The Wayland Report:

Sketches of a Manned Starship

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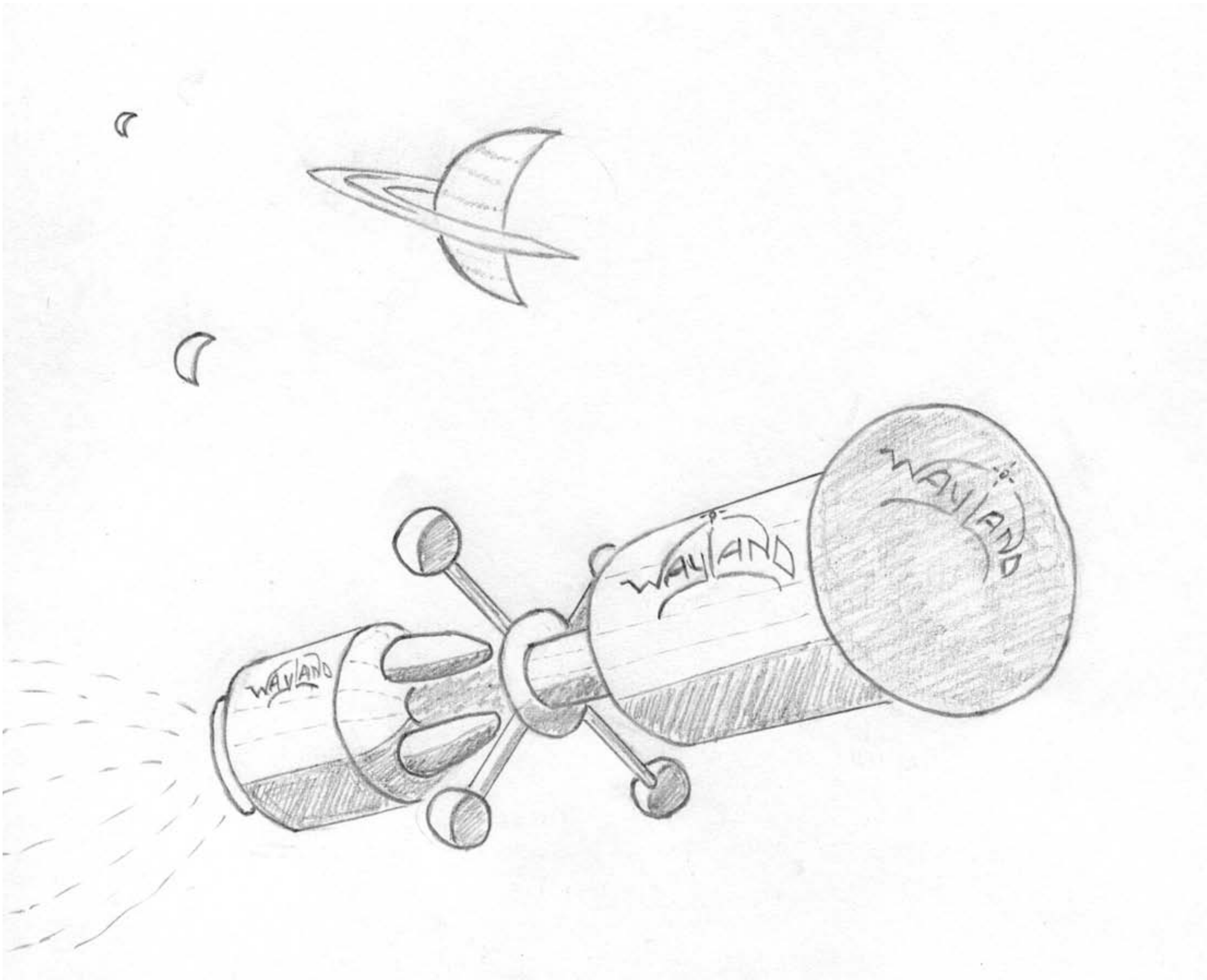

Wayland leaving the Solar System

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Wayland is a set of design sketches for a manned starship.

These unofficial notes have been produced in parallel with the Icarus project (http://www.icarusinterstellar.org/), itself an updating of the Daedalus project of the 1970s. Daedalus produced a detailed design for a robotic probe which might be launched on a flyby of a nearby star (Barnard's Star was chosen) within a couple of centuries, while Icarus has its sights on a departure by the end of the 21st century.

But Wayland looks further ahead to ask whether, when and how human beings might voyage to the stars in person. While speculative, Wayland shall still remain physically plausible.

The name "Wayland" has been chosen since a character of this name was the Anglo-Saxon equivalent to the Daedalus of ancient Greek mythology.

The top-level design guidelines for the Wayland starship are as follows:

- Propulsion – the most difficult and costly part of any starship design – must be based on a technology that will see large-scale prior application in the domestic Solar System economy. This criterion throws up a short-list of candidate technologies.
- Because of the uncertainties in looking ahead to a futuristic technology, it will be useful to focus the different possibilities on the objective of a cruising speed of one tenth of the speed of light, this being the minimum speed that will bring the handful of closest stars within range of a voyage that can be completed within a century.
- The vehicle is to carry a sufficiently large number of crew and passengers to work effectively at their destination in total physical isolation from the Solar System.

- The design of the propulsion system yields a figure for the energy consumption of each ship, which can then be used, in conjunction with a range of speculative future economic growth rates, to estimate when the first manned interstellar voyage might become possible.
- A range of different destination stars shall be considered, Wayland being regarded as a generic vehicle which remains in production for a period of time, not a one-off venture.

Many scientists and engineers continue to believe that the voyage of a manned starship, bringing our own descendants into direct physical contact with extrasolar planets and ultimately extrasolar alien life, is too difficult a project ever to bring to fruition.

The numbers suggest otherwise. Although a manned starship is certainly way beyond our *current* abilities, so long as technological progress and economic and population growth remain possible then a point can be reached when the capabilities of civilisation match the challenge. The question becomes one of asking how much growth and progress is the precondition for a starship of a given speed and size.

Since the future expansion of civilisation inevitably entails our occupation of the Solar System, growth on the interplanetary frontier will prepare us in many different but complementary ways to eventually face the interstellar frontier.

Contents

1. *Introduction*

Because interstellar distances are so vast, a vehicle that would cross the gulf of space between nearby stars within a human lifetime must travel at an immense speed. And because every doubling of speed requires a fourfold increase of energy, this translates into an immense energy cost.

This cost is particularly acute in the case of a manned vehicle. Whereas robotic systems have been progressively miniaturised, a human crew needs an irreducible mass of life-support paraphernalia. It needs radiation protection, environmental recycling machinery, a varied diet, a stimulating social environment, and pressurised working, living and recreational space.

Suppose that today's International Space Station with Space Shuttle and Soyuz attached, weighing 500 tonnes, together with its crew of six astronauts on board were to be propelled onto an interstellar trajectory at a cruising speed of one tenth of the speed of light. Then it would have to be given a kinetic energy of 2.25×10^{20} joules. If it had been launched by the most efficient rocket theoretically possible, the total energy expense would then be 1.54 times greater, thus 3.47×10^{20} joules. This is equivalent to the energy consumption of the entire present-day global economy for a full year (global power consumption taken as 10 TW). It is about 30 million times the energy burnt up to propel a single Apollo flight with a crew of three to the Moon and back.

A realistic manned starship would carry more than six astronauts and weigh more than 500 tonnes, perhaps sixty times more, including comprehensive radiation shielding, propellant tanks and an extremely powerful engine. Instead of supporting its crew for a few months, as the ISS does between resupply flights, it would have to provide all life-support, exploration, maintenance and repair functions, with no possibility of resupply from Earth, for essentially the rest of the star-travellers' lives. And on arrival at its destination after a voyage of more than 40 years to even the very nearest star, its huge kinetic energy would have to be removed by braking to allow the ship to come to rest in its target planetary system.

Doubling the exhaust velocity of its propellant in order to maintain the condition of maximum energy efficiency, even so the addition of the braking manoeuvre requires the total energy consumption to be multiplied by a factor of four. With a modest allowance for inevitable inefficiencies in the conversion of raw energy to rocket thrust, the energy budget climbs to several centuries' worth of current global energy use.

Many alternatives to rocket propulsion have been proposed, from the plausible (riding a beam of light from a giant laser orbiting the Sun) to the dubious (the interstellar ramjet) to the wildly speculative (antigravity; wormholes in spacetime; zero-point quantum energy). The present study will remain within the bounds of physical plausibility as currently understood, and will therefore accept that enormous energy budgets are unavoidable.

This has two fundamental implications:

(1) The technology used for the first manned starships will be based on existing technologies for large-scale power production and transport within the Solar System. Developing a radically new technology to such a large scale of application for only a single customer (the starship programme) is not credible.

(2) The realisation of manned starships will depend upon economic growth beyond the current level by several orders of magnitude. Until that happens, the cost of a starship will remain far beyond what any social institution can afford.

These implications lead directly to a third one:

(3) A necessary condition for the construction of manned starships is the transformation of early 21st-century global civilisation from a one-planet economy to a Solar System-wide one.

Expansion is likely to focus initially on settlements on the Moon and Mars. But safe and regular passenger access to these bodies requires a cycler architecture, with permanent cycler stations which provide a safe haven for travellers in transit, and large quantities of chemical rocket propellants for in-space refuelling of ferry vehicles. These two requirements lead naturally towards the use of resources from the near-Earth asteroids, and thus consequently towards exploiting those asteroids for the construction of free-flying colonies in space.

Once this process is well under way in near-Earth space, it may logically extend to the main asteroid belt, whose material resources are about one thousand times greater than those near Earth. Although tiny in comparison with any planet, the one twentieth or so of a lunar mass of material in the main belt is all potentially accessible for mining, and can be used to create a far greater area of living-space for future human populations than could a far larger mass collected into a single planetary body. Thus John S. Lewis has estimated that the main belt could support at least 10 million billion people (*The High Frontier*, p.140-141; *Mining the Sky*, p.196); while Marshall Savage settles for 7.5 million billion (*The Millennial Project*, p.271).

Are such huge populations credible? In terms of energy usage, solar power is an obvious resource. If 10^{16} people demand an average of 10 kW of power each, similar to the present-day level of energy consumption in industrialised countries, the total power demand comes to 10^{20} watts. Meanwhile the Sun generates 3.8×10^{26} W, thus at say 26% conversion efficiency 10 million billion people would need just one millionth of the solar output to satisfy their power demands. There is therefore no shortage of energy for a civilisation many millions of times more populous than our present-day global village.

In terms of materials for space construction, the key concept is that, from the point of view of creating living-space with gravity and an atmosphere, a planet represents a highly inefficient use of resources.

The Moon, for example, has a mass of 7.35×10^{19} tonnes and a surface area of 38×10^6 km^2, thus 1.93×10^{12} tonnes of mass are required for each square km of habitable area (an additional artificial lunar atmosphere, at around 10^{15} tonnes, would not significantly change this figure). For comparison, the space colony design Island One has a projected total mass of about 3.5×10^6 tonnes (including comprehensive radiation shielding) and offers a pressurised surface area of 0.45 (living) + 0.64 (agricultural) = 1.09 km^2 for a population of 10,000 people (O'Neill, p.57-59). In the space colony, therefore, about 3.2×10^6 tonnes are required for each habitable square kilometre, a mass less than that of the Moon by a factor of 600,000. To put it another way, a fully inhabited Moon at 10,000 people per square km would provide enough space for 3.8×10^{11} people. Could the Moon be broken up into tiny fragments and converted entirely into artificial space colonies, there would be enough space for 2.3×10^{17} people, 600,000 times greater than before.

The reason is that in the case of the Moon, Mars, Earth or any other planetary sized body, almost all the mass of the planet serves little function, from the point of view of its surface life, other than to provide surface gravity, while an artificial space colony can provide the same gravity by the much more efficient method of rotation. On Earth the body of the planet also provides a magnetic field and geothermal heat, resulting in an active surface geology, but the Moon provides neither of these services, and a space colony would find other means to replicate their beneficial effects while avoiding their detrimental ones, such as volcanic eruptions and tsunamis.

The conclusion has to be drawn that, while a planet is a good place for life to get started using unconscious means which can evolve spontaneously, once life has reached our stage of development its future growth depends on the use of technology to construct artificial space colonies which use the material resources of the Solar System at a much higher level of efficiency.

The main asteroid belt is like a small moon which has been left unassembled, so that we do not have to dismantle it ourselves in order to obtain the materials for space construction. Its estimated total mass is about 3×10^{18} tonnes. If for the present we set aside Ceres, whose mass is about one third of this total, and two or three of the other large asteroids (starting with Vesta and Pallas, at about 3×10^{17} tonnes each), the remaining 10^{18} tonnes could be converted into space colonies whose habitable surface area of 3×10^{11} km^2 would provide enough space for 3×10^{15} people – a little lower than the estimates cited above, which presumably envisage using all the material available, but still many orders of magnitude higher than any human population that has yet existed.

Looking a little further out, the Greek and Trojan asteroids which share the orbit of Jupiter have an estimated total mass of 6×10^{17} tonnes, one fifth of that of the main belt itself. If developed as space colonies, they could therefore offer an additional surface area of 1.9×10^{11} km^2 for a further 1.9×10^{15} people.

In the Solar System as a whole even larger populations are conceivable. Frank Drake and Dava Sobel have put the overall carrying capacity of our system at "more than a hundred billion billion human beings" (p.128). Savage suggests a figure a thousand times larger (p.303). Presumably, estimates such as these envisage breaking up the moons of the outer planets for construction materials. But either way, the point is made that the propensity for economic and population growth characteristic of industrial civilisation is well matched with the opportunities offered by its local environment, provided that the 21st century sees the beginnings of large-scale development of the natural resources of near-Earth space.

As populations move outward, firstly via the near-Earth asteroids, the Moon and Mars to the main asteroid belt, later to the moons and trojans of the giant planets, later still to the centaurs and the Kuiper belt, the question arises as to how they will obtain their electric power. There are in principle five possibilities:

(1) Ever-larger solar arrays (the flux of sunlight at the orbit of Ceres is one eighth that at Earth; at Jupiter it is one twenty-seventh; at Saturn one hundredth; at Pluto one thousandth).

(2) Nuclear fission using fuels (uranium, thorium) imported from the inner Solar System or found in the asteroid belt.

(3) Nuclear fusion using fuels (deuterium, helium-3) from local resources.

(4) Solar power harvested in the inner Solar System and beamed outwards as microwave or laser power.

(5) Solar power harvested in the inner Solar System, stored as antimatter and shipped outwards.

Option (1) seems unlikely if more concentrated forms of energy are available. It is also ineffective for rapid interplanetary transport.

