throughs such as the invention of space warps or anti-gravity, and can be accomplished with 10-30 year projections of present day technology.

I request that the subcommittee seriously consider such a program and recommend that Congress make available through NASA a few million dollars per year for the next fifteen years to provide the seed money for initial program planning and exploration of critical technology areas.

It is important to realize that an interstellar exploration program does not need a plan. It will come without planning. Our developing capabilities in controlling fusion, beaming laser energy through space, generating antimatter particles, tailoring new structural materials, and redUcing the size and cost of computers will make interstellar exploration technologically feasible. All that will be required to focus this technology on interstellar exploration will be the political need. Political needs are necessarily of shorter range than technological growth capabilities. If there is no planning for interstellar exploration, the political need will be met, but at the cost of the disruption of the rest of the activities within our society. With proper planning in the coming years, it would be hoped that the political need, when it comes, can be met with a minimum disruption to our then on-going interplanetary space programs and our life here at home on Earth. With planning, we can produce an interstellar exploration program that will not only send us to the stars once, but will produce a strong technology base for our continued exploration of the Universe and the determination of our place within it.

4. Feasibility of Interstellar Flight

Going to the stars is not easy - but it is not impossible either. Our Sun is in the outskirts of the Milky Way galaxy where stars are few and far between. To travel to the stars will take years of time, gigawatts of power, kilograms of energy, and billions (if not trillions) of dollars. Yet it can be done — if we wish to.

Now, there have been many people (some of them quite well known), that have "proved" by "calculation" that interstellar flight is "impossible"[3,4,5,6,7]. Actually, in each case, all they "proved" was that given the initial assumptions that they forced on the problem, that the problem was made so difficult that they were unwilling to consider it further.

There are people who might admit the ultimate physical feasibility of interstellar flight, but who question the desirability of such a program when we can gain information about interstellar intelligence more cheaply and much faster by listening with radio telescopes here on Earth. I agree that if there is someone at the other end who is willing to talk, this approach will make a significant contribution to our knowledge. However, interstellar exploration with automated probes, while possibly more expensive, is definitely more certain to produce a contribution of equivalent value.

"This proxy exploration of the Universe is certainly one way in which it would be possible to gain knowledge of star systems which lack garrulous, radio equipped inhabitants." (Arthur Clarke[8]).

5. Interstellar Distances

It is not easy to comprehend the distances involved in interstellar travel. After all, we are only just beginning to appreciate the distances involved in interplanetary exploration.

Of the billions of people living today on this globe, many have never travelled more than 40 kilometers from their place of birth. Of these billions, a few dozen have travelled to the Moon which is 10,000 times 40 kilometers away. Soon one of our automated interplanetary space probes will be passing the orbit of Pluto, 10,000 times further out at 4 billion kilometers. However, the nearest star at 4.3 light years is 10,000 times further than that, at 40 trillion kilometers (4×10^{13} km).

The pictures in Figure 1 may also help in trying to comprehend the scale of the distances involved in interstellar travel. The first circle encloses a region 10^{-4} light years in radius. The scale is such that we can see the orbit of Earth. The successive circles have radii increasing by factors of 10. We have to take five jumps from the initial circle before our expanding sphere of interest encompasses the nearest stars.

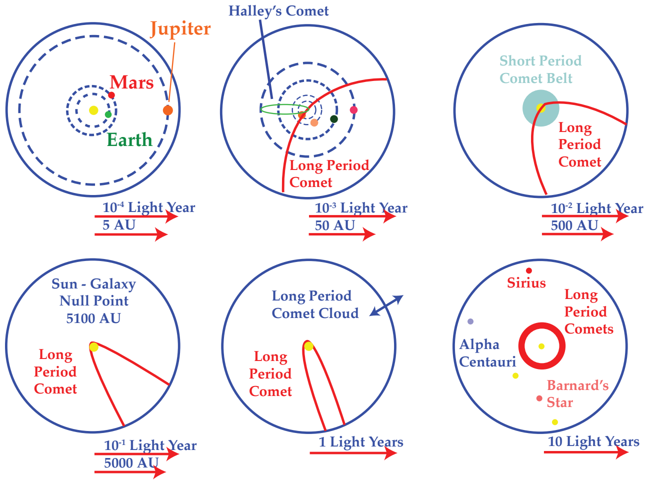

Figure 1 — The scale of deep space (adapted from Hennes et al[9])

Although these distances are large, they are not unspannable. It will take time and effort, but they can be bridged. First by automated exploration probes, and then by man — leaving his home to go off to explore new worlds around strange suns.

6. Mission Times to the Stars

It would be a waste of effort to send out a probe on an interstellar mission unless we could get the data back from it in time to be of use. Because of the present exponential growth of scientific and technological progress, the large spacing between stars out here in the outskirts of the Galaxy, the slow crawl of the speed of light, and the human race's inability to stand still, it is probable that any scientific probe which requires a total mission time greater than 50 years will be superseded either by a faster probe, or by completely new concepts of obtaining information at long ranges. These considerations, which are independent of the type or method of propulsion, lead us to some interesting conclusions on the velocity and acceleration ranges for a usable interstellar probe.

One should realize that even with very advanced propulsion systems, the mission times are going to be long. Even if we had a propulsion system that could get our probe up to the speed of light instantaneously, it would still take 4.3 years for the probe to travel to the nearest star, and 4.3 years for the messages from the probe to travel back. Thus, the minimum interstellar mission time is about 9 years, or 18% of our 50 year maximum. For other interesting stars, like Tau Ceti at 11.8 light years, the minimum mission time is 24 years.

"There are also those who argue that the journey to our nearest star neighbor, which would take 4.3 years at the speed of light, is too long to consider. Truly, we are accustomed today to journeys half way around the world in a matter of hours, and shudder at the thought of a 4-year journey. We should be reminded, however, that in the past, explorers faced such journeys with less trepidation. Marco Polo spent 24 years on his round trip from Venice to China. It is also noteworthy that the Dutch successfully colonized the Indies in spite of the fact that it took some 4 years to voyage there and back by ship." (Oran Nicks[10]).