Option (2) may run up against the limits of available fissionable fuels, which are relatively rare elements, even in the rocky inner Solar System. It does, however, offer rocket propulsion with an exhaust velocity of 10 km/s and above.

John S. Lewis has estimated that if the total resource of fissionable uranium and thorium available in the main asteroid belt were to be used to produce energy, its output would be equivalent to the quantity of energy generated by the Sun in one second, thus 3.8×10^{26} J (*Mining the Sky*, p.197). While this is a million times current annual global industrial energy consumption, it would not last long if extraterrestrial populations expanded towards the carrying capacity of the main belt, reckoned by the same author, as noted above, to be a million times Earth's current population. It would also pose severe problems in connection with the large-scale disposal of the resulting radioactive waste.

Options (3) to (5) seem most likely to be developed to power a Solar System-wide civilisation. All offer concentrated energy in effectively unlimited quantities, and all three are applicable to both electricity supply and high-energy rocket propulsion.

But all three – nuclear fusion, solar-derived beamed power, and especially solar-derived antimatter power – are still at an early stage of development, and it is impossible to predict which will predominate in the interplanetary civilisation of centuries hence. Perhaps first one technology will be dominant, then later another. Perhaps propulsion will prefer one and electricity generation another. Or perhaps each of the three will capture a third of the energy market and there will be no clear winner.

But if the assumption is made that one of these power technologies is dominant at the time the first starships are launched, then it will determine the choice of interstellar propulsion technology. Ships will be built with what is familiar, available and economic, which will not necessarily be the theoretically best choice on paper.

Similarly, the first astronauts to be launched into space in the 1960s flew on converted military ballistic missiles – Redstone, Atlas, Titan, R-7 – which were familiar and available, not on high-performance aircraft, which, though theoretically a more elegant and suitable solution, were at the time too far from space capability.

A comprehensive starship study may therefore split into three alternative design scenarios, based on fusion, laser beam and antimatter power. While this study will focus on the last of these, it must be borne in mind that future economic developments may force the choice of one of the others.

But before propulsion is tackled, it will first be useful to consider the issues raised by the starting assumption of this study, that people will be travelling on board.

2. *Life on board*

Given the starting assumption of a human payload on board the Wayland starship, certain consequences follow.

Guaranteeing reliability

Firstly, entrusting a group of people to a space vehicle in which they must live for at least many decades in total physical isolation from the rest of civilisation would be inconceivable unless living in space was already widespread practice in the Solar System. Just as the enormous propulsive energy required of a starship implies a Solar System-wide home economy far larger than is possible on Earth alone, or even on Earth, Moon and Mars combined, so too the requirement for absolute reliability in closed-cycle life support systems over periods of at least half a century – the minimum journey time at our anticipated cruising speed of $0.1c$ – imply that a significant fraction of that economy must encompass people living their lives from cradle to grave in artificial space structures.

Therefore, on arriving in a new planetary system, human star travellers will consider it natural to contine a space-based mode of life. They will not be looking for extrasolar analogues of Earth or Mars to colonise. If they find any such, that planet's utility as an object of non-invasive scientific study will greatly outweigh any value it may have as a material resource.

But material resources will be needed. On arrival after such a long journey through the interstellar void the star travellers will spend at least a period of years exploring the extrasolar planetary system, even if it is their intention to eventually return. But because of their extreme isolation they will be dangerously vulnerable to equipment failure and to accidents. And because of the high energy cost of getting there, propellants for exploration after arrival will not be carried if local sources can be accessed. The most sensible strategy in this situation is for the star voyagers to take along with them the machines with which to set up a local resource extraction and manufacturing capability for such things as radiation shielding, energy, rocket propellants and physical products.

For raw materials they will naturally turn to the asteroids native to that extrasolar system. These primordial bodies of silicates, metals and ices represent the most accessible local resources, not being located at the bottom of a gravitational well as planetary materials are. They can be put to use with familiar techniques already honed by long experience of transforming the Solar System's asteroids and minor moons into space colonies.

Our first conclusions are therefore that the expedition will carry embryonic space factories, and that the initial focus of its activity after arrival will be prospecting the asteroidal debris which is expected to be found orbiting all main-sequence stars, even those without any major planets of their own.

Secondly, given the precondition that the star travellers will mostly be veterans of life in space colonies in the Solar System, the continuation of that way of life in an extrasolar planetary system will not represent a significant change in lifestyle. Having both the inclination and the means to settle permanently, they will presumably do so, rather than undertake the decades-long return trip. At the same time, the one-way voyage will clearly be very much less expensive than a two-way one, again tipping the scales towards extrasolar colonisation on the first visit.

Health and safety

The two key health and safety issues which strongly determine the overall architecture of any habitable space construction are whether or not to provide shielding against ionising radiation, and whether or not to provide artificial gravity.

The present-day International Space Station offers neither, and as a result its occupants are subject to a chronic radiation dose of around 10 rem/year, forty times higher than the natural sea-level exposure rate, and must live in a permanent microgravity environment.

Other important design choices include atmospheric composition and pressure, methods of bacterial control, and systems for food production and recycling. But while these factors are significant design inputs, they do not determine a vehicle's overall configuration, and may therefore be passed over lightly here.

Galactic cosmic radiation poses a major threat to health in interplanetary space, and even more so outside the partial protection of the solar heliosphere. The Apollo astronauts completed their lunar voyages successfully without shielding and without serious health problems, but for the long-term occupation of space some sort of cosmic ray protection will be mandatory. This issue is so crucial and complex that it will have a full chapter devoted to it, following the present one.

Artificial gravity

Given current knowledge, the human experience of weightlessness resembles exposure to radiation: it is tolerable for a few months to a year or so, but likely to be dangerous to health if prolonged much beyond that, and is certainly not acceptable for periods of a decade or more, let alone a lifetime in space.

Weightlessness (or more accurately microgravity) differs, however, from radiation exposure in that it does not directly attack the body. The problem is rather that the body adapts to weightlessness in perverse ways – notably by losing bone and muscle mass and blood volume.

It is therefore reasonable to expect that over some centuries of large-scale Solar System colonisation, ways will be found to induce the body's autonomous mechanisms to behave in a more beneficially adaptive way in space. The presumption of large extraterrestrial populations creates a large market for any medical advances of this kind, and therefore the economic muscle to ensure that relevant research is vigorously pursued.

What is true of adaptation to weightlessness in space is even more true of the less extreme adaptation required for the low-gravity environments of the Moon, Mars, Callisto, and other potential habitable worlds. Meanwhile, artificial space colonies in orbit may provide Earth-normal gravity at their rim (e.g. *High Frontier*, p.29), or only a fraction of this. Taking into account the familiarity and practical convenience of at least a partial gravity environment, together with the opportunity for reduced physical stress and increased enjoyment in people's day-to-day living, and the reduced structural stress on the colony's material structure, offered by choosing only a fraction of Earth's gravity at the rim, and noting also the likely widespread experience of lunar and martian conditions before large-scale space colony construction begins, and the likely concurrent advances in space medicine, all in all one is led to the expectation that space colonies will offer their inhabitants partial gravity habitable volume at the rim, and zero gravity volume along their rotation axis.

The passenger space vehicles from which starships will evolve may be expected to grow out of the same design philosophy.

While a space colony needs only minor station-keeping manoeuvres, and can therefore grow to an arbitrarily large size and mass, a space vehicle is designed primarily for large velocity changes and must therefore keep its payload mass down. The habitable volume of space vehicles will therefore consist of pressurised modules at the ends of long arms on which they rotate about the centreline of the vehicle, together with another module on the centreline offering weightless conditions, this configuration being more economical of mass than a rotating cylinder or torus.

The arms need to have either a pressurised tunnel for access to the centre, or small lift cars which run up and down; here the latter is assumed. A system for pumping ballast water between the centre and the periphery maintains the centre of gravity at the geometrical centreline, minimising wear on the bearings (if any) of the rotating structure and holding the centreline steady for ferry vehicles to dock. A secondary rotating ring (if required) completes the pressurised access between modules, spinning up to dock with the lift cars, and then undocking and spinning down to redock with the central core module.

A suitable arm length and spin rate have yet to be determined by practical tests. Too short a lever arm or too fast a rate of spin will presumably make the occupants giddy and nauseous. For the present purpose it will be adequate to assume an arm length of 75 metres and a rotation period of 30 seconds, thus generating one third of an Earth gravity, about the same as prevails on the planet Mars, and twice lunar gravity.

Hibernation or wakefulness?

One standard science-fictional approach to the length of an interstellar voyage is to place the travellers in an artificial state of suspended animation, in which they sleep away the light-years (for example, in the series of *Alien* films, and the novel *Alpha Centauri*; a serious discussion is found in *Starflight Handbook*, ch.14). Quite apart from any biological barriers to achieving this safely, I would argue that this will not be done.

Future star voyagers will remain in states of normal consciousness during their journey, firstly and most obviously because their living quarters will be of a type in which they are long accustomed to live, so they will see nothing tedious or boring with simply getting on with their lives in the normal way.

Furthermore, a community that was expecting never to return to the Solar System would have an age range spanning the whole spectrum, from infants to pensioners, and the education of their children would fill a major part of their schedule both during the crossing and after arrival. A ban on pregnancies before or during a voyage of several decades would be counter-productive in that it would cause an awkward and possibly dangerous gap of the same size in the age range after arrival.

A second factor is that useful scientific observations of the interstellar medium and nearby stars can be made during the trip, and scientists on board would expect to study the data as they came in rather than just leaving the tape recorder running and automatically transmitting everything back to the Solar System for analysis. One noteworthy opportunity comes en route from the Solar System to Tau Ceti: a ship making this crossing would pass the double red dwarf star Luyten 726-8 A/B at the relatively close range of only 0.357 light-years about three-quarters of the way through the journey.

A third point is that the starship will need regular maintenance, which for the foreseeable future will remain easier if humans are in charge than if managed by untended machines. And fourthly, the travellers will need to keep all their skills sharply honed for their exploration and construction activities when they arrive. Going to sleep for forty years or more may not be the best way to ensure alertness and professional excellence on waking. But this point has deeper significance. A civilisation that can launch fast starships is bound to be characterised by dynamic growth. New scientific discoveries will be in progress, and new inventions and techniques will be continuing the technological and economic revolutions that made the starship possible.

If they are not to fall decades behind the state of the art, the star voyagers will therefore need to spend much of their time en route studying the latest scientific and technical papers coming in over the radio from the Solar System. As the radio time lag lengthens, they will be in an increasingly poor position to actively contribute to scientific debate back home, but they will still need to keep abreast of events, particularly as regards technologies that they themselves will be using after arrival. Developments in nanotech manufacturing and biological analysis might well be directly relevant to what they will be doing, and capable of testing and implementation in the starship's laboratories. Just as early robotic probes such as Voyager have benefited from being reprogrammed while in flight, so the interstellar expedition could arrive with more capabilities than it had when it first set out.

Granted, however, that for these reasons the astronauts will not slumber away the voyage in suspended animation, then additional maintenance tasks will arise in support of an active crew. Much of the recycling of food, water and oxygen will be done automatically, but the recycling systems will still need routine checking, cleaning and maintenance. The microbiological environment will need constant monitoring to ensure that harmful strains of bacteria are kept in check. An on-board manufacturing capability will be required, with appropriate human supervision and decision-making, for consumable items like domestic cleaning materials, toiletries and medicines, and for items that quickly wear out with use such as clothing and soft furnishings. And if a human society worthy of the name is to function, there will also be a vibrant social programme of recreations, games and sports, poetry and literature, arts and theatre, comedy, music, fashion, philosophy, exchanges of news and views with the Solar System, debates, discussions, and time set aside for simple conversation. And, as was seen above, raising families and educating the next generation.

So as James Oberg once wrote about the future pioneers on the first voyage to Mars: bored astronauts? They wish! They might hardly have time to look out of the window, so busy will they be with routine maintenance, software upgrades, training and study. And entertainment and relaxation, too, if they can manage to make time for it. (*Mission to Mars*, p.85-92.)

There is a basic philosophical point at issue here, one which strongly conditions debates about spaceflight in the early 21st century: is space only for exploration, or is it for living? Is the natural occupant of any kind of artificial space vehicle or station a hardy, heroic, highly trained explorer, venturing into an irreducibly hazardous environment at vast public expense? Or is that space occupant an ordinary person living a normal life, earning a living and raising a family in space, contributing to and benefiting from a multiglobal space economy, who just happens to have been born in and to spend all his or her life in space rather than on the planetary surface on which the species originated? Will people ever call space or other worlds *home*?

If the first is true, then manned starflight, if it is even possible at all, might involve a crew of perhaps no more than a dozen who have in effect taken monastic vows, renounced their claim to a normal life and dedicated themselves to spending the rest of their lives in what the rest of humanity would regard as a highly artificial, highly restrictive and isolated environment, presumably in the sacred cause of science. Living conditions would resemble the spartan accommodation on a submarine, or indeed a present-day space station.

In such a case, artificial hibernation may indeed be seen as the optimum solution for maintaining the crew during the decades-long voyage. The sponsors of the mission would then have to choose between paying the huge transport cost of returning the explorers to the Solar System at the end of their work, or telling prospective crew members that they would be expected to explore until their consumables ran out or until they died of old age. The last survivor of the mission might be given the option of suicide, using a hibernation chamber as a coffin.

It was argued at the beginning of this chapter that, on the contrary, a necessary condition for launching a manned starship is the growth of a substantial extraterrestrial population who regard life in space colonies as perfectly normal, and who would model starship life on what is familiar to them. Living conditions in that case could resemble first-class on a large ocean liner, with much thought having gone into creating an attractive and comfortable environment.

Crew size and passenger capacity

The number of people aboard each starship is not easy to guess in advance.

As a general rule, the earliest model of a new type of vehicle is quite small, but leads to a pattern of evolutionary growth in later models, as has been seen down the years in ships, aircraft and spacecraft. If starships follow the same pattern, the first ones will only have room for a fairly small number of people, perhaps close to the minimum required to maintain a viable human society.

This minimum will not be determined by genetics, as genetic variety can be ensured artificially, perhaps by carrying a sperm and egg bank containing contributions from people who support the programme but could not be accommodated in person. Rather it will be a question of maintaining sufficient numbers for a satisfactory social environment, and particularly of maintaining sufficient technical expertise to cover all necessary professional areas in science, computing, engineering and vehicle maintenance, health, entertainment and culture, and so on.

Both these aspects of space colony and starship life will be profoundly affected by the way information technology develops over the coming centuries. The star travellers' mental, working and social lives could be as different from ours as ours are from those of the illiterate villagers of medieval Europe. Yet some things will surely remain constant: a variety of personalities with shared or clashing interests, leading to conflicts over management policy, over allocation of scarce resources, over sex … for all their technological enhancements, our descendants will still carry the weight of their ancient biological heritage.

Before the agricultural revolution, humanity lived in small roaming tribes, materially independent of one another, but since then the story has been one of increasing division of labour among ever larger populations of mutually interdependent people whose work is increasingly specialised. Early 21st century life is thus based on global networks of activity among millions of people.

When the first permanent colonies are established in space they will necessarily start out as relatively small communities, but they will be able to draw on the entire knowledge base of humankind. The trend will then presumably be towards the broadening of professional expertise and the supplementing of it with specialist knowledge contained in computer systems which become progressively more closely integrated into all human activities. For example, medicine may be practised by doctors whose training is generalist, but who are supported by interactive digital databases (hard-wired into the doctors' brains) which have wireless access to the sum of human knowledge in surgery, pharmacology, childbirth, dentistry, and so on.

If this seems implausible to anyone with experience of early 21st century machines, it may help to remember that the first programmable computers were only built in the 1940s. The computer revolution is thus only 70 years old and continues to show rapid growth and innovation, while this study is looking many times that period into the future.

Manufacturing could follow a similar trend. At present, a specialised machine is required to manufacture each component part of a product, but as asteroidal materials at remote locations come into use the emphasis will be on computer control of versatile machines which can produce a wide variety of parts from a given stock of raw materials. The control of matter at progressively smaller scales, optimistically known as nanotech since the ultimate object is to manipulate matter at a nanometre scale, is likely to contribute to this trend.

The deployment of both human capital and machine assistance is therefore still at a low level of efficiency. Space colonisation at progressively more distant locations within the Solar System will clearly demand improvement of that efficiency.

The minimum viable society of humans and their machines, operating much closer to their maximum efficiency than present-day society does, would have a human population which is arguably greater than 10 but smaller than 1000. When the time comes, the number chosen could be anywhere between about 50 and about 500, drawing on extensive practical experience with space colonies of various sizes and various degrees of isolation from the major population centres of the Solar System, and taking into account the unforeseeable effects of the evolving relationship between human intelligence and the digital systems which supplement it.

For our present purpose a representative round number is needed which is modest enough for an early expedition but substantial enough for a viable mini-society. We can therefore do no better than settle on a figure of 100 star travellers aboard the first Wayland starships.

3. *Radiation issues*

There can be no doubt that one of the strongest design criteria for a manned starship is the need to protect its occupants against galactic cosmic radiation.

The three sources of biologically harmful ionising radiation in space are planetary, solar and galactic, to which a starship moving at high speed adds a fourth component induced by its motion, as neutral hydrogen atoms in the thin interstellar medium slam into its bow. Planetary Van Allen belt radiation and solar flare particles are not an issue for a vehicle on an interstellar transit, and motion-induced radiation is weak in comparison with the extremely high-energy natural galactic cosmic particle flux, which must therefore dominate the discussion.

Robert Zubrin's lucid discussion of radiation risks within the inner Solar System (*The Case for Mars*, p.114-121) gives the interplanetary dose rate of galactic cosmic radiation as varying between 20 rem/year at solar maximum, when the stronger solar magnetic field partially shields the Solar System, and 50 rem/year at solar minimum. Eugene Parker's rather more muddled recent article in the *Scientific American* includes a graphic giving the corresponding range as low as 13 to 25 rem/year, while figure 2-16 in the European Space Agency's 2004 manned Mars mission study suggests the much higher range of 30 to 85 rem/year.

There is closer agreement on the intensity of cosmic radiation debris products which reach Earth's surface: 30 millirem/year, part of a natural terrestrial radiation environment which varies between 200 and 800 millirem/year depending on altitude above sea level and surface rock type, but with a global average of 270 millirem/year. The interplanetary space exposure (not including Van Allen or solar flare radiation) is therefore some 100 to 200 times the normal radiation intensity experienced from all sources on Earth. It should be noted that the cosmic particle flux includes damaging heavy primaries in the form of ionised nuclei of heavy elements, which are never encountered on Earth since they are stopped by the atmosphere at an altitude of 20 to 25 kilometres.

The cosmic ray intensity beyond the heliosphere, where a starship would be for virtually all of its journey, is at present a matter of conjecture, but recent research by R. A. Mewaldt and collaborators suggests that even at solar minimum the Sun provides significant protection. The present study will therefore take the dose rate in interstellar space to be 100 rem/year.

Zubrin's discussion makes it clear that chronic exposure at this level is less than the threshold required to produce radiation sickness. It does, however, create a long-term cancer risk which increases the longer the exposure continues.

The comprehensive 1972 US National Academy of Sciences / National Research Council study known as the Biological Effects of Ionizing Radiation Report, referenced by Zubrin (but apparently unknown to Parker), estimated the statistical probability of fatal cancer within thirty years induced by a chronic radiation dose totalling 100 rem in individuals over the age of ten to be 1.81% for women, 1.36% for men (who are not susceptible to breast cancer).

Taking therefore 100 rem as the annual unshielded dose in interstellar space and the female risk as representative of the species, the radiation-induced cancer risk per year caused by one year's exposure is one thirtieth of 1.8%, or 0.06%.

If the exposure continues for a second year, then at the end of that year the annual risk has doubled to 0.12%, and in general an individual exposed for n years suffers an annual risk of $0.06n\%$ thereafter. Thus after say 20 years of exposure the annual risk is 1.2%, and in a population of 100 people exposed in this way one individual will be struck down with a fatal radiation-induced cancer every year thereafter.

An additional harmful biological effect not raised by Zubrin occurs when radiation destroys nerve cells, which the body does not replace. A study by G. M. Comstock, R. L. Fleischer and collaborators, published in *Science* (9 April 1971), was based on cosmic ray data from Apollo 12. The researchers estimated that during that ten-day lunar mission the astronauts' loss of smaller nerve cells and retinal cells, due to cosmic ray damage, was a few in a million, and their loss of neurons, the largest body cells, was about one in ten thousand (*High Frontier*, p.52; repeated in vague language in *Starflight Handbook*, p.170).

At this rate, during a one hundred year period of exposure an individual would lose one third of his or her nerve cells, including cells of the brain and eyes. Whether such an onslaught would stimulate the body to replace them, or whether they could be replaced artificially by genetic modification or surgical intervention, is not yet known.

All in all, the conclusion has to be that while humans can endure short periods of exposure to galactic cosmic radiation with relatively minor health impacts, as the Apollo astronauts did, the longer the exposure period becomes the less tolerable it is and the greater the danger to health and life, though with no particular cut-off point. Clearly, pregnant women and young children are especially susceptible to radiation-induced damage, since the foetus or child is at a vulnerable developing stage.

A community living permanently in space must therefore regard comprehensive shielding against galactic cosmic radiation as an absolute necessity. This is simplest achieved by surrounding habitable structures with a jacket of some radiation-absorbing substance such as water, which then doubles as a thermal buffer. Water has the clear advantage, as Marshall Savage has pointed out (p.143-144), that it is transparent to light. It is easy to obtain, especially in the middle to outer Solar System, and offers effective shielding per unit mass due to its hydrogen content.

Alternative methods of shielding using electrostatic or electromagnetic fields are discussed by Parker, who dismisses them as unworkable (to be sure, he dismisses the passive mass shield as unworkable, too, since it is too heavy to be launched from Earth in the Space Shuttle's cargo bay). It is certainly true that protective fields would have to be extremely strong in order to repel such high energy particles. But some research sponsored by NASA is continuing. It is assumed here that a shield of inert mass is the most likely to be available for Wayland, due to its simplicity and reliability.

Hydrogen has generally been regarded as the optimum shield material per unit mass, partly because its mass is spread as widely as possible (heavy nuclei contain particles which are shadowed by other particles in the same nucleus, adding to the mass while contributing nothing to the area density) and partly because, when hit by incoming particles, hydrogen generates the minimum shrapnel (heavy nuclei may shatter and broadcast a shower of high-energy fragments from one collision).

Hydrogen, however, is not easy to store, and a hydrogen-rich compound such as water or methane is the next best choice. Parker mentions ethylene (C_2H_4) as another good choice, with the advantage that it can be polymerised into polyethylene. Plastics derived from this offer structural materials which contribute to radiation protection, in contrast to materials such as aluminium, hitherto the traditional spacecraft construction material, whose relatively heavy nuclei produce showers of secondary particles when hit, and thus in a thin shield (though not a thick one) are liable to make the radiation environment inside a spacecraft worse than in the open space outside, as Mark Hempsell and Roger Moses have described.

The requirement for mass shielding forces pressurised modules to adopt a spherical shape in order to maximise the interior volume per tonne of shielding. There seems to be general agreement that a 5-metre thick layer of water, with a mass of 5000 kg m^{-2}, is needed to provide adequate protection against the cosmic flux (Lewis, p.54; O'Neill, p.53 – 2 metres of 'soil', presumably of around 2000-3000 kg m^{-3} density; Parker, p.25; Savage, p.144; *Starflight Handbook*, p.170). According to Savage, the dose rate behind a 5-metre water shield would be 0.5 rem/year, the same as in Denver, the 'mile-high' city. A water shield equivalent to the full depth of Earth's atmosphere would be 10 metres thick (10,000 kg m^{-2}), but this is probably not necessary.

The fact that the radiation flux outside the heliosphere is believed to be at least twice as strong as within it does not alter the depth of shield required, as that depth is determined by the particle energies, not by their numbers.

Within any planetary system, adequate protection against the sporadically high-intensity but relatively low-energy solar flare and planetary Van Allen belt radiation requires a layer of water 30 to 50 cm thick, thus weighing 300 to 500 kg m^{-2}. Any shield capable of stopping the far higher energy galactic cosmic radiation is therefore more than adequate against solar and planetary threats. Similarly, the motion-induced radiation of a cruising starship would be easily mopped up by a comprehensive galactic shield.

So far, so good. But the attempt to convert the radiation shielding requirement into a specific design runs up against the high mass of shielding material required. If we take a population of 50 star travellers living in one module, and if they are each allowed 60 m^3 of living, working and supporting equipment space, then the module will require an internal volume of 3000 m^3. Its basic mass will then be some 300 tonnes, if its structural density is similar to that of present-day space station modules, to which one should add about 100 tonnes for supporting structure and internal fixtures and fittings. Its internal radius will be 9 metres, and its external radius, adding the thickness of the water jacket, will therefore be 14 metres. The mass of the water jacket then comes to 8440 tonnes, twenty-one times the mass of the module itself.

If half of the original payload of the starship is accounted for by the habitable accommodation, one is forced to draw the conclusions that when radiation shielding has been added, 90% of the payload must consist of that shielding, and that the need for shielding drives up the mass of the entire vehicle, and therefore its already enormous energy cost, by close to an order of magnitude.

One possibility that suggests itself is to use the second-stage rocket propellants as shielding. The hydrogen for deceleration could be used for protection throughout the long cruise. The occupants would then have to endure only a couple of years of exposure, from the start of the deceleration burn to the time when the shielding could be replaced using materials mined in the target system's Kuiper belt or icy outer moons. Such a period of exposure with minimal protection would be very similar to that experienced on an early Earth to Mars round trip.

Firstly it will be necessary to consider the merits of different candidate radiation shielding materials.

Effectiveness of different shielding materials

The *relative nuclear cross-section* of a nucleus of atomic weight W may be defined as its cross-section relative to a hydrogen nucleus (a single proton), and is therefore $W^{2/3}$.

E.g. an aluminium nucleus with 27 nucleons tightly packed has a relative cross-section only $27^{2/3} = 9$ times greater than that of hydrogen. This represents the size of target that an infalling cosmic ray particle must hit in order to interact with the shield. (One may visualise the nucleus as a Rubik's cube formed of three nucleons on a side:

two thirds of the nucleons are shadowed by the remaining one third, and play no part in fielding cosmic rays, while they still add to the shield's mass.)

The *relative shield mass* of aluminium is then the atomic mass divided by the relative nuclear cross-section (both numbers relative to hydrogen) = 27/9 = 3. A shield made of aluminium would have to be three times the mass of a hydrogen one in order to be as effective (assuming for the present a flat shield).

The relative shield mass of a molecular substance is the molecular weight divided by the sum of the relative nuclear cross-sections of the atoms within it (ignoring the possibility that one atom may shadow another). For example, in the case of water, the oxygen atom has a relative nuclear cross-section of $16^{2/3}$ = 6.350, whence the relative shield mass is 18 / (2 + 6.350) = 2.156.

Results for a number of different materials follow. Boiling-points have been indicated for volatile liquids as a guide to the thermal control implications of using them to protect a habitable module held at room temperature.

Substance	*Formula*	*Boiling point*	*Relative shield mass*	*Mean atomic wt. (if not an integer)*
Hydrogen	H_2	–253 °C	1.000	
Helium	He	–269 °C	1.587	
Lithium hydride	LiH		1.712	lithium: 6.94
Methane	CH_4	–164 °C	1.731	
Diborane	B_2H_6	–92 °C	1.750	boron: 10.8
Lithium	Li		1.907	lithium: 6.94
Ammonia	NH_3	–33 °C	1.930	
Ethylene	C_2H_4	–104 °C	1.933	
Methanol	CH_3OH		2.053	
Glycerol	$C_3H_5(OH)_3$		2.151	
Water	H_2O	100 °C	2.156	
Cellulose	$(C_6H_{10}O_5)_n$		2.213	
Silane	SiH_4	–112 °C	2.420	
Silica	SiO_2		2.737	
Aluminium	Al		3.000	
Iron	Fe		3.822	iron: 55.85
Lead	Pb		5.917	lead: 207.2

Suppose that a water shield 5 metres deep is required to provide a satisfactory level of radiation protection. This corresponds to an area mass of 5000 kg m^{-2}, and the area mass of hydrogen that would be required is therefore 5000/2.156 = 2319 kg m^{-2}. To find the corresponding mass of a different substance, one has to multiply 2319 by the relative shield mass given above, and to find the depth of a shield made from that substance one then divides by the density.