Surprisingly, if you have the energy, it does not take long to get to the speed of light. If a probe accelerates at one earth gravity (1 g) for one year, it will have reached greater than 90% of the speed of light in a distance of 1/2 light years. It could now coast for 3 years, then decelerate for one year to arrive at Alpha Centauri in about 5 years. This time is not much longer than the minimum travel time of 4.3 years. Thus, vehicle accelerations greater than 1 g do not improve the mission time significantly. Too Iowan acceleration can be a problem, however.

A probe with an acceleration of 1/100 g would take 20 years to reach the Alpha Centauri half-way point, and would only have reached 1/5 the velocity of light. It would now take another 20 years to decelerate. Add in the 4.3 years of communication time, and we see that the mission time is close to the 50 year maximum. Thus, there is a range of accelerations (0.01 g to 1 g) that are usable for an interstellar mission.

There is also a range of usable velocities. This is seen in the following tables for the mission times to Alpha Centauri and Tau Ceti for various velocities. As we can see in the Tables, as the probe coast velocity becomes higher than 0.1 c the coast time becomes shorter, but the acceleration periods become longer. Soon, a law of diminishing returns sets in, and we see that velocities much greater than one-half light velocity do not significantly improve the mission times to the nearby stars.

Table 1 — Mission times to Alpha Centauri (4.3 light years)
Minimum Mission Time — 9 years

Maximum Velocity	Acceleration Time at 0.1 g, years	Coast Time, years	Data Return, years	Mission Time, years
1.0 c	10	0	4.3	14
—	—	—	—	—
0.5 c	5	6	4.3	15
0.4 c	4	9	4.3	17
0.3 c	3	13	4.3	20
0.2 c	2	21	4.3	27
0.1 c	1	43	4.3	48
0.05 c	0.5	85	4.3	90

Table 2 — Mission times to Tau Ceti (11.8 light years),
(18 other stellar systems are nearer) Minimum Mission Time — 24 years

Maximum Velocity	Acceleration Time at 0.1 g, years	Coast Time, years	Data Return, years	Mission Time, years
1.0 c	10	6	12	28
—	—	—	—	—
0.5 c	5	21	12	38
0.4 c	4	28	12	44
0.3 c	3	40	12	55
0.2 c	2	60	12	74
0.1 c	1	120	12	133

Interstellar mission times for flyby probes assuming 1 /10 earth gravity launch acceleration and no deceleration (Forward[11]).

The important point to be recognized is that a usable interstellar probe will very likely operate in the acceleration range from 0.01 g to 1 g, and the velocity range from 0.1 to 0.5 c.

7. Energy Requirements

The energy requirements for an interstellar probe are going to be high. If we estimate that the mass of a small interstellar probe is about 100 kg after it has reached its coast velocity, and we assume that the coast velocity is 1/3 the speed of light (high enough that the total mission time is reasonable), then the energy that we have put into that 100 kg payload traveling at 1/3 the speed of light is about 1011 kilowatt-hours or the total electrical energy presently produced in the United States for two weeks.

Another way to try to comprehend the amount of energy involved is not to express it in terms of kilowatt-hours, but in kilograms. This can be done with the famous equation discovered by Einstein that describes the tremendous amount of energy that can be released by the conversion of mass to energy

$$E = mc^2$$

Using this formula, the 1011 kilowatt-hours of energy in the 100 kilowatt-hours of energy in the 100 kilogram probe traveling at 1/3 c turns out to be equivalent to 5 kilograms of mass. (The interstellar probe actually weighs 10^5 kilograms - not 100!)

This sounds like a large amount of energy, until we begin to realize that, in the year 1975, in the coal grates and the gas and oil burners of the electrical power plants in the United States, that over 100 kilograms of the millions of tons of fuel put in to burn is not coming out as ash, or dust, or pollution, but instead is disappearing, to reappear in the form of electrical energy. Looked at in this way, we begin to recognize that mankind is already in significant control of awesome amounts of energy. Our energy control capability is increasing exponentially from year to year, and will take a significant jump when we solve the problems of controlled fusion in the coming decades.

The energy requirements for an interstellar probe are high. But when the time comes to launch the first automated interstellar probe, the required 5 (or 50) kilograms of energy will be an insignificant part of the annual national energy budget.

8. Communication Over Interstellar Distances

Communication over interstellar distances turns out to be comparatively easy, assuming planning and cooperation between transmitter and receiver. There are debates in the technical literature as to whether lasers or microwaves are the best for interstellar communication but either can be used with reasonable projections of present day technology. For one example, we will give a few numbers for a non-optimized laser communication system for transmission of data from an interstellar probe back to Earth.

The laser communication system is assumed to have a transmitter power of 1 kilowatt and a transmitting aperture of 100 meters (300 feet). The transmitting antenna could either be a half-silvered balloon, a thin plastic film hologram lens or a large array of laser diodes each emitting a small fraction of a milliwatt, but adding up coherently into a powerful beam. The non-trivial problem of maintaining accurate figure and alignment of the transmitter would be aided significantly by a bright, steady pilot beam coming from a large laser on Earth. When adjustments are made on the probe optics so that the pilot beam is a steady point at the proper place in the field of view, then the transmitted beam from the probe is uniform and pointed back in the right direction.

When the narrow laser beam from the probe reaches the Earth over four light years away, it will have expanded so that it will illuminate a large region of space about the Earth. The laser flux will be about 10 million photons per second per square meter of collector area (this would be bright enough to see on a dark night if it weren't for the light from the Alpha Centauri star system). The data transmission rate that can be sent over the beam is then limited only by the size of the collecting array that we wish to build. (It is interesting to note that, because of the time scales involved in interstellar missions, we do not need to get around to building the collecting array until ten years after the probe leaves.)

9. Planning an Interstellar Mission

Most space programs in the past have had a very structured method for approaching the problem of planning a mission. First, the launch vehicle was picked, then intermediate boost stages compatible with the launch vehicle, the spacecraft, and the mission distance were picked. Then after the weight deductions for the propulsion fuel needed to reach or orbit the target were deducted from the spacecraft total weight, the remaining weight (what little was left) was allocated for experiments. This historical method of approaching a mission grew out of the necessity for NASA to start operations with the boosters that were available from military rocket programs. Then, the time urgency placed on NASA to get a man on the moon by the end of the decade kept it constantly in a state of having to rely on booster limited missions.