Coverage of plastics is expanded to include polypropylene, $(C_3H_6)_n$, whose relative shield mass is the same as that of ethylene, and NASA's new polyethylene-based material RXF1 (described by Barry):

Substance	*Density*	*Shield mass/area*	*Shield depth*
Hydrogen	71 kg m^{-3}	2319 kg m^{-2}	32.66 m
Helium	125 kg m^{-3}	3680 kg m^{-2}	29.44 m
Lithium hydride	800 kg m^{-3}	3970 kg m^{-2}	4.96 m
Methane	423 kg m^{-3}	4014 kg m^{-2}	9.49 m
Diborane	421 kg m^{-3}	4058 kg m^{-2}	9.64 m
Lithium	534 kg m^{-3}	4422 kg m^{-2}	8.28 m
Ammonia	682 kg m^{-3} (liquid)	4476 kg m^{-2}	6.56 m
Ammonia	817 kg m^{-3} (solid, –80 °C)	4476 kg m^{-2}	5.48 m
Ethylene	568 kg m^{-3}	4483 kg m^{-2}	7.89 m
Polypropylene	855 kg m^{-3} (amorphous)	4483 kg m^{-2}	5.24 m
Polypropylene	946 kg m^{-3} (crystalline)	4483 kg m^{-2}	4.74 m
RXF1 (ref. Barrry)	1038 kg m^{-3}	4483 kg m^{-2}	4.32 m
Methanol	792 kg m^{-3}	4760 kg m^{-2}	6.01 m
Glycerol	1261 kg m^{-3}	4988 kg m^{-2}	3.96 m
Water	1000 kg m^{-3}	5000 kg m^{-2}	5.00 m
Cellulose	1500 kg m^{-3}	5132 kg m^{-2}	3.42 m
Silane	556 kg m^{-3}	5612 kg m^{-2}	10.09 m
Silica	2634 kg m^{-3}	6347 kg m^{-2}	2.41 m
Aluminium	2700 kg m^{-3}	6957 kg m^{-2}	2.58 m
Iron	7874 kg m^{-3}	8863 kg m^{-2}	1.13 m
Lead	11,340 kg m^{-3}	13,722 kg m^{-2}	1.21 m

These figures suggest that a shield of liquid hydrogen is much the most economical of mass, though it requires an enormous depth.

But the analysis so far applies only when a collimated beam of radiation is incident upon a flat radiation shield. In reality the radiation is omnidirectional and the radiation shield, if optimised to cover the largest interior volume, must be spherical and enclose a spherical inner volume. When the shield depth is a significant fraction or a multiple of the radius of the interior, the difference between the surface areas of the shield's inner and outer sides creates a geometrical inefficiency which is greater the lower the density of the shield material, and which tends to reverse the balance of mass economy away from hydrogen-rich, low-density materials towards more compact ones.

For a shield of a certain desired thickness, the inefficiency depends upon the size of the volume to be protected – thus if the shielded volume is say a dozen kilometres across, the geometrical inefficiency of a shield even 33 metres deep, as in the case of hydrogen shown above, is insignificant. But a practical habitable module on a starship will have a size on the order of only a dozen metres.

Thus the ideal radiation shielding material will have the paradoxical properties of containing low-mass atoms, in order to maximise its relative nuclear cross-section per unit mass, but a high bulk density, in order to minimise shield thickness and thus minimise the geometrical inefficiency of the spherical shape. It will represent a trade-off between these incompatible opposites.

Take as an example a habitable sphere with radius 9 m, thus an interior volume of 3054 m^3. The *total mass of shielding* required in order to provide that interior with the same degree of protection as is afforded by a 5 metre deep water shield is then:

Substance	*Shield depth*	*Shield volume*	*Shield mass*
Hydrogen	32.66 m	299,809 m^3	21,286 tonnes
Helium	29.44 m	234,870 m^3	29,359 tonnes
Lithium hydride	4.96 m	8,342 m^3	6,673 tonnes
Methane	9.49 m	23,425 m^3	9,909 tonnes
Diborane	9.64 m	24,075 m^3	10,135 tonnes
Lithium	8.28 m	18,559 m^3	9,911 tonnes
Ammonia (liquid)	6.56 m	12,736 m^3	8,686 tonnes
Ammonia (solid)	5.48 m	9,658 m^3	7,891 tonnes
Ethylene (liquid)	7.89 m	17,129 m^3	9,729 tonnes
Polypropylene (amorphous)	5.24 m	9,041 m^3	7,730 tonnes
Polypropylene (crystalline)	4.74 m	7,811 m^3	7,390 tonnes
RXF1	4.32 m	6,845 m^3	7,105 tonnes
Methanol	6.01 m	11,111 m^3	8,800 tonnes
Glycerol	3.96 m	6,064 m^3	7,647 tonnes
Water	5.00 m	8,440 m^3	8,440 tonnes
Cellulose	3.42 m	4,971 m^3	7,457 tonnes
Silane	10.09 m	26,087 m^3	14,504 tonnes
Silica	2.41 m	3168 m^3	8,345 tonnes
Aluminium	2.58 m	3,445 m^3	9,303 tonnes
Iron	1.13 m	1,295 m^3	10,198 tonnes
Lead	1.21 m	1,404 m^3	15,924 tonnes

There are some surprises. Hydrogen is now close to the worst possible shielding material in terms of the mass that has to be carried, considerably worse than using solid lead or iron (only a helium shield exceeds it). The surface area of our 9 metre radius sphere is 1017.88 m^2. A volume 32.66 m deep on a flat base of this size would be 33,244 m^3. The actual volume and therefore mass of liquid hydrogen required is 9.02 times greater, due entirely to the geometrical inefficiency of the spherical shape in conjunction with the large depth of shield relative to the radius of the inner sphere. Any plan to use the second stage hydrogen propellants for radiation shielding during the interstellar cruise has to deal with the extremely low density of the material.

Plain water is a fair choice but by no means the best: it is undercut by silica (e.g. glass) and even more by solid ammonia, glycerol, and cellulose (a major constituent of plant fibre – astronauts may yet fly to the stars in a wooden spacecraft!). Polymerised hydrocarbons perform better still: plastics like polypropylene and the polyethylene-based RXF1 take the shielding mass down to only 84% of the mass of the water shield.

But the real star of the show is the standard radiation shielding material commonly used in nuclear reactors on Earth: lithium hydride, at only 79% of the corresponding water shield mass. Unfortunately lithium hydride is dangerously reactive on contact with air or water. Since it would normally be permanently sealed away from the living accommodation, it may even so be acceptable for use in a manned vehicle.

The challenge for the designer is then to develop an inert hydrocarbon-based plastic that can approach or surpass the shield lightness of lithium hydride. Otherwise, a small mass penalty is probably preferable for the sake of using a material which is not explosive in the event of a puncture in the cabin wall, for example by a meteoroid.

Note that while this calculation takes into account the differing sizes of different nuclear cross-sections, it does not take into account the fact that heavier nuclei may shatter when hit and create a shower of shrapnel. This factor has differing significance for the designer in two different cases.

If the shield is thin (on the order of centimetres), which will be the case if it is primarily designed to stop lower energy but higher particle flux solar flare radiation, then cosmic ray secondaries will penetrate through the shield and multiply the cosmic ray dose experienced by an astronaut on the other side. But at the same time the more secondaries that are produced, the more the initial impact energy of the primary particle is divided up, the less the energy of any one secondary, and the fewer the number of follow-on collisions required to stop it altogether.

If therefore a shield is thick (on the order of metres), which will be the case if it is designed to provide comprehensive protection against the highest energy cosmic rays, a material which produces more secondaries will, other things being equal, absorb the same impact energy in a shorter distance and can therefore be thinner than one which produces fewer secondaries. It will, however, have heavier nuclei, and so will not necessarily be less massive overall.

One possible avenue of research would be to investigate whether a mass saving can be made with a two-layer defence. Obviously, this is only a possibility for a comprehensive cosmic ray shield, and would not work for a thin shield against solar and planetary radiation alone, which would allow most of the secondaries through.

The outer layer would consist of some high atomic weight material such as aluminium, steel or lead. Its function is to catch as many high-energy primary particles as possible and create showers of medium-energy secondaries. The inner layer then consists of a lighter material to a depth sufficient to absorb all the collision fragments. If the rate at which an incoming particle's energy is divided among many collision fragments in the outer layer is greater than the rate at which that particle would be slowed down by collisions which do not form multiple fragments in an equivalent mass of the material of the inner layer, then a saving of shield mass is possible.

One might even imagine multiple layers, each layer of the shield consisting of atoms which suffer maximum fragmentation when hit by incident particles of a particular energy , thus maximising the number of secondaries caused by each primary and maximising the rate at which its kinetic energy is divided up and hence dissipated.

But this factor does not easily lend itself to mathematical modelling, and it is here assumed that the nuclear cross-sections given above reasonably accurately reflect for the present purpose the masses of different materials required to construct a shield.

It is henceforth assumed that a comprehensive radiation shield for a 9 metre radius habitable sphere will be made of a polyethylene-derived plastic and will weigh in the region of 7000 tonnes.

Comparison of different shielding strategies

A rough outline vehicle design will suffice at this point to illustrate the different options for shielding strategies against galactic cosmic radiation.

The baseline vehicle is derived from the following assumptions:

- Main propulsion by hydrogen-antiproton magnetoplasma rocket for both acceleration and deceleration (see chapter 5).
- Antimatter mixture ratio $\alpha = (v_e/c)^2$ / 1.67464 (see chapter 5).
- Cruising speed 0.1c, whence total propulsive ΔV = 0.2c (chapter 8).
- Hydrogen tankage taken as weighing 5% of contents (somewhat better than available today, but not unreasonably so, given the low mechanical and thermal stresses to which the tanks are subjected in space).
- Antiproton storage and feed system taken as weighing ten times contents (highly speculative).

- Basic vehicle mass (structure, engines, tanks, payload) = 5000 tonnes on arrival at its destination.
- Flight accommodation consists of two spheres of radius 9 metres, mass 400 tonnes each including supporting structure, fixtures and fittings (a minimum of two balancing spheres is required for artificial gravity generation and operational redundancy).
- The cost of a flight is expressed as the mass of antimatter required to power that flight (antimatter cost is expected to dominate, creating a pressure towards maximum energy efficiency).

Option (1): no shielding

To begin with we investigate a vehicle carrying no dedicated shielding. This establishes the overall proportions of a ship designed on the assumptions above.

The mass ratio that satisfies the criterion of maximum energy efficiency is 4.9, whence:

Hydrogen propellant:	19,500 tonnes
Rest of vehicle:	5,000 tonnes
Total at Solar System departure:	24,500 tonnes

However, this assumes a single-stage vehicle. The arguments presented in chapter 2 suggested that the star travellers will not be planning on a return to the Solar System. Nor will it even be possible for them to return until several centuries of economic and population growth in their target planetary system have enabled a substantial local industrial capability. It is therefore advisable to economise by jettisoning the empty propellant and antimatter tanks from the first stage during the cruise.

For the second stage, the mass ratio $R = \sqrt{4.9}$. With $\Delta V = 0.2c$ overall, $v_e = 0.1258c$ and $\alpha = 0.00945$. Then:

Second stage hydrogen propellant:	6011 tonnes	
Second stage antimatter:	56.8 tonnes	(= 0.00945 × 6011)
Rest of vehicle:	5000 tonnes	
Total at second stage ignition:	11,067.8 tonnes	

The second-stage tanks, engines, structure and payload break down as follows:

Hydrogen tanks:	300.6 tonnes	(= 0.05 × 6011)
Antimatter tanks:	568.0 tonnes	(= 10 × 56.8)
Design margin:	131.4 tonnes	

The tankage totals around 1000 tonnes, leaving 4000 for:

Engine and supporting structure:	~ 1,000 tonnes	
Habitable modules:	~ 1,000 tonnes	(= 2 × 400 plus margin)
Landing vehicles:	~ 2,000 tonnes	

For the first stage, the mass ratio is again √4.9, whence:

First stage hydrogen propellant:	16,104.0 tonnes
First stage hydrogen tanks:	805.2 tonnes
First stage antimatter:	152.2 tonnes
First stage antimatter tanks:	1522.0 tonnes
Engines and second stage:	11,067.8 tonnes
Total at Solar System departure:	29,651.2 tonnes
Total at first stage burnout:	13,395.0 tonnes

The total payload is 3000 tonnes. The total antimatter cost is 56.8 + 152.2 = **209 tonnes**. 14.35 tonnes of payload are being delivered per tonne of antimatter burnt.

Option (2): full permanent shielding

To the above configuration, we now add two dedicated plastic radiation shields at 7000 tonnes each, thus a total payload of 17,000 tonnes, an increase over 3000 tonnes by a factor of 5.667.

If all the quantities of propellants, tanks, engines and structure are assumed to increase in proportion, all the mass figures in option (1) may now be multiplied by 5.667 to obtain an aggregate mass at Solar System departure of 168,023.5 tonnes and an antimatter cost of **1184.3 tonnes**. Only 2.53 tonnes of useful payload are now being delivered per tonne of antimatter.

Option (3): full shielding using second stage propellants

To the configuration in option (1) we now add two hydrogen radiation shields at 21,300 tonnes each (42,600 tonnes) plus appropriate tankage (2130 tonnes) totalling 44,730 tonnes. The payload remains at 3000 tonnes.

The actual second stage propellants required in option (1) consist of 6011 tonnes (hydrogen) plus 300.6 (tanks) = 6,311.6 tonnes. Implementing option (3) therefore requires the second stage propulsion to be run at less than optimum efficiency.

The additional second stage propellants amount to 42,600 – 6011 = 36,589 tonnes. The additional second stage hydrogen tankage amounts to 2130 – 300.6 = 1829.4 tonnes. Assuming that the antimatter supply, the engines and other structures remain the same, the mass at second stage ignition is 11,067.8 + 36,589 + 1829.4 = 49,486.2 tonnes and its mass at second stage burnout is 5000 + 1829.4 = 6829.4 tonnes, whence R = 7.246 and v_e = 0.0505c. Then the required mixture ratio α = 0.00152. The mixture ratio using the antimatter supply from option (1) is 56.8/42,600 = 0.00133, therefore more antimatter has to be added to perform the same ΔV of 0.1c, as expected when we move away from the condition of maximum energy efficiency.

Consistent values are obtained when the mass at second stage ignition is 49,583 tonnes, at burnout it is 6917.4 tonnes, $R = 7.168$, $v_e = 0.0508c$ and $\alpha = 0.00154$. The mass of antimatter carried is then 65.6 tonnes, requiring tanks weighing 656 tonnes:

Second stage hydrogen:	42,600.0 tonnes
Second stage hydrogen tanks:	2130.0 tonnes
Second stage antimatter:	65.6 tonnes
Second stage antimatter tanks:	656.0 tonnes
Design margin:	131.4 tonnes
Engine and supporting structure:	1000.0 tonnes
Payload:	3000.0 tonnes
Mass at second stage ignition:	49,583.0 tonnes
Mass at second stage burnout:	6917.4 tonnes

The mass at second stage ignition is 4.480 times greater than in option (1), therefore all the first stage parameters may be multiplied by this factor to obtain:

Total at Solar System departure:	132,837.0 tonnes
First stage antimatter:	681.9 tonnes

Again with a total payload of 3000 tonnes, the total antimatter cost is now 65.6 + 681.9 = **747.5 tonnes**. With this option, 4.01 tonnes of payload are being delivered per tonne of antimatter burnt.

It is noteworthy that the second stage antimatter cost has not suffered much by running the engine at less than optimal efficiency: an increase of 15.5% is indicated. But the first stage antimatter cost is 4.48 times greater than in option (1) as a result of having to multiply all the first stage parameters by this factor in order to accommodate the 7 times greater hydrogen load on the second stage.

Conclusions regarding different shielding strategies

Antimatter costs are:

Option (1): no shielding:	209.0 tonnes
Option (2): full plastic shielding:	1184.3 tonnes
Option (3): full shielding using second stage hydrogen:	747.5 tonnes

Option (2) is 5.7 times as expensive as option (1) and 1.6 times as expensive as option (3); option (3) is 3.6 times as expensive as option (1).

The decision to supply full shielding against galactic cosmic radiation in one form or another therefore incurs major additional expense (which would not have to be paid if the payload was purely robotic, or if during the intervening centuries space medicine had advanced to the point that genetically modified astronauts were available who were fully radiation-hardened).

Option (3) offers itself as a short cut: the second stage hydrogen fulfils two functions at once, and permanent shielding is sourced after arrival from local resources.

Against these advantages may be counted the following disadvantages:

- The habitable volume at room temperature is closely surrounded by tanks of liquid hydrogen at or below –253 °C, requiring active cooling.
- The mass of each unit containing living quarters and shielding together is 21,600 tonnes, compared with 7400 tonnes if plastic is used, requiring a more massive rotating structure to carry the units for the purpose of generating artificial gravity.
- When the time comes for the second stage engine burn, either the artificial gravity has to be turned off in order to enable the hydrogen tanks to be plumbed into the core of the ship, or the entire ship has to rotate as a unit – while the latter solution would certainly assist in feeding propellants to the engine, the low level of gravity and coriolis forces close to the centreline would probably complicate the delicate business of moving antimatter to the engine safely.
- Most importantly, the occupants of the starship would be progressively exposed to the cosmic ray flux as the second stage burn proceeded, and fully exposed for a period of perhaps a year or so before significant quantities of local shielding material could be loaded, depending on how thoroughly the smaller bodies on the outskirts of the target system had been surveyed by previous robotic probes.

All in all, the cost of providing dedicated plastic radiation shielding is less than double that of the botch-up job with the second stage propellants. In return for the extra expense it simplifies design by decoupling propulsion from shielding, it offers continuous protection at all stages of the voyage, and it removes the urgency of having to replace the shielding first thing on arrival in the destination planetary system.

At the same time, the installation of dedicated shielding does not deprive the star travellers of an early opportunity to make use of local resources. Because of the low mass of the basic habitable module relative to its shielding, it will be quite possible to take along additional modules which are not used in transit, but which can be used after arrival after they have been provided with shielding from local asteroidal material.

It would appear likely that most of the people who embark on the starship will hope to be still alive on arrival in the new system. Therefore births during the journey will probably outnumber deaths, and the starship population will grow in transit. This emphasises the attractiveness of an option in which living space can be quickly expanded after arrival. Such a strategy combines the advantages of options (2) and (3): it provides security on the voyage, but also makes prompt use of the simplest local resources to extract and employ.

This, therefore, will be the basis of the design drawn up in chapter 8 below.

4. *Life on arrival*

What will be the star travellers' programme of work on arrival at their target extrasolar planetary system, and how does this affect the design of the Wayland vehicle?

Three broad areas of activity may be identified, which should be begun in the following order:

(1) Acquisition of local resources for expanding accommodation on board the starship.

(2) Scientific investigations of the extrasolar sun, its planets, moons and asteroids, and its interplanetary environment, and transmission of the findings back to the Solar System.

(3) Acquisition of local resources for building new permanent infrastructure for sustainable long-term habitation.

Initial resource use

As was seen in the preceding chapter, it will be advisable for Wayland to include some spare accommodation modules without the extremely heavy shielding against galactic cosmic radiation which they will need in use.

On arrival, the vehicle will enter orbit in the mid to outer planetary system, where ice is plentiful. This characteristic of our Solar System is likely to be a feature of all planetary systems, due to the way that refractories and volatiles are roughly sorted by radiation from the young star during the condensation of a solar nebula and its accompanying protoplanetary disk.

In the case of a moderately close double star such as Alpha Centauri A-B, the question remains open as to whether the best place to look for ice is in an orbit near 3 AU distance from either one of the stars, whose separation varies from 11 to 35 AU, or in a much more distant orbit, 100 AU or more out, circling both stars together. In the similar cases of Sirius A-B and Procyon A-B, the situation is modified by the fact that the B star has already gone through its red giant stage, presumably dessicating the inner system in the process.

As mentioned in chapter 2, it may be expected that all stars in our region of the Galaxy possess orbiting material as a byproduct of their formation, even when that material is not plentiful enough to have formed major planets, or was too disturbed by gravitational influences or strong radiation early in its history. The absence of major planets would greatly diminish the scientific interest of an extrasolar system, but would not detract from its practical utility as a new home for humanity, provided that sufficient material existed in its analogues of our asteroid, Kuiper and Oort belts.

The presence of that asteroidal matter can be expected to have been established before the starship departed from the Solar System, either by telescopic observations – from the Solar System or from another starship in transit to or already in a nearby system – or by close-up observations made by a robotic precursor mission.

The simplest method of loading large tonnages of material aboard Wayland is to have the ship approach and dock with a small asteroid, using robot arms to grip it securely. The surface gravity of an asteroid 1 kilometre in diameter with a density of 2000 kg m^{-3} is 2.7×10^{-4} m s^{-2}, or 27 microgravities, posing no difficulties to rendezvous and docking using auxiliary thrusters. With its mass of one billion tonnes, sourcing from that body 17,000 tonnes of water to make up the radiation shielding on two 9 metre radius habitation spheres should be no problem. Robotic mining units on umbilical hoses may be lowered to the surface to sort and separate the primordial materials they find there. Such units will be off-the-shelf equipment, having seen many centuries of prior large-scale application in the Solar System.

Scientific investigations

Before Solar System departure a great deal will be known about the major and minor bodies in an extrasolar system, thanks to many generations of improved telescopes. But the level of detail of prior knowledge will depend upon whether precursor starship probes like Daedalus or Icarus have been despatched there, and what their capabilities were. Detailed information about planetary surfaces and interiors, and especially about any living creatures there, will depend upon close-up observations from low orbit and from landers on the surface. Obtaining this knowledge from even the largest conceivable telescopes based an interstellar distance away would be impossible.

The theoretical limit of angular resolution θ for a telescope with objective lens or mirror diameter, or interferometer baseline, D at wavelength λ is:

$$\theta = 2.5 \times 10^5 \frac{\lambda}{D} \text{ arc seconds} \quad = 2.5 \times 10^5 \frac{\lambda}{D} \times \frac{\pi}{3600 \times 180} \text{ radians}$$

The maximum luminosity of a sunlike star, which provides the best illumination of its planets, is at about 500 nm wavelength (for the majority of stars, which are cooler than the Sun, the spectrum peaks at a longer wavelength in red or infra-red light). An interferometer whose baseline was the diameter of Earth's orbit, if such is possible, would then in theory be able to resolve details as small as 8 cm across on a planet in the

Alpha Centauri system, 4.3 light-years distant.

In conjunction with a robotic lander on the surface this could be a powerful tool, but without that ground truth the correct interpretation of those fine details would remain problematic, as well as being completely unable to discern bacterial life or multicellular creatures on the scale of Earth's abundant population of insects. And if the planet had a hazy or cloudy atmosphere – like Earth, Venus, Mars and Titan – or if the surface was barren and life was sheltering underground or underwater – as was true of Earth for most of its history, and may now be true of Mars or Europa – then, no matter what the angular resolution of a telescope, its users would be reduced to making deductions from indirect clues in the planet's spectrum or gross surface morphology.

The lesson of Mars exploration in the 19th to 20th centuries is instructive: the picture built up by even the best telescopic observations was completely overturned by the new data from spacecraft missions, and the smaller worlds of the outer Solar System remained completely unknown except as pinpoints of light until they were visited by Voyager, Galileo and Cassini-Huygens. Conditions on the surface of Venus were highly speculative before the first landers arrived there, and the planet has only been mapped in detail thanks to radar imaging from orbit – a technique impossible at interplanetary, let alone interstellar, distances.

Due to the complexity and variety inherent in biology, the close investigation of any living organisms in an extrasolar planetary system is much the most interesting scientific question to be addressed there. Due to our own biological nature, that question transcends science and touches on our fundamental philosophical view of the place of our own species in the universe. But it cannot be satisfactorily answered from an interstellar distance.

Therefore a wealthy Solar System civilisation with the power to build starships will surely use that power and, whether robot or manned – or whether by that time people and machines live in such intimate symbiosis that the robotic/manned distinction has become meaningless – those ships will be designed for detailed studies of any planetary bodies on which life might be present in some shape or form. Sharing the findings with the Solar System, and with any other system occupied by that time, will be an activity of major importance. For the people and institutions back home who have contributed to the cost of the expedition, this information will be their main payback.

Each Wayland starship will therefore carry a variety of smaller exploration vehicles, but the particular choice of which vehicles to carry will depend upon the planets that are known to exist at a particular destination.

In general there may be giant planets, predominantly of hydrogen and helium, and terrestrial planets formed of varying proportions of rock and ice, some with an atmosphere and others airless. Worlds dominated by gas must be giants like our Jupiter and Saturn, as an Earth-sized gas planet would not have sufficient gravity to maintain itself against evaporation into space. But there must be a continuum of planets with a rocky or icy core and an atmosphere, from the size of our Titan, to Earth, to super-Earths several times the mass of our planet of origin but with a surface still discernible beneath a thick atmosphere, to giants like our Uranus and Neptune, whose solid surface is hidden so deep that it is inaccessible to remote observation, though a dedicated one-way atmospheric penetrator like the Soviet Venera landers or the Galileo Jupiter entry probe, resistant to the high pressures and temperatures at great depths, might be able to reach it.

Finally, the smallest rocky and icy worlds, the size of Mercury and below, will have no effective atmosphere, or only a wisp of one as is the case with Triton and Pluto, and may be expected to be extremely common, though individually undetectable by telescope from the Solar System. They may however be sites of subsurface oceans containing living organisms, as may possibly be the case with the satellites of our outer planets, among which Europa has raised particular interest, as surface mapping and magnetic measurements have yielded especially strong evidence of a hidden subsurface ocean there.

As the examples of Titan and the similarly sized Ganymede show, the size range of worlds with substantial atmospheres overlaps that of those without.

One question which will not have any particular scientific interest is how many planets an extrasolar system has.

The debate about the status of Pluto – planet or not? – has not only thrown up a wealth of terminology to describe the place – planet … minor planet … dwarf planet … asteroid … iceteroid … plutoid … plutino … Kuiper belt object … trans-Neptunian object … – but has also highlighted the fact that the classical planet / moon or satellite / asteroid or minor planet division is a fundamentally pre-space age concept. With close-up spacecraft observations has come the realisation that the complexity and types of phenomena found on a world are not strongly coupled to whether it orbits a larger world, belongs to an asteroid belt or has a solitary independent orbit around its sun. Titan resembles Mars, even Earth, more than it resembles other large moons such as Ganymede or Callisto; the surface morphology of Mercury resembles the Moon more than it resembles its fellow planets Venus or Earth.

If asked how many planets orbit the Sun, it is at least possible to be certain that we have four gas giants (Jupiter, Saturn, Uranus, Neptune). In addition, there are a larger number of intermediate-sized worlds, which in descending order of diameter may be listed as: Earth, Venus, Mars, Ganymede, Titan, Mercury, Callisto, Io, Moon (some use the name Luna for Earth’s moon), Europa, Eris, Triton, Pluto, Titania, …. There is no particular cut-off point, and no clear size gap between large moons and small planets (though Mercury is 2.2 times heavier than Ganymede and 2.4 times heavier than Titan, the moons have respectively 16% and 11% more surface area than the planet). One could if one wished arbitrarily choose a minimum diameter of 2000 km and a minimum mass of 10^{22} kg as a dividing-line, which in our Solar System, given current knowledge, would neatly divide Pluto from Titania and give us thirteen terrestrial worlds to add to our four giants (until very probably more icy worlds larger than Pluto are found in the dim outer reaches of our system).

But the point here is that there are a number of different scientific questions that may be asked, and each question divides up the collection of worlds in a different way. If the interest is in orbital dynamics, then, to be sure, planets, moons and asteroids fall into their traditional groupings. (Comets are included here as asteroids; an asteroid may have a variety of different compositions in which iron, stone or volatiles may predominate; a comet properly speaking is the phenomenon observed when an ice-rich asteroid approaches the Sun closely enough for some of its volatiles to boil off and create a coma and a tail of small particles; but there is no particular value in having a separate name for a class of asteroids of ice-rich composition which would become a comet nucleus if they happened to approach the Sun, particularly as the vast majority of them do not in fact make that approach.)

If, however, the point of interest is planetary atmospheres, than Titan (a moon) takes its place alongside Venus, Earth and Mars (planets), but not Mercury (an airless planet) or the Moon. If it is surface morphology such as craters and volcanoes, then the terrestrial planets must be considered alongside moons and asteroids, but not with the giant planets, which do not form observable craters or volcanoes. If it is extraterrestrial life, then the prime candidates at the time of writing are Mars (a planet) and Europa (a moon).

One could imagine a planetary system essentially identical to ours except that its equivalent of Mars was found orbiting its equivalent of Uranus – would that system have one less planet than ours? Not in any meaningful sense. One could imagine a system in which an earthlike world was orbiting a jovian gas giant – and science fiction writers often have imagined just such a situation (for example, Aldrin and Barnes) – would that extrasolar Earth count as a moon or a planet? Clearly, if it closely resembled a planet in the Solar System then one would naturally think of it as a planet, even though it was technically a moon. One could imagine a system in which a terrestrial planet, an extrasolar Mars or even an Earth analogue, was found at a Lagrange point on the orbit of an accompanying gas giant – would those planets have to be downgraded to asteroids because they were sharing the same orbit? Absurd!

So as Michael Brown of Caltech, the discoverer of Eris (originally known as 2003

UB313 "Xena"), once wrote on his website, trying to come up with a precise scientific definition of a "planet" is a futile exercise, akin to trying to give a precise definition of a "continent" and then getting into pointless terminological disputes: are North and South America one continent or two?; are Europe and Asia one continent or two?; is Australia a small continent, a large island, or an island continent? Such questions shed no light on the planet we inhabit, and scientists can perfectly happily discuss continental rocks and continental shelves without ever needing a precise answer to the question of exactly how many continents there are on Earth.

Similarly, planetary scientists can study and compare the atmospheres and surfaces of Earth, Mars, Titan and Pluto without ever needing to slot those bodies into precise categories of "planet" versus "non-planet". Nature is untidy in that way, because the continuum of bodies runs across pre-space age dividing lines. Our concepts have been carried forward from ancient times and carry too much cultural baggage to submit to scientific precision.