It is recommended that, because of the very high energy requirements for even the most modest interstellar mission and the rapid development progress being made in many of the propulsion technologies, that a well planned interstellar exploration program should start at the other end of the rocket ship in the design of the probe itself.

10. Stellar Target Selection

Before examining designs for automated interstellar probes, it is advantageous to formulate a list of stellar system targets for these probes. This is necessary to gain an appreciation of the immense distances involved, and will be useful later for assessing the propulsion system requirements.

Within 20 light years of the Sun, there are 59 stellar systems containing 81 visible stars. These include 41 single stars, 15 binary, and 3 triple systems. At present, only eight planetary companions to these stars have been detected, and even these have strained existing detection techniques.

Most discussions of interstellar missions, either manned or unmanned, have assumed that the primary goal was the detection of life, and have chosen target stellar systems accordingly. To this end, it would be desirable to select a group of stellar systems from within the 20 light-year sphere which have the best possibilities of containing planetary systems conducive to life.

Since one star, our Sun, is positively known to possess a planetary system, it can only be assumed that stars similar to the Sun is spectral type, mass, radius and luminosity also have some possibility of possessing a planetary system. By using a star's similarity to the Sun as a selection criterion, we hopefully will be choosing target stellar systems not only for their potential planetary systems but also on their ability to support life.

There are many criteria by which to choose the prime targets for an interstellar probe mission. The criteria and the list will change as we learn more about the formation of planetary systems, and as we search the neighboring stellar systems for planets. At the present time, there are seven prime targets within 12 light years of the Sun. They are listed in Table 3.

Table 3 — Prime Targets for Interstellar Missions

Stellar System	Distance (light years)	Remarks
Alpha Centauri	4.3	Closest system. Triple (G0, K5, M5). Component A almost identical to Sun. High probability of "Life bearing" planets.
Barnard's Star	6	Closest system known to have one, and perhaps two or more planetary companions. Very small, low luminosity red dwarf (M5).
Lalande 21185	8.2	Red dwarf star (M2) known to have a planet.
Sorois	8.7	Large, very bright star (A0) with white dwarf companion.
Epsilon Eridani	10.8	Single star system; slightly smaller and cooler than the Sun (K2), may have a planetary system similar to the solar system.
Procyon	11.3	Large, hot white star (F5), second only to Altair in luminosity (within 20 light years). System contains small white dwarf.
Tau Ceti	11.8	Single star system, similar in size and luminosity to the Sun (G4). High probability of possessing a "Solar-like" planetary system.

11. Interstellar Probe Design

The design of the autonomous interstellar exploration probe is the critical driving item in any program for interstellar flight. The probe must go to the stellar system and carry out a preliminary exploration before we can plan the manned mission. Because of the very long travel and communication times involved, the probe must leave decades ahead of man. The rigors and length of a journey involving high gravity accelerations with high energy density engines, the years of bombardment against interstellar matter at a relative velocity of 1/3 the velocity of light, and the decades of operation with no means for repair, or even diagnostic help from Earth, means that a new level of self-diagnostiC, self-repairing, multiply-redundant probe design must be developed. The long, round trip communication time (8.6 years) makes any sort of Earthside control of the mission completely out of the question. The autonomous features of the computational circuitry of the probe will have to be developed to the extent that the probe will exhibit semi-intelligent behavior when presented with new and unforeseen circumstances.

The requirement for multiple planetary exploration at each stellar system will limit the number or weight of lander probes available and puts a premium on long-range sensor capabilities to gather the same data from orbit. These, in turn, require very high resolution capability from orbital altitudes, which drive up the size of the transmitting and collecting apertures desired.

Yet, despite these needs for performance, the energy requirements for achieving velocities near that of light are so large that the weight of the probe should be kept to a minimum. Development efforts on multiple function emitters, antennae, sensors and data processors are needed to minimize the payload.

What we desire in an interstellar probe is a large physical size (to give the transmitting and receiving apertures desired), and high power (for active sounders and data transmission), all combined with light weight.

One conceptual approach to an interstellar probe is to have the basic structure to be in the form of a large sphere of wire mesh. The wires that form the backbone of the mesh would not only serve as structural material, but also as the electrical interconnections between the various active components. With the new advances in organic superconductors underway, it is quite possible that these "wires" will not be made of metal, but instead will be made of fine bundles of organic fibers, chemically tailored to have high strength, display superconducting (zero loss) behavior even at room temperature or higher and, in addition, exhibit conductivity only along the direction of the fiber, with very low conductivity across the fiber; thus, bundles of these fibers could be placed side-by-side without insulation and still have negligible cross talk.

Surrounding each of the structural interconnecting bundles would be a dense covering of active circuit components such as broadband solid state sensors for any form of electromagnetic radiation from radio waves to ultraviolet light and solid state laser diodes capable of efficiently emitting electromagnetic radiation of many wavelengths. Intermingled with these would be particle detectors and chemical sensors, all solid state, all very small, and all integrated into electronic digital circuits that couple and coordinate the activities of the detectors and emitters with signals passed back and forth through the mesh structure.

Again, with advances in organic conductor research, these solid state detectors, emitters and circuit components may no longer be made of microcircuits in semiconductor silicon chips, but will be mini-microcircuits (nano-circuits) formed out of large semiconducting organic molecules, each large molecule chemically designed to perform a certain function in the circuit. The circuits would be "grown" along with the organic superconducting mesh rather than made separately and added to the structure. There would be no central computer in this model of an interstellar probe. The computer, instead of being concentrated in one place where it could sustain catastrophic damage, would instead be "distributed" everywhere along the mesh in a multiply-redundant fashion. Any small section of the mesh would have the ability to perform any function of the whole mesh (although not so well).

The power for the operation of the probe could come either as a bleed-off from the propulsion system (if a superconductive magnetic bottle containment of the propulsion plasma is used, this would be obtained in direct electric form) or collected by the solid state detectors from the target star radiation.

If these advances in organic nano-circuits and computer architecture are realized, then the probe payload mass could be made quite small while still retaining a large fraction of the operational capabilities of a more conventional method of assembling a scientific exploration payload. A mesh sphere of 1/ 10 millimeter (40 gauge) wire 100 meters (300 feet) in diameter with intersections every centimeter would only weigh a few tens of kilograms. Each hemisphere would have about 10^8 mesh intersections with active circuits that, when properly phased, could provide a substantial active aperture for both transmission and collection of energy.

I would like to emphasize that the above is only one conceptual approach to the design of an interstellar probe. That particular one assumes certain technological advances in the particular field of organic conductors.

Other concepts would use technological advances expected in other fields.

Since the design of the probe is the critical driving item in an interstellar exploration program, we should start work on alternative preliminary designs right now. As the alternative designs take form, we can carry out exploratory feasibility studies on the critical technological problems uncovered. As the probe design work proceeds toward the difficult goal of a completely autonomous, high power, long life, lightweight design, the technologies associated with sensors, solid state emitters, microminiaturization, and computer sciences will be driven hard. The technological fallout from this program will be great. New and better sensors, new fabrication techniques for electronic circuits, new designs for self-repairing, self-diagnostic computers, and new sources for the generation and transmission of coherent energy will provide significant new capabilities in our increasingly electronic world.

After a number of iterations of the exploratory probe design, the weight and size of the payload needed for the mission will have been defined closely enough so that design and engineering of the propulsion system can be undertaken. In the 10 to 15 years involved in probe design, we expect significant progress will have been made in high energy beamed power lasers, controlled fusion using either magnetic containment or laser induced implosions, nuclear warheads, and nuclear physics. There may even have been scientific breakthroughs that would provide new forms of energy conversion, storage or transmission. One or more of these developments will provide the technological basis for an interstellar propulsion system.

12. Interstellar Propulsion Techniques

Once the design of the interstellar probe has stabilized in size and mass and has therefore sized the mission, then we can proceed with definitive studies on the propulsion mechanism that we are going to use to launch the probe on its interstellar journey.

12.1 General Discussion of Interstellar Propulsion Techniques

The equations to describe the optimum design of a propulsion system required to reach near-relativistic velocities can be very complicated. However, the basic features of the desired propulsion system can be explained without equations.

A space vehicle is pushed forward by its rocket engine because the rocket engine is throwing propellant particles out its exhaust at a high speed in one direction, so the spaceship responds by moving in the opposite direction.

Now, one might think at first that if the rocket exhaust velocity were 1/10 the speed of light, that the fastest the spaceship could move would be 1/10 the speed of light. However, the propellant is moving along with the spaceship and the velocity that counts is the velocity with which the particles leave the rocket, not the velocity that they have with respect to space. Thus, a spaceship can attain a final velocity that is higher than the velocity of the particles in its exhaust jet. There is a severe penalty for this, however.

If you desire a final spaceship velocity that is greater than the exhaust velocity, then you must carry a lot more propellant to compensate for the inefficient operation and your mass ratio will increase. (The mass ratio is the initial mass of the rocket loaded with all of its fuel, divided by the final mass of the rocket at burnout.) Unfortunately, the mass ratio increases exponentially as you go to higher and higher final spacecraft velocities, so you rapidly reach a point of diminishing returns, and it is better to spend more effort to find a more energetic fuel.

However, surprisingly enough, a very highly energetic fuel is also not necessarily what you want for most efficient operation. It turns out that for most efficient operation of a rocket, the velocity of the particles in the exhaust jet should be close to the velocity of the spacecraft. If the particle velocity is too high (as it is in a photon rocket, where the exhaust particles consist of raw energy moving at the speed of light), then during the initial phases of the thrust period, the energy of the fuel is still largely in the rapidly moving exhaust and not in the spacecraft. Similarly, if the exhaust velocity is too low, then toward the end of the thrust period, the ejected particles are left in space moving along in the direction of the rocket, and you have therefore lost some of the spacecraft energy in carrying the fuel along with you.

Thus, whenever the exhaust velocity is too high or too low, we have energetically inefficient system and we must carry along a lot more fuel to make up for the inefficiency.

There are some propulsion systems where we are allowed to pick the propellant mass and energy source separately (this is the case for present day solar electric propulsion systems and the proposed laser heated rockets and antimatter energized rockets discussed later in this section). For these types of propulsion systems, calculations show that the optimum exhaust velocity is about 6/10 the final velocity you want in the spacecraft, and the mass ratio is about 5. That is, for every kilogram of payload, you need only four kilograms of propellant, or a total launch mass of 5 kilograms. If you want to decelerate again at the target star, then this requires a mass ratio of 5 in each stage, or a total launch mass ratio of 25. (This mass ratio minimum is relatively independent of the final velocity except for velocities greater than 1/2 c.)

A mass ratio of 25 is not a high mass ratio, and most of our space shots have used much higher ones. To attain this minimum, however, requires that we separate the energy source for the rocket from the propellant particles (reaction mass).

Now in many propulsion systems, we are not allowed to pick our exhaust velocity arbitrarily. In those systems where the source of exhaust particles and the source of energy are one and the same (as in present day chemical rockets and the proposed fusion rockets and nuclear pulse rockets), the exhaust velocity is determined by the characteristics of the fuel. Typically, these exhaust velocities are lower than we would like, and therefore these rockets require large mass ratios.

The design, feasibility demonstration, and development of the propulsion system will be the most expensive portion of the interstellar exploration program. Since the difficulty and cost is proportional to the size of the payload that must be launched, it is recommended that significant effort on the propulsion portion of the program be deferred until the mission and probe design are more certain.

There are not one, but five possible techniques for interstellar propulsion that have received enough technical study so that we know that they have the basic physical feasibility as well as energy and power capacity to be considered for interstellar propulsion. All of them still retain a number of technical uncertainties and will require significant engineering effort before they can be said to be engineeringly feasible.

The five techniques are: nuclear pulse propulsion, controlled fusion rocket, interstellar ramjet, beamed power laser propulsion, and antimatter energized propulsion.