The starfarers on a Wayland starship will therefore need exploration vehicles for close-up studies of the worlds they find, however those worlds may be organised in orbital space. The fundamental distinctions to be drawn are:

- Vehicles which carry people versus those which carry only a miniaturised robotic payload;
- Vehicles designed for a one-way trip to a planetary surface or atmosphere (the latter with a hydrogen or hot-air balloon), where they will subsequently remain, versus those for a two-way trip, returning a crew or robotically gathered samples to orbit after a period of exploration;
- Vehicles with aerodynamic shielding, versus those without.

It may be worth while to comment here on why I believe that the distinction between manned and unmanned vehicles will still be valid at whatever future time the first starships are constructed. The human being is an autonomous general-purpose organism, capable of abstract thought, physical enjoyment, procreation, culture, and so on; these general abilities are irrelevant to a specialised exploration robot, which is a single-purpose device with more limited capabilities. While one can imagine a telepresence so intimate that a conscious human being seems to himself or herself to *be* that robot, the inevitable absence of so much that is human would render that state unsatisfactory for longer than a single work shift at one time. We may become our robots for a day, but at the end of that day's work we will still want to come home and relax with a beer.

The ideal human state – the one towards which the pressure of market forces points and in the future will continue to point – is to continue to be a fragile, softbodied, oxygen-breathing, food-eating, waste-excreting, sometimes curious, sometimes bored, sometimes passionate, sometimes angry, sometimes in love, irreducibly biological organised mass of living cells, *but* to be augmented to the hilt with as much genetic, information, pharmacological and medical prosthetic technology as can be crammed in to give us perfect health, instant online information access, physical skill, dexterity, power, grace, beauty, sexual attractiveness, happiness and wisdom, and preferably immortality with a biological age set at a perpetual 30 years old.

The first starfarers may not have achieved such a nirvana, but they will still be recognisably human, and will still need life-support systems which we would recognise as highly evolved descendants of the primitive systems in use today aboard the International Space Station. Therefore both starships and local exploration vehicles will continue to observe the key distinction between manned and robotic, just as today's spacecraft do.

Current planetary orbiters and landers are strongly constrained in their capabilities by the limitations of chemical rocket propulsion. In the following chapter there will be presented some remarks on a more powerful type of engine: the hydrogen-antimatter magnetoplasma rocket. In the version applicable to starship propulsion, an exhaust velocity of 12.6% of the speed of light is required for that engine's economical operation, requiring a mixture ratio of 1% of antimatter fuel to 99% of normal hydrogen as annihilation and reaction mass. It is reasonable to anticipate that when such an engine is first introduced, its antimatter proportion and hence exhaust velocity will be very much lower, appropriate to rapid interplanetary transport. If this type of engine is available for interstellar propulsion, it will therefore also be available for interplanetary use on arrival, and only a relatively small additional load of antimatter will need to be carried for this purpose.

The starship's hangar may then contain a selection of manned atmospheric and non-atmospheric landing craft, and similar but smaller robotic probes. The single-use, non-returnable probes may use chemical propellants or solar sails, if these are more economical than the complex and expensive antimatter-based equipment, which would presumably need to see multiple use in order to justify its greater cost. But there may also be antimatter-powered multiple-use probes which could be programmed to tour an asteroid belt or a giant planet's retinue of moons, eventually to return to the mothership with a selection of samples.

As the expedition penetrates the inner planetary system, there seems little point in splitting up into two or more exploration parties. The star travellers will be isolated as nobody has ever been before (except other star travellers), and extremely vulnerable should any equipment malfunction in the only partly understood alien environments they will be encountering. They are best advised to stay together, park the starship in orbit above the most interesting planetary target (be it "planet", "moon" or "asteroid") and send out one landing party at a time, with a second ready to perform a rescue mission if required. Their robots, however, having a high level of autonomy, may be scattered widely throughout the system on arrival. They will be constantly returning data from a wide variety of locations to the mothership for analysis, from which a digest will be compiled for regular transmission back to the Solar System and to other starships.

Settling in

The starship will arrive with a sufficient reserve of power for a few years of exploration, but eventually the star voyagers will need to begin building new permanent infrastructure for power, propellants and habitation.

Their preliminary studies of the system will therefore have two distinct goals:

- Gathering pure scientific knowledge for sharing with the rest of civilisation;
- Practical prospecting for the resources with which to construct a new local branch of that civilisation.

As has been argued in chapter 2, the new construction is likely to follow the model with which the starfarers were most familiar in the Solar System: artificial space colonies built of asteroidal materials. Living planets – extrasolar analogues of Earth and perhaps of Mars or Europa – offer less favourable conditions for permanent occupation since they are in fixed orbits, have poor access to solar energy and offer relatively small surface area per unit mass of their substance.

Given the key importance of power, the starship is likely to carry a small antimatter factory with either photovoltaic solar arrays or a thermodynamic solar generator. This should be fully automated, and deployed at an early stage into a close heliocentric orbit. The starship itself would eventually retire from the location of greatest scientific interest to one of greatest resource utilisation interest. Docking once again with a suitable asteroid with a varied content of volatiles, rocks and metals, the mining units would be redeployed, and in conjunction with manufacturing equipment would begin to transform the asteroid, firstly into purified and sorted usable raw materials, and thence into manufactured component parts for the construction of new accommodation and production units.

Once this process is well under way in a particular exoplanetary system, there seems little point in despatching a second starship to that star. The first colonists will have taken with them all the equipment they need to settle in, and the reliability of that equipment will have been established through centuries of prior development and use in the Solar System. But in two cases more than one starship might be targeted at a particular star.

Firstly, the expedition might be planned from the outset to be split over two or more vehicles, despatched fairly closely together, say at intervals of a couple of years. This might be the case if the mining and production machinery needed for permanent occupation was too massive to be carried on a single ship, or if it was thought necessary to have the extra security of a back-up mission closely following the primary one. One may also mention the possibility that interest in the venture was so high that funds were available for two or more ships, unlikely as that may strike us with our current experience of economics. The other circumstance would be if for some reason an expedition had met with disaster, and it was decided to make a second attempt. In this case, the time delay between news of failure reaching the Solar System and the arrival of a second starship would be at least several decades – the light travel time back to the Solar System, plus the decision time to launch a second starship, plus its flight time.

Carl Sagan and others have speculated (for example in Sagan's book *Pale Blue Dot*) that once the small icy worlds beyond Neptune and out into the Oort belt have been colonised, world ships from there might make slow interstellar voyages.

The power source of these colonies would be nuclear fusion, and because of the remoteness of their starting-point their occupants might never have seen the Sun with the unaided eye as other than a bright star. They would therefore have no qualms whatsoever about living in interstellar space, and could lead a permanently nomadic existence, taking thousands of years to cross between stars and only pausing at a new exoplanetary system for long enough to replenish their material reserves from its outer asteroidal halo. In millennia to come, a large fraction of our descendants could live in this way, but fast starships such as Wayland will presumably get there first.

Talking with aliens

The *Starflight Handbook* (p.1-3) reports the view of pioneer radio astronomer Edward Purcell and others, that interstellar spaceflight will never be attempted because it will always be much easier to obtain information about other planetary systems by radio or laser communication with their supposed inhabitants.

Such an argument, however, presumes that all the stars of interest to science (i.e. all stars) will have at least one planet inhabited by beings who are both interested in and capable of interstellar communication using technologies familiar to us, who are members of a supposed galactic internet that humanity could log on to. But not even the most optimistic estimates of the number of technological civilisations in the Galaxy expect to find more than a small fraction of planetary systems thus occupied. Cohen and Stewart, for example (p.125-128), expect to find 3000 civilisations sufficiently similar to us to permit radio communications within the Galaxy, roughly one per ten million stars.

Meanwhile the perceived probability of finding communicative aliens within radio range has suffered with the discovery since 1995 that many planetary systems are inhospitable to earthlike worlds, thanks to giant planets having migrated into highly eccentric orbits or having invaded the inner system. The nature of biological evolution also suggests that for every planet which evolves intelligence, a large number will not do so.

Most of the planets in our Galaxy on which life has begun will possess only microbial inhabitants; on a fraction of these multicellular life will have evolved, on a fraction of these some sort of intelligence will have appeared, and on a further fraction of these the intelligent locals will have had an industrial revolution which equips them to communicate. The actual size of all those fractions is currently unknown, though arguably they could be very small fractions indeed, and Ward and Brownlee's book *Rare Earth* has famously argued the uniqueness of Earth. But we will not really know until we have carried out close-up surveillance of a large number of extrasolar planets in our immediate galactic neighbourhood.

The conclusion that human intelligence and civilisation are probably unique in our Galaxy was also reached by Alan Bond in his investigation of the evolution of complex life published in *JBIS* in 1982. This should be regarded as the resolution of Fermi's Paradox ("Where are they?"), which should henceforth be known as Fermi's Effect: the first species in a galaxy to develop science and technology with interstellar reach will be surprised to find that it is alone in the universe. Of course, if our own civilisation were shortly to collapse, another species would eventually develop the same capabilities and be surprised that it appeared to be the first.

Cohen and Stewart condemn this kind of reasoning (ch.6). To them, life is sufficiently resilient and adaptive to flourish practically anywhere. Drawing on science fiction for examples, they posit silicon-based aliens, balloonlike beings floating in the atmospheres of giant planets, plasmoid aliens made of magnetic vortices in the solar photosphere or roaming interstellar space as natural Bussard ramjets, and even living beings who inhabit neutron stars (p.132; 211-212; 230-236; 246; 327). They argue that wherever life can appear, it does, and that given time it always goes on to evolve intelligence (p.127).

However, they also argue that, once a star-voyaging race evolves in a galaxy, it quickly occupies the entire galaxy (p.123-124). Why then are they not here? Cohen and Stewart's preferred explanations are that if they were here, we would not recognise them and would have no common ground of communication with them, but they are probably too lazy to bother to send more than their robots (p.142; 238-242; 326-328). But even on this view, very few stars would possess inhabitants sufficiently similar to us that we could enjoy a meaningful conversation with them.

Either way, it is incorrect to claim that interstellar communication is cheaper than interstellar travel. In order for communication to be possible, there must be a communicating civilisation in the extrasolar system of interest, and in the case of the large, if not overwhelming majority of planetary systems throughout the Galaxy – especially those radically different from our own and therefore of greater interest – that civilisation first has to be established though interstellar travel, which must then be added to the costs of communication with that system.

On the prospects of communicating with aliens, my personal view is that there exists no more evidence for non-carbon-based, non-water-based aliens than for angels or fairies, and, while we should certainly keep an open mind when investigating new environments, our own kinds of biochemistry and technology are the only examples we know about at present that actually work outside the pages of speculative fiction.

It sounds very high-minded to say that real aliens would be utterly different and utterly incomprehensible to us; I doubt it. To me it sounds like gratuitous mystification. If they share the same universe they are subject to the same physical constraints as we are. No doubt their detailed biology will differ from that of terrestrial vertebrates. But they will still need legs to get around (you can't build radio telescopes or space vehicles while living underwater or floating in the clouds), hands to manipulate objects, brains, digestive systems, a mouth, sensory organs that would make perfect sense to us, even if inhabitants of cooler stars had infra-red vision and those at hotter stars could see (as our bees can) into the ultra-violet. They might even look superficially similar to us, as convergent evolution has shaped dolphins similarly to fish and marsupial mammals similarly to their ecological equivalents elsewhere in the world.

Given that the starry universe is apparently still very young (13 billion years into a lifetime of at least trillions of years), I am comfortable with the propositions that the human species is one of the first intelligent races to arise in the Galaxy, and that none of the intelligent species that have appeared so far has yet embarked on interstellar travel. If it had, there would be signs of intelligent activity that would be obvious to us, unless it happened very recently (on the astronomical timescale), say within the past 50 million years, and at a remote location in the Galaxy.

But those signs would not include radio messages. The giveaway would come in the forms of an anomalous red-shift of radiation from stars of which a substantial fraction of their radiation was being intercepted by orbiting space colonies to power the technologies of life, and the radiation from the exhaust of starships built on the same lines as Wayland.

The CETI (Communicating with ExtraTerrestrial Intelligence) project is premised on the idea that an alien civilisation might have originated on a sunlike star, might expect other, similar civilisations to arise at similar stars, and might beam welcome messages to nearby sunlike stars with suitable orbiting planets, including ours. But they will be aware that it may take billions of years for a communicating civilisation to evolve, if it even evolves at all. Meanwhile, the time for robotic starship probes to reach a wide selection of nearby sunlike stars is on the order of only a few centuries (a few decades for the closest ones), and, providing the probe continues to operate normally, the return of detailed information about its destination is assured.

The strategy of transmitting an unexpected welcome message therefore only makes sense if the aliens already know that a technological civilisation exists at the target star. If that civilisation is at our early stage of development, having not yet succeeded in either large-scale space colonisation or starship-building, the aliens can only know of our existence by sending a starship probe. The hope (or fear) that they could pick up our domestic radio and TV transmissions, dramatised in Carl Sagan's novel *Contact*, is unfounded: omnidirectional radio broadcasts are diluted below the threshold of detection by the vast interstellar distances, and modern programmes are distributed by radio beams narrowly focused on the receiver precisely in order to reduce wastage, or by optic cable, which has no electromagnetic spillage at all.

Therefore we can only expect to receive a message if an alien probe is already in the Solar System, and presumably in the vicinity of Earth. The longer our activities in space continue, the less likely it appears that such a probe would have been overlooked.

Thus once again the conclusion has to be that in order to receive communications from other stars, we must first establish our own colonies at those stars.

5. *Propulsion*

The propulsion method chosen here for further analysis is the hydrogen-antimatter magnetoplasma rocket (HAMR). Although far beyond current engineering capabilities, there is nothing intrinsically implausible about projecting future technologies for the large-scale manufacture of antimatter, its storage, and the subsequent release of its stored energy in an electrical power station or a rocket engine.

The attraction of antimatter for starship propulsion is simply explained. The propulsive energy demand of any manned vehicle capable of making an interstellar crossing within a human lifetime is on the order of 10,000 TW years (3×10^{23} J), thus equivalent to about a thousand years' worth of global industrial energy consumption at early 21st-century levels.

The power production of the Sun, however, is vastly greater again: with a luminosity of 380 trillion TW, the Sun broadcasts a thousand starship loads of energy per second in all directions. It has done so, second by second, for billions of years in the past, and astronomers guarantee that it will continue to do so for billions of years to come. Obviously this is also true of other sunlike stars, and even a feeble red dwarf like Proxima Centauri, which radiates at only a thousandth of the Sun's power, still has a generative capacity equivalent to one starship fuel load per second.

The question therefore arises as to whether a trivial fraction of this enormous flood of solar energy can be diverted to run starships. If so, then there will never be any shortage of fuel.

Beaming this power to a ship by laser offers a method of using it which combines energy production and its consumption for propulsion into a single sequence of operations. But the manufacture of antimatter from solar power is the only currently known means of storing that power over time at an energy density appropriate to starship propulsion. Physically transporting the energy in the highly condensed form of antimatter, if it proves technically possible to do so in bulk, avoids the problems of beamed energy, notably including accurate collimation of the beam over multi-light-year distances and the inefficiency losses in converting the beam energy into motion at the vehicle.

Robert Forward and others have described the physics of the antimatter rocket in the *Journal of the British Interplanetary Society* in 1982. In brief: electrons annihilate with positrons to produce gamma rays with wavelengths about 10^{-5} that of visible light. These energetic photons are useless for rocket propulsion unless they can be channelled into an exhaust stream directed away from the vehicle. No method is currently known for reflecting radiation with such short wavelengths.

Protons and antiprotons annihilate similarly, with an end product consisting of gamma rays, neutrinos and antineutrinos. But here there is a brief intermediate stage consisting of pi-mesons or pions: an average of 1.5 positively charged pions, 1.5 negatively charged pions and 2 neutral pions are created per proton-antiproton annihilation. The neutral pions decay quickly, but the charged pions wait longer before they too dissolve into neutrinos and electromagnetic radiation. Thus 60% of the reaction products survive as charged particles long enough to be channelled into an exhaust stream by a magnetic nozzle.

In practice, an antimatter engine or HAMR would mix antimatter in short bursts with a much larger quantity of normal hydrogen, creating a high-energy plasma which can be magnetically directed along the desired thrust vector. Most if not all of the annihilation energy is thus taken up by the protons and electrons in the plasma, which are susceptible to magnetic control.

The ideal engine would employ pure hydrogen, rather than, say, methane or water, as a propellant in order to avoid neutrons being knocked out of the nuclei of heavier elements. Neutrons are not useful for propulsion since they cannot be controlled, and thus they mostly end up impacting the material structure of the engine, weakening it and causing it to become radioactive and brittle.

As for the type of antimatter used, the ideal engine would perhaps use a stream of antiprotons rather than neutral antihydrogen atoms, because antiprotons can always be controlled with electromagnetic fields, and because the reaction then reduces the amount of energy appearing in the form of gamma rays while still in the reaction chamber, making the takeup of energy by the hydrogen plasma easier. However, since only one part in 1837 of the mass of the antihydrogen atom consists of its positron, the takeup of annihilation energy may not be significantly changed by the elimination of the positron. Meanwhile, antihydrogen atoms from a macroscopic-sized block held in deep cryogenic storage can presumably be ionised by illuminating them with light of an appropriate wavelength, and thus split into charged particles which can then be electromagnetically directed away from the storage area to the reaction chamber, so there is no absolute reason why neutral antihydrogen should not be carried on the vehicle.

Ultimately the choice of antiprotons against neutral antihydrogen will depend on the differing practicalities of different methods of storage, to which we shall return in the next chapter.

The antimatter mixture ratio

The physics of rockets requires that the energy E in the exhaust stream is apportioned among the different types of particles in the stream according to:

$$E = \frac{1}{2} n_1 m_1 v_1^2 + \frac{1}{2} n_2 m_2 v_2^2 + \ldots \qquad \text{(i)}$$

where n_i particles each of mass m_i exit the engine with a velocity v_i which is interpreted in gas physics as the root mean square velocity, and in rocket engineering as the exhaust velocity.

If all the particles are identical, e.g. molecules of water from a hydrogen-oxygen chemical rocket whose mixture ratio is adjusted for 100% combustion, then:

$$E = \frac{1}{2} n\, m\, v_e^2 \qquad \text{(ii)}$$

where $n\ m$ is the total mass in the exhaust, and the exhaust velocity is written as v_e in the usual way.

If two or more kinds of particle are present, then the energy is apportioned between them according to:

$$m_1 v_1^2 = m_2 v_2^2 = \ldots \qquad \text{(iii)}$$

The overall exhaust velocity for rocket performance calculations is however given by:

$$v_e = \frac{m_1 v_1 + m_2 v_2 + \ldots}{m_1 + m_2 + \ldots} \qquad \text{(iv)}$$

Let us define p_i as the proportion by mass of each kind of particle, and M as the total mass of the exhaust:

$$p_i = \frac{n_i m_i}{M} \qquad \sum p_i = 1 \qquad M = \sum n_i m_i$$

The energy in the exhaust in equation (i) may then be written:

$$\frac{2E}{M} = p_1 v_1^2 + p_2 v_2^2 + \ldots$$

But from equation (iii) above: $v_2{}^2 = v_1{}^2\,(m_1 / m_2)$, therefore:

$$\frac{2E}{M} = p_1 v_1{}^2 + p_2 \left(\frac{m_1}{m_2}\right) v_1{}^2 + \ldots$$

$$= \left(p_1 + p_2 \left(\frac{m_1}{m_2}\right) + p_3 \left(\frac{m_1}{m_3}\right) + \ldots \right) v_1{}^2$$

Similarly, equation (iv) becomes:

$$v_e = \left(p_1 + p_2 \sqrt{\left(\frac{m_1}{m_2}\right)} + p_3 \sqrt{\left(\frac{m_1}{m_3}\right)} + \ldots \right) v_1$$

Given all the p_i and m_i as our starting-point, we can then work out ${}^{2E}/_{M}$ and v_e , eliminate v_1 and obtain an expression relating ${}^{2E}/_{M}$ to v_e , and hence the antimatter mixture ratio for a given exhaust velocity.

For a plasma formed from hydrogen, the relative particle masses are protons 1836, electrons 1. It is assumed that the proportion of antimatter added is small in order to ensure that sufficient mass surrounds the reaction to mop up as large a fraction of the annihilation energy as possible, and therefore the numbers of protons and electrons in the plasma are taken as being equal.

The equations displayed above then produce:

$$\frac{E}{M} = 0.955429\, v_e{}^2$$

Note that if all the exhaust particles had been the same size, equation (ii) would have given:

$$\frac{E}{M} = 0.5\, v_e{}^2$$

Thus a significant energy inefficiency has appeared: a given amount of energy per unit mass of propellant produces only about $\sqrt{0.5}$ / $\sqrt{0.9554} = 0.7234$ of the exhaust velocity in the case where half the exhaust particles weigh 1 unit and half weigh 1836 units, compared with the case where all exhaust particles have a mass of 918.5 in the same units. In the case of a plasma exhaust, this inefficiency is unavoidable.

If m_f is the mass of antimatter fuel, the annihilation energy is $E = 2\, m_f\, c^2$. But not all of this can be harnessed for propulsion: some will escape in random directions in the form of gamma rays or neutrinos, and some will contribute to the brilliance of the exhaust stream in various wavelengths of light. Some is also lost in the form of the ionisation energy of the neutral hydrogen propellant – for the exhaust energies considered here, however, the ionisation energy is comparatively insignificant.

But as we have seen, 60% of the immediate annihilation products are charged particles which will therefore go into the magnetically directed exhaust stream. It is here assumed that half of the remaining annihilation products, the neutral pions, will yield their energy to other charged particles, and half escape, thus 80% of the total annihilation energy goes into rocket thrust:

$$E = 1.6\, m_f c^2$$

Writing the antimatter mixture ratio $(m_f/M) = \alpha$ and eliminating E/M:

$$1.6\, \alpha\, c^2 = 0.955429\ v_e^2$$

Whence the mixture ratio equation is:

$$\frac{v_e^2}{c^2} = 1.674640\, \alpha \qquad \text{(v)}$$

To some extent, the mixture ratio equation allows the engineer the luxury of setting the exhaust velocity to match the required performance.

Provided that the rate of takeup of annihilation energy into the kinetic energy of the plasma particles is satisfactory, and that their control and ejection by the magnetic nozzle is efficient, the engineer can choose an exhaust velocity for maximum energy efficiency.

The Wayland study takes a cruising speed of 0.1*c* as the performance baseline. The total propulsive ΔV for acceleration at the start of the journey followed by braking at the end is then 0.2*c*.

The criterion for maximum energy efficiency is $(\Delta V/v_e) = 1.59$, whence the desired exhaust velocity is 0.126*c*.

The mixture ratio is then 0.00945, or just under 1%. For every tonne of hydrogen propellant, 9.45 kilograms of antimatter (antiprotons or neutral antihydrogen) will be required.

The resulting plasma will clearly be extremely hot, and a comparison with the 21st-century state of the art will be helpful. From gas physics, the temperature T of a gas or plasma is:

$$T = \frac{v^2 N_0 m}{3R}$$

where: v is the velocity of the protons in the plasma, $= v_e/1.023$
m is the mass of a proton, $= 1.6726 \times 10^{-27}$ kg
N_0 is Avogadro's number, $= 6.022 \times 10^{23}$
R is the gas constant, $= 8.314$ J K^{-1} mole^{-1}

The temperature of the plasma corresponding to an exhaust velocity of $0.126c$ then works out as 5.5×10^{10} K.

According to Chang Díaz in his *Scientific American* article on the VASIMR engine, present-day laboratory plasmas can go up to about 10^8 K. An improvement by a factor of 550 is perhaps not unreasonable, looking some centuries ahead.

Comparison of different propellants

Hydrogen is not the only possible propellant. In particular circumstances it may be more convenient to work with methane, water, or some other substance or mixture of substances. The advantages of doing so may sometimes outweigh their reduced propulsion efficiency.

In all cases it is assumed, as before, that 80% of the total annihilation energy can be captured as rocket thrust, and that the proportion of antimatter to reaction mass is small (on the order of 1% or less). Then the same calculation as above yields the following comparative mixture ratios:

Hydrogen:	$(v_e/c)^2 =$	1.674 641 α
Methane:		0.789 744 α
Ammonia:		0.653 906 α
Water:		0.531 190 α

At maximum energy efficiency, $\Delta V/v_e = 1.59$. The mixture ratios required for a ΔV of $0.1c$ and one of $0.2c$ are then:

Propellant	*α for $\Delta V = 0.1c$ whence $v_e = 0.0629c$*	*α for $\Delta V = 0.2c$ whence $v_e = 0.1258c$*	*Relative anti-matter cost*
Hydrogen:	0.002 362	0.009 448	1.00
Methane:	0.005 009	0.020 035	2.12
Ammonia:	0.006 049	0.024 196	2.56
Water:	0.007 447	0.029 786	3.15

It is clear that hydrogen is by far the best propellant in terms of minimising the antimatter cost for a given propulsive manoeuvre. If a vehicle of a given engine, structural and payload mass carrying 3.9 times that mass of hydrogen propellant (for maximum energy efficiency) requires 1 kg of antimatter to energise that hydrogen for a manoeuvre, then substituting methane for the reaction mass will require 2.12 kg of antimatter, substituting ammonia will require 2.56 kg, and water, 3.15 kg of antimatter.

Given the expected high cost of antimatter relative to the common substances used as propellant reaction mass, this is a serious consideration.

The antimatter storage factor

The Space Shuttle's external tank weighs 35.4 tonnes empty. Normally it contains 616.5 tonnes of liquid oxygen and 102.0 tonnes of liquid hydrogen, thus the mass of the tank is 0.05 times the mass of its contents.

If completely filled with hydrogen alone it would contain only 140.7 tonnes of propellant, due to the extremely low density of liquid hydrogen. But the propellant tanks for Wayland are used exclusively in space, where they are subject to relatively mild accelerations and to no aerodynamic forces at all. It is therefore reasonable to assume that the more benign levels of mechanical stress will roughly balance out the need for greater volume and that its hydrogen tanks will likewise weigh in the region of 0.05 the mass of their contents, so this is the figure chosen.

Antihydrogen resembles hydrogen in many ways, but the requirements for its safe storage and transport on board a ship made of normal matter are not one of them.

The following chapter will present some ideas for methods of bulk storage of antimatter, but as yet the subject is entirely open because only trifling quantities have so far been produced. The record production rate of antiprotons currently stands at 10^{14} in a month, achieved at Fermilab in the USA in June 2007 (Close, p.150). If maintained for a year, this production level would result in a mass of antiprotons weighing 2.0×10^{-12} kg – two nanograms. The Fermilab antiprotons were not captured, and while CERN does trap antiprotons and make them into antihydrogen, its production rate is 100 times smaller.

What can be said at this stage is that the tankage required for safe storage of bulk antimatter, be it in the form of antiprotons or of neutral antihydrogen atoms, is likely to weigh considerably more than 0.05 the mass of its contents, and may well have to weigh many times that mass.

It is instructive to assess the feasibility of the HAMR engine by comparing two key quantities: the antimatter mixture ratio α, introduced above, and the antimatter storage factor s, which may be defined as the mass of tankage required to store one kilogram of antimatter.

The following working definitions and assumptions are made concerning the architecture of a single-stage rocket vehicle:

- Payload mass = P; hydrogen propellant mass = H; antimatter mass = A.
- Hydrogen tankage mass = $0.05H$.
- Antimatter tankage mass = sA.
- Antimatter mixture ratio $\alpha = A/H$.
- Engine and structural mass = tankage mass = $0.05H + sA$.