"With so many theoretical possibilities for interstellar flight, we can be sure that at least one will be realized in practice. Remember the history of the atomic bomb; there were three different ways in which it could be made, and no one knew which was best. So they were all tried — and they all worked." (Arthur Clarke [12]).

12.2 Nuclear Pulse Propulsion

The nuclear pulse propulsion concept was developed in the early 1960's at Gulf General Atomic (Project Orion). The propulsion system operates simply by jettisoning a nuclear bomb, exploding it, and absorbing part of the momentum of the resulting debris. Figure 2 shows a sketch of a small nuclear pulse vehicle. The rear of the vehicle or "engine" is composed of essentially three parts: an ablation shield/pusher plate, an array of large shock absorbers, and a mechanism for ejecting the bombs. The forward section of the vehicle consists of the fuel or bomb magazine, and the payload.

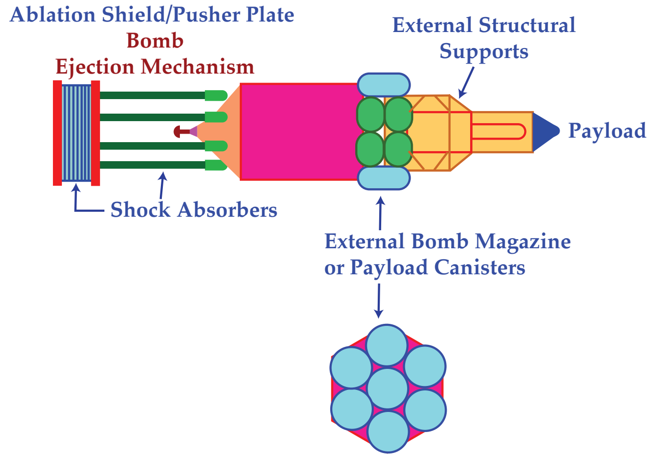

Figure 2 — Nuclear Pulse Vehicle[13]

Since much of the work done on pulse propulsion remains classified, it is difficult to obtain specific system parameters and assess its applicability to interstellar flight. However, Freeman J. Dyson has reported a generalized pulse system which will give the reader some idea of its potentials and drawbacks.

The "Ablation Space Ship"[14] is similar in design to the one shown in Figure 2, except with a larger and partially hemispherical pusher plate. This allows for a more efficient absorption of energy and momentum. This system has a total mass of 4×10^8 kg, with 4.5×10^7 kg set aside for payload (large enough to contain a small human community). 300,000 thermonuclear bombs or pulse units account for two thirds of the vehicle's mass (at one ton per megaton of yield) with the remaining 10^8 kg accounted for by structure, ejecting mechanism and shielding. The construction of the pusher plate limits the velocity transfer to about 30 m/second per explosion. This vehicle is to be accelerated at one g, requiring an explosion every three seconds. The shock absorber stroke length necessary to maintain a smooth and constant acceleration at this pulse repetition rate is about 75 meters.

Dyson's nuclear pulse vehicle is able to maintain a one g acceleration for about 10 days, when its bomb supply will be exhausted. At this time, it will have reached a velocity of 10,000 km/second (0.033 c). The flight time to Alpha Centauri is 130 years. However, these flight times do not account for any deceleration at the target stellar system. Retaining half the bombs for this deceleration would more than double the mission time for this size vehicle. At one hundred dollars per pound of deuterium, the total fuel cost is on the order of sixty billion dollars.

Although the nuclear pulse vehicle discussed above has rather long flight times, refinement of this propulsion system does hold some promise for interstellar vehicles. However, the Nuclear Weapons Test Ban Treaty prohibits the explosion of nuclear weapons in space, and hence presently inhibits any significant development work on such a system.

Variants of the nuclear pulse technique such as those considered for Project Daedalus using small pellets of deuterium ignited to fusion temperatures by pulsed lasers[15,16] or by relativistic electron beams[17] are newer concepts that are worthy of continued further study.

12.3 Controlled Fusion Rocket

One of the more technologically promising concepts for an interstellar propulsion system is to use a controlled fusion reaction as the propulsion power source. The present extensive scientific and engineering efforts in the United States and around the world on controlled fusion are concentrating on the development of "magnetic bottles" to contain a high temperature fusion plasma. Most of that effort is spent struggling with the problem of making the magnetic bottle leakproof. Fortunately, for the propulsion application, what is desired is a "leaky" magnetic bottle. The hot plasma emitted from the "leak" providing the desired rocket thrust.

We are at present not certain which of the many proposed techniques for controlled nuclear fusion will prove feasible, but whatever method results, it will be a prime candidate for the propulsion portion of an interstellar exploration mission.

Spencer[18] has examined the problem of nuclear propulsion for interstellar travel from the viewpoint of rocket staging and energy available as a function of propellant mass, without regard to any particular propulsion system.

Since no particular propulsion system was treated, the problem of acceleration was not touched upon. If, however, we assume a hypothetical propulsion system capable of one g acceleration and a mass ratio of 10, a deuterium fusion rocket could reach 1/10 the velocity of light. At that velocity, it would take about 45 years to reach Alpha Centauri.

It is difficult to predict at present whether these propulsion systems are engineeringly feasible. One major problem to be overcome is the efficient utilization of the several different forms of energy released during a fusion reaction. Only about 20 per cent of the released energy will be contained in the kinetic energy of the fusion particles. Ten per cent is in the form of IR-UV radiation, but 70 per cent is released as X-rays. Figure 3 schematically illustrates a method of reclaiming this X-ray energy by using an auxiliary laser thruster, powered by the waste X-rays. The X-rays escape the fusion chamber, and are absorbed by the gas lasers (perhaps doped with xenon). The X-ray energy is then converted into a collimated light beam thruster. If the efficiency of the laser's X-ray to collimated light conversion process is around 40 per cent, the laser aided fusion rocket[19] can achieve a velocity of about 0.10 c with a mass ratio of 20.

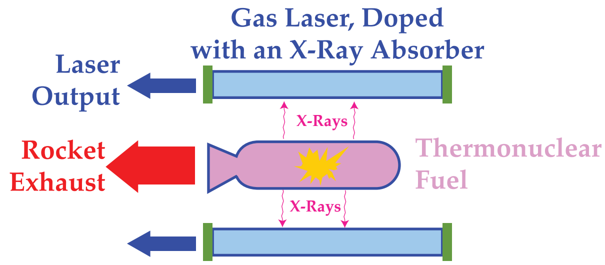

Figure 3 — Schematic of a thermonuclear rocket-laser drive propulsion system (adapted)[19]

12.4 Interstellar Ramjet

The Interstellar Ramjet[20] was devised to overcome the large mass ratios required when terrestrial fuel must be brought along onboard "conventional" interstellar vehicles. The interstellar ramjet collects interstellar matter to fuel its fusion rockets, thus eliminating the need to carry large masses of fuel.

Figure 4 schematically illustrates the ramjet concept. As the ramjet moves (to the right), ions are caught by its magnetic field scoop which funnels them into a fusion reactor. Within the rocket, energy is released and fed back in some manner into the reaction products. These particles are then used to provide thrust for the vehicle. Bussard originally estimated that a 10^6 kg vehicle would require a frontal intake area of between 10^4 km^2 and 10^7 km^2 to achieve a one g acceleration through interstellar space with a nucleon density between 1 and 1000 nucleons/cm^3.

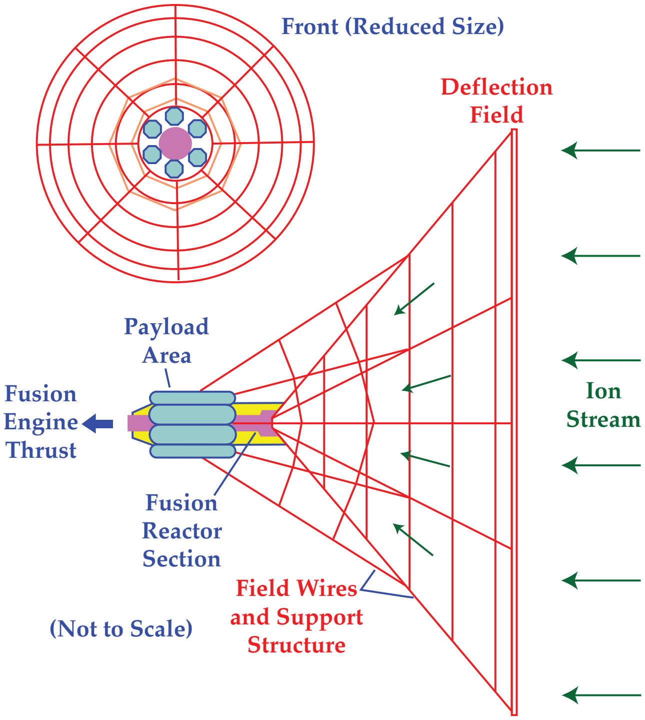

Figure 4 — Bussard Interstellar Ramjet

This vehicle has several advantages over other types of propulsion systems. The ramjet take-over velocity is extremely low so that conventional ballistic rockets could provide the initial acceleration. As the vehicle increases its velocity into the relativistic region, the interstellar fuel flow appears to increase in density due to Lorentz contraction in the vehicle's space-time. The engine efficiency can then be reduced, or the vehicle can navigate through lower density areas of space, without affecting its acceleration[21]. The ramjet can start out in areas of fairly high hydrogen density, cross areas of low density, and slow down again in areas of high density, without suffering in performance.

Several authors maintain that since the cross section of the proton-proton reaction is only around 10^{-47} cm^2 and the density of deuterium in interstellar space so low (1 :8000 atoms of hydrogen) the reactions used by the ramjet are not feasible in interstellar space[22]. However, the idea of picking up your fuel along the way in your journey across space is too valuable to lose and further work needs to be done on the concept.

12.5 Beamed Power Laser Propulsion

The concept of using beamed energy from lasers for interstellar propulsion appeared in a popular article by Forward[23] shortly after the invention of the laser in 1960. The author suffered from what Arthur Clarke calls one of the hazards of prophecy — "a failure of nerve"[24] and said that building a large laser in space was too difficult and some other method for interstellar propulsion would have to be found. Further studies, and the advancement of laser technologies, have now made the ideas look more attractive.

A drawing of the operation of the original proposed concept is shown in Figure 5. The idea is to use the photon pressure of the laser light pushing against a giant sail to accelerate the interstellar probe up to relativistic velocities. The first concepts for beamed laser propulsion suffered from the problem that once the interstellar probe was up to speed, there was no apparent way to decelerate the probe when it reached the target stellar system, and the concept was therefore limited to flyby probe missions.

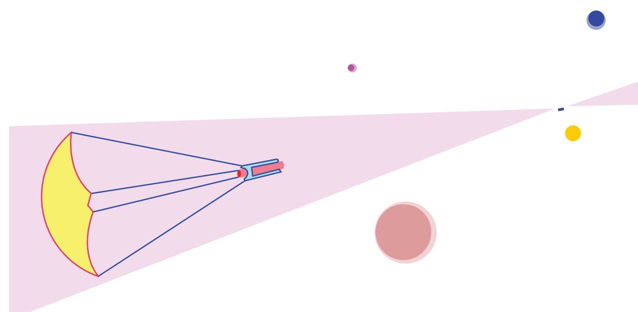

Figure 5 — Beamed Power

However, an ingenious paper by Philip Norem[25] combined two ideas which had already appeared in print to come up with a beamed power laser system that could decelerate at the target star (see Figure 6). The laser would be used to accelerate the probe up to relativistic velocities[23], then the probe would extend out long wires which would be charged up to high voltages. The charged wires would then interact with the interstellar magnetic field to swing the space vehicle around in a large circle as proposed by Forward[26] in 1964. The probe course would be chosen so that it would swing out around behind the target system and pass by the target star on its return, with its velocity vector pointing at Earth. The laser would be turned on again, and probe decelerated by the long distance laser beam from the solar system. (Since Norem's concept was based upon the simple combination of two separate ideas published by the same person, one can only conclude that person suffered from the other hazard of prophecy mentioned by Clarke — "a failure of imagination.")

To carry out a rendezvous mission with the direct laser photon propulsion technique would require very large (250 km) laser arrays, possibly in close solar orbit and drawing their energy requirements from the high solar flux available there. The sail on the interstellar probe could be of very thin material, but for optimum coupling to the laser beam, it too should be of the order of 250 km in diameter, and even with very thin, low density material, we are talking about thousands of tons of sail.

The large size of the laser is required so that the laser beam has not diverged significantly at the 6 light year distances required to decelerate the probe. For the initial acceleration period a much smaller laser of the order of 10 km in diameter would suffice since the probe is so close to the solar system.

Although the laser arrays must be large to achieve the desired beaming distances and the energy must be high enough to push the probe to relativistic velocities, the energy flux from the laser is not high. In typical systems, the laser beam is no more powerful than sunlight.

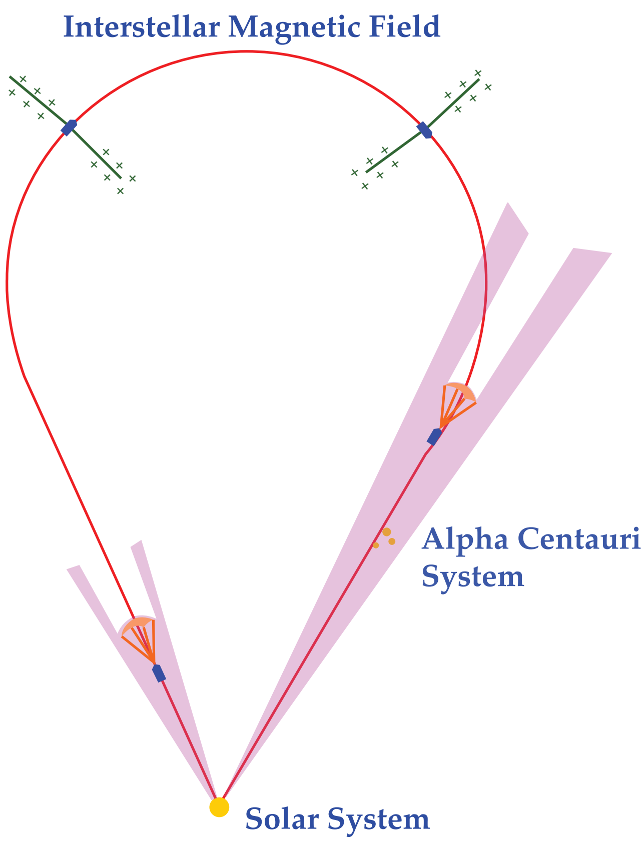

Figure 6 — Interstellar Travel Using Beamed Laser Power

However technically interesting these ideas of photon propulsion may be, a more practical method would be to carry along some mass to use as propellant, and just use the laser beam to energize the propellant. There have been a few studies that have considered the use of beamed laser energy for energizing reaction mass in an interstellar propulsion system[27], but much more work needs to be done.

The field of beamed power laser propulsion is in a rapidly developing state with significant engineering efforts underway in NASA and DOD for generating and beaming large amounts of energy through the atmosphere and into space. Although the energy levels and transmission distances presently being considered are a long way from the levels needed for interstellar propulsion, this rapidly developing technology seems to be one of the more promising candidates for an interstellar propulsion system.

12.6 Antimatter Energized Propulsion

The idea of using antimatter as the energy source in an interstellar vehicle has been in the technical literature for a long time. All of the concepts have assumed that the propulsion system would use half regular matter and half antimatter as fuel. When the regular matter and the antimatter are mixed together, we get complete conversion of the two into energy in the form of gamma rays, neutrinos, and high energy electrons and positrons. Approximately half of the energy is in the neutrinos which immediately escape from the system.

Although studies have been made of the conceptual design of gamma ray reflectors to turn the gamma ray photon energy into thrust, most authors have given up at this point and placed antimatter propulsion into the "impossible" category. But for missions to the nearby stars, we do not need vehicle velocities very close to that of light, so we do not need the exhaust velocity to be that of light. A more efficient method is to use a small amount of antimatter to energize a much larger amount of regular matter[28].

An optimized engineering study of an interstellar probe propulsion system using antimatter has yet to be done, but some approximate numbers can be estimated now. If an antimatter propulsion system is optimized for a probe coast velocity of 1/3 the speed of light, then the minimum in the mass ratio of each propulsion stage[28] occurs at a mass ratio of 5, and the antimatter mass required is 1/10th of the burnout mass or 2% of the initial mass.

If we assume the development of a very lightweight (10 kg) interstellar exploration probe design, the interstellar vehicle at launch would consist of a 51 kilogram second stage, 200 kilograms of propellant and 5 kilograms of antimatter. This would suffice to accelerate the second stage to 1/3 the velocity of light. The 51 kilogram second stage would consist of the 10 kilogram exploration probe payload, 40 kilograms of propellant and 1 kilogram of antimatter which would be used to decelerate the probe at the target star.

Besides the obvious engineering problems that remain to be solved in the design of an engine that can effectively convert the antimatter energy into directed thrust of the propellant, there is a real question of the obtainability and control of the antimatter.

The containment and control of the antimatter, once made, should not be too difficult since we have a number of ways of applying forces to the antimatter without touching it. Electric fields, magnetic fields, RF fields and laser beams are all used in present day technology to levitate and control small amounts of regular matter that we do not want to contaminate. These would all be equally effective on antimatter.

The generation of appreciable amounts of antimatter is the primary engineering problem that should be addressed early in any investigation of the feasibility of using antimatter for interstellar propulsion. As we pointed out in the section on energy requirements for interstellar propulsion, we already destroy hundreds of kilograms of regular matter each year in our electric generating plants and convert it to electricity. All we need to do is develop efficient methods for turning that energy back into antimatter instead of regular matter.

The present methods for producing antimatter involve the use of large accelerators which can produce a proton beam of 10^{15} protons per second. When such a beam collides with a target, antiprotons are produced as part of the debris.

The antiproton yield of present machines is very low. However, the presently used methods are not designed for antimatter production but rather for studies in the physics of elementary particles. Rough calculations assuming special purpose high amperage colliding beam accelerators indicate that the generation of kilograms of antimatter per year is not out of the question. A study to investigate the possibility of increasing antimatter production rates to the level required for propulsion applications would be one of the critical technology areas that should be studied in the initial phases of an interstellar exploration program. The problems of antimatter storage, annihilation rate control, and development of practical propulsion schemes are also those on which future studies should be focused.

13. A Proposed Program for Interstellar Exploration

The proposed 50 year phased program starts with a fifteen year period of mission definition studies, automated probe payload definition studies and development efforts on critical technology areas. The funding required during this initial phase of the program would be a few million dollars a year. As the automated probe design is finalized, work on the design and feasibility testing of high energy, ultra-high velocity propulsion systems would be initiated. Annual funding for this phase of the program would climb to the multi-billion dollar level, to peak around 2000 AD with the start of the launch of a number of automated interstellar probes per year to carry out an initial exploration of the nearest stellar systems. Development of man-rated propulsion systems would continue for 20 years while awaiting the return of the automated probe data required before we could proceed with manned exploration. Assuming positive returns from the first probes, a manned exploration starship would be launched in 2025 AD, arriving at Alpha Centauri 10-20 years later.

Year	
1975	Interstellar mission definition studies Initiate search for planetary systems around nearby stars Feasibility design studies of automated probe payload
1980	Initial studies of potential propulsion systems Development of critical probe technologies Prototype design studies of automated probe
1985	Design of interstellar communication system Prototype design studies of propulsion system Fabrication of prototype automated probe payload
1990	Fabrication of 1/10 scale prototype propulsion system Test prototype by 0.1 light year round-trip "search for life" in our solar system
1995	Start fabrication of interstellar probe vehicles Launch of Alpha Centauri probe
2000	Launch of probes to Barnard's Star, Sirius and Lalande 21185 Start 10-20 year orbital life test of manned spacecraft design
2005	Continue launch of probes to further stellar systems Design man-rated propulsion systems
2010	Fabricate and test prototype man-rated propulsion systems Prepare communication receiver for probe data return
2015	First data return from Alpha Centauri probe Start fabrication of manned exploration vehicles
2020	First data return from Barnard's Star probe First data returns from Sirius and Lalande 21185
2025	Launch first interstellar manned exploration expedition

14. Synopsis of an Interstellar Probe Mission

In 1998, an interstellar spacecraft, which has been drifting in space in the region beyond the Moon, launches itself toward the triple star system Alpha Centauri. It thrusts at high acceleration, its engines running at a power level that is ten times the power of a Saturn V rocket. The exhaust of hot hydrogen plasma glows like a bright star, visible both night and day. After four months the probe has left the solar system, and has reached 1/3 the velocity of light. It begins its long drift through interstellar space using its bulky first stage shell as a radiation barrier to protect it from the constant rain of high energy particles produced by its high speed through the interstellar hydrogen.

After drifting quiescently for 12 years (it has now covered four light years), it sheds its first stage, turns around, and begins deceleration. As the probe velocity drops well below relativistic speeds and it approaches its target, the spacecraft opens up from a compact mass into a one hundred meter diameter sphere. The sphere is a dense wire mesh embedded with arrays of tiny sensors and transmitters, close coupled to complex digital molecular circuitry, all held together and interconnected with high strength, one dimensional super-conductive fibers.

The probe turns its attention back to Earth to receive its latest instructions. A pulsating laser beam, bright through the background glare of the now distant sun brings a message from its masters on Earth. Large new telescopes on the Moon combined with sophisticated image processing techniques have detected a planet within the life-supporting zone of the small red dwarf star, Proxima Centauri — "Go and investigate!" The message is over four years old, but it is the most current that the probe can expect.

The array of sensors spaced over the hundred meter sphere collect the light and radiation from the three stars in the Alpha Centauri system and correct the rocket thrust to zero in on Proxima Centauri. As it approaches the small red star, the probe searches for the planet. It is there, along with three others further out. The other three are cold, and probably lifeless, but they will be visited before the probe leaves Proxima to investigate the other two stars in the Alpha Centauri system. With its thruster at low power, the probe approaches the planet Proxima Centauri One, constantly beaming pictures and sensor data back to Earth using a phased array of solid state lasers scattered densely over its mesh surface. Earth will not see the pictures of the new planet for 4.3 years, long after the probe has completed its survey and moved on to the other planets and stars in the Alpha Centauri system.

With no feedback possible from Earth, the computer circuits distributed through the sphere analyze for themselves the information its sensors collect as it approaches and the probe swings into a near polar orbit of the new planet and begins a survey. Wide-band sensors sensitive to the entire electromagnetic spectrum produce imagery in the radio, microwave, infrared, visible, and ultraviolet bands. The one hundred meter size of the detector array gives the pictures a resolution of less than 1 m even from the 1000 km orbital altitude. Picosecond pulses of laser light beam down as a laser radar to measure the height variations of the topography. Certain regions that might have life are interrogated with selected laser wavelengths, and their return light analyzed to look for absorption or fluorescent bands characteristic of organic compounds. A few regions that have the most potential for life are selected.

Small portions of the sensor mesh on the sphere detach from the main probe mesh and are driven down into the atmosphere with radiation pressure from the lasers on the probe. The small mesh sections drift down to the surface, collecting and storing images as they descend. The mesh settles on the surface where specialized chemically sensitive molecular circuits react to the various forms of chemical compounds found there. The orbiting probe interrogates the lander mesh with a laser beam, collects the images and chemical data it has stored, combines it with the other information that it has collected, and sends a detailed report back to Earth.

The probe then moves on to the next planet in the system, more slowly now, for it is no longer as lavishly supplied with fuel as it was at the start of its mission. It will not stop until it has made a complete survey of every planet in the three star system. This will take a long time, but the probe has a lot of time. It will be at least 30 years before man will arrive to take over.

2007 Postscript

The spelling was changed from English to American usage, the document was reformatted to be double column, and the illustrations were redrawn as color vector drawings in December 2007.

Robert L. Forward (August 15, 1932 to September 21, 2002) was a well known physicist and science fiction writer. He wrote over 200 papers and articles, eleven novels, and was granted twenty patents. His scientific papers have been archived at the University of Alabama in Huntsville.

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