Thus the functional hardware mass is divided equally between tankage, and engine plus supporting structure, reflecting the likelihood that if antimatter is more difficult to store, it will also be more difficult to work with in the engine, and if more hydrogen is carried, then a higher engine thrust will be needed for the same starting acceleration. Then:

$$R = \frac{P + 1.05H + (1 + s)A + (0.05H + sA)}{P + 0.05H + sA + (0.05H + sA)}$$

It will be useful to express the payload as a fraction of the hydrogen propellant carried (normally the most massive single item on the vehicle). Substituting for $A = \alpha H$ and rearranging:

$$\frac{P}{H} = \alpha\left(\frac{1}{R-1} - 2s\right) + \left(\frac{1}{R-1} - 0.1\right) \qquad \text{(vi)}$$

The mass ratio $R = 4.9$ for maximum energy efficiency, whence:

$$\frac{P}{H} = 0.2564\alpha - 2s\alpha + 0.1564 \qquad \text{(vii)}$$

If we then choose values for α and s, this equation tells us the payload fraction. But if:

$$0.2564\alpha - 2s\alpha + 0.1564 = 0$$

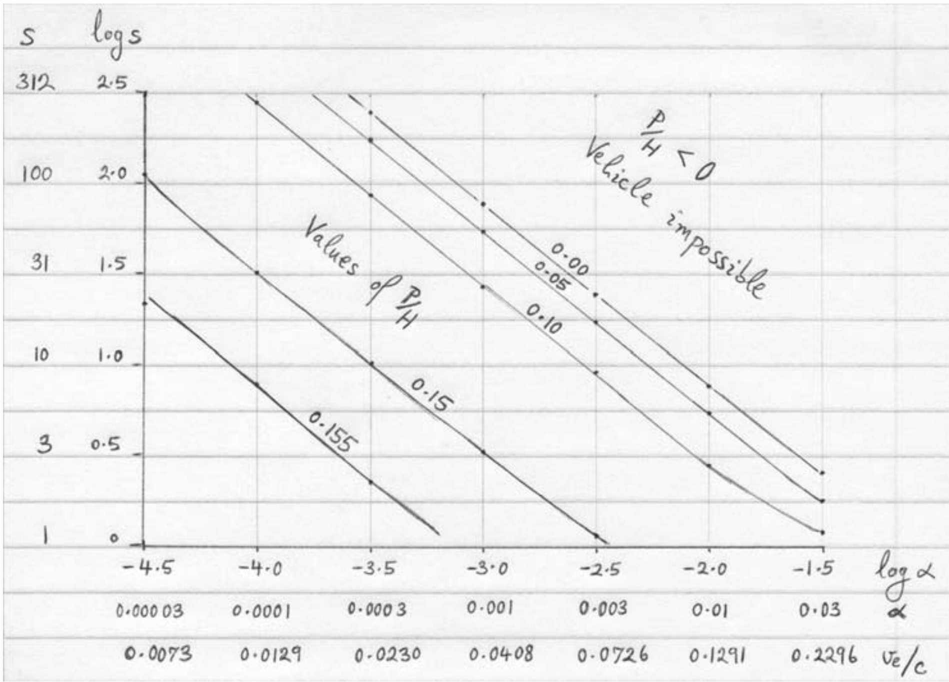
then there will be no spare mass available for payload, so the vehicle will be pointless and will not be built. The condition for payload to be possible at the chosen mass ratio is:

$$s < 0.1282 + \frac{0.0782}{\alpha} \qquad \text{or:} \qquad \alpha < \frac{0.1564}{2s - 0.2564}$$

In order to investigate how α and *s* behave for a given mass ratio *R* and payload fraction *P*/*H*, equation (vii) is rearranged for *s*:

$$s = 0.1282 + \frac{0.1564 - (P/H)}{2\alpha}$$

Graph 1 presents a log-log plot of *s* against α in this equation for different values of the payload fraction. It shows a region in which a vehicle designed on the above working assumptions can carry payload, and another region in which the payload would be negative, in other words the vehicle cannot even carry its own structural mass. Values of the exhaust velocity are added to the horizontal axis, since they are directly determined by α.



Graph 1

The graph demonstrates that payload fraction, antimatter mixture ratio and antimatter storage factor constrain one another, such that large values of all three variables in the same vehicle are impossible.

If a high payload fraction is required, both α and *s* must be small, and a payload fraction greater than 0.1564 is impossible.

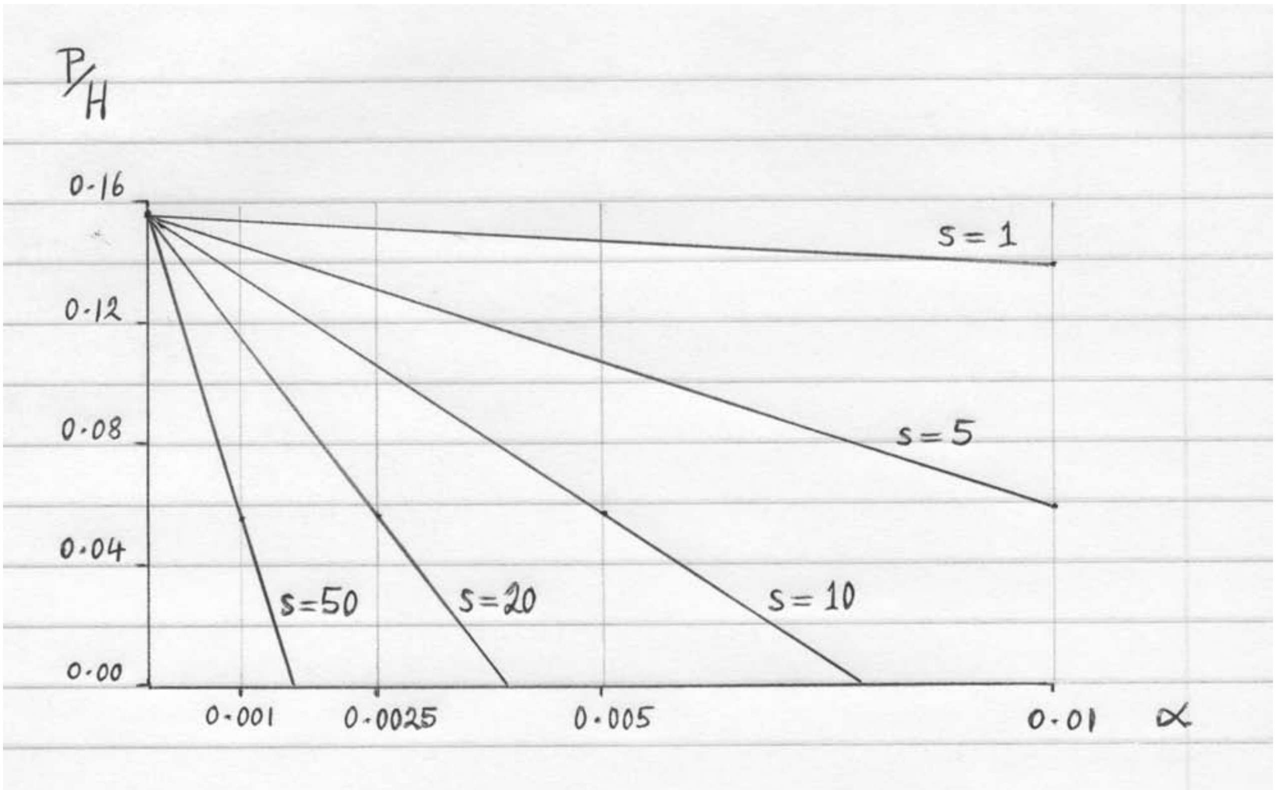
For any given payload fraction, a high antimatter mixture ratio forces a low antimatter storage factor, and vice versa. Since the storage factor will be set by the available technology, this will impose an upper limit on the mixture ratio (which is at the same time constrained by the efficiency of the takeup of annihilation energy into the directed exhaust stream), hence on the exhaust velocity (by the mixture ratio equation, equation (v) above), and hence on the maximum achievable ΔV.

The only way to increase ΔV beyond that would be to move away from the condition of maximum energy efficiency by increasing the mass ratio. But for any given mass ratio the qualitative conclusions of this discussion will remain valid.

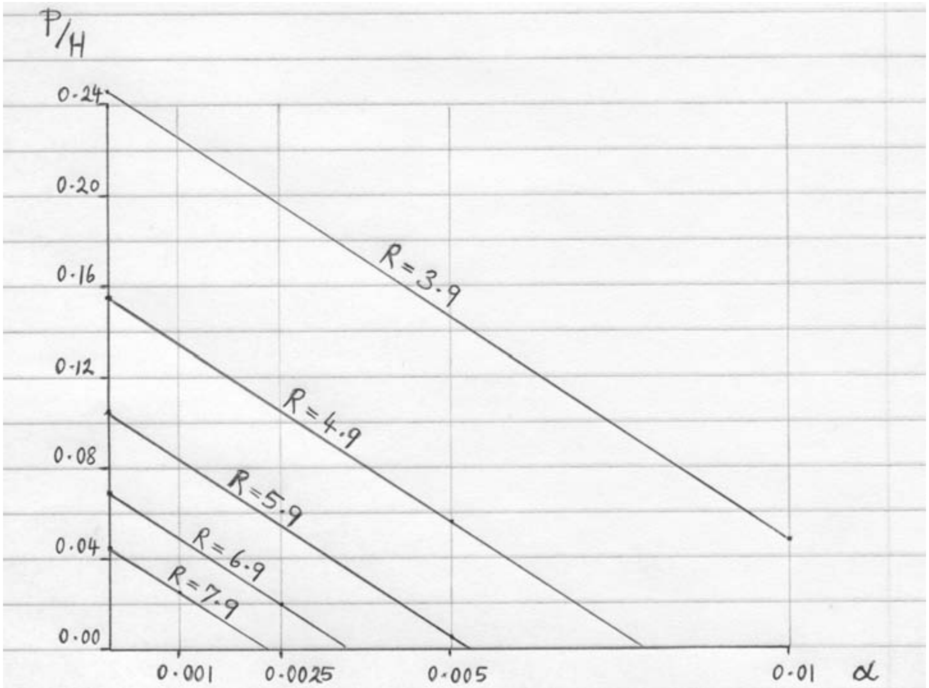
Another way to analyse the relationships implicit in equation (vi) is to plot α against P/H for various values of s and R. Graph 2 holds R constant at 4.9 and takes a range of values of s, while Graph 3 holds s constant at 10 and varies R. The plot for R = 4.9 and s = 10 is common to both graphs.

Graph 2 ($R = 4.9$): $$\frac{P}{H} = \alpha\,(0.2564 - 2s) + 0.1564$$

Graph 3 ($s = 10$): $$\frac{P}{H} = \alpha\left(\frac{1}{(R-1)} - 20\right) + \frac{1}{(R-1)} - 0.1$$



Graph 2



Graph 3

From these graphs one obtains an impression of the trade-off between payload fraction and antimatter mixture ratio, and hence the exhaust velocity. A high payload fraction can only be achieved at the expense of a low mixture ratio, and vice versa. The relationship is linear, with the slope of the line controlled by the storage factor and its intercepts on the axes controlled by the mass ratio.

These fundamental constraints on the operation of a hydrogen-antimatter magnetoplasma rocket arise from the two key features by which it differs from a conventional chemical or nuclear rocket engine:

- The exhaust velocity depends entirely upon the mixture ratio of its two propellants;
- One of those propellants is expected to require tankage which weighs, not a fraction of the propellant mass as in conventional rockets, but a multiple of that mass.

While the antimatter storage factor for macroscopic quantities of the stuff is at present entirely conjectural, the figure of $s = 10$ has been chosen for further development of the Wayland design. However, it should be borne in mind that this quantity is not a design choice in the sense that mass ratio or mixture ratio may be arbitrarily chosen by the designer; it will be pre-set by the technology of the time, and the designer will have to accept the figure which that technology produces, just as today he or she has to accept without demur the specific impulses of particular chemical rocket propellants.

A critical conclusion from this discussion is therefore that s imposes an upper limit on α, and hence on the exhaust velocity attainable with this technology, according to the following condition derived from equation (vi):

$$\alpha < \frac{1 - 0.1\,(R - 1)}{2s\,(R - 1) - 1}$$

Comparison with earlier work

After having written all the above material for the present chapter, this author took the opportunity to read the papers on the subject published in *JBIS*, vol.35 (September 1982), held at the library of the British Interplanetary Society in London.

In his article "Antimatter Propulsion", Robert Forward reports the work of Dipprey, which was published in a summary of studies carried out at the Jet Propulsion Laboratory some years earlier ("Frontiers in Propulsion Research", JPL Technical Memorandum 33-722, ed. D. D. Papailiou, 1975).

Dipprey showed that the original concept of antimatter propulsion, going back to Eugen Sänger (date given variously as 1953 or 1963), of using equal amounts of matter and antimatter, is not the best one. Rather, the annihilation energy of a small amount of antimatter should be used to heat a much larger quanty of matter, which then serves as reaction mass (as has been assumed from the start of this chapter).

Dipprey assumed that the rocket was 100% efficient, presumably meaning in terms of the conversion of annihilation energy to rocket thrust (Forward's account is unclear on the exact meaning). He or she also assumed that the vehicle would operate close to maximum efficiency in the conversion of the energy in the rocket exhaust to kinetic energy of the empty vehicle after burnout, for which, so long as the speed at burnout is less than about half the speed of light (the classical case), a mass ratio of 4.9 is required. He or she then derived the following equation for the mass of antimatter M_a required for a given mission velocity ΔV:

$$M_a = 0.38\ M_{pl}\,(\Delta V / c)^2$$

(equation (1) in Forward's article). M_{pl} represents the mass at burnout, so including payload, engine and tanks.

Forward next reports that Dipprey's work was extended in 1981 by B. N. Cassenti, who showed that heating liquid hydrogen propellant with antimatter reaction products should produce a maximum efficiency of only about 44%. The amount of antimatter required for a given ΔV therefore has to be increased by a factor of about 2.3 over Dipprey's estimate, thus:

$$M_a = 0.9\ M_{pl}\,(\Delta V/c)^2$$

(equation (2) in Forward's article).

This equation may be compared with the antimatter mixture ratio equation derived earlier in this chapter. At maximum energy efficiency, $R = 4.9$ and $\Delta V = 1.59\ v_e$. If M_h is the total mass of hydrogen propellant, then the final mass after engine burnout is $(M_h + M_a)/3.9$. Cassenti's equation above then becomes:

$$M_a = 0.9 \times (M_h + M_a)/3.9 \times 1.59^2 \times (v_e/c)^2$$

$$\frac{M_a}{(M_h + M_a)} = 0.583\,(v_e/c)^2$$

The antimatter mixture ratio defined in this chapter is $\alpha = M_a/(M_h - M_a)$, i.e. the mass of the antimatter divided by the mass ejected in the exhaust. If we define a modified mixture ratio $\alpha' = M_a/(M_h + M_a)$, then, because the mass of the antimatter represents only a small fraction (<~1%) of the mass of the hydrogen, α and α' are almost equal, to two significant figures, and Cassenti's equation may be rewritten:

$$(v_e/c)^2 = 1.7\,\alpha'$$

Comparison with equation (v) above, the antimatter mixture ratio equation derived by the present author, reveals that the two equations are essentially identical.

Doubts, however, remain. The analysis offered earlier in this chapter assumed an uptake of annihilation energy into the directed rocket exhaust of 80%, being all the energy of the charged pions plus half the energy of the neutral ones (i.e. assuming that there is sufficient time for half of their kinetic energy to be transmitted to charged particles in the plasma). Cassenti estimated a maximum efficiency, presumably for the same process, of only 44%. It is therefore unclear how the present author and Cassenti could both have arrived at the same end result.

Meanwhile David L. Morgan, in the same issue of *JBIS* (p.409-411), estimates that 40 to 50% of the proton-antiproton annihilation energy is converted into directed exhaust energy, agreeing with Cassenti.

Morgan presents two design concepts. One is for a low thrust, high exhaust velocity engine employing equal quantities of hydrogen and antihydrogen and developing an exhaust velocity of 0.95*c*. The other design is for a higher thrust, lower exhaust velocity engine, in which a small amount of antiprotons is reacted with a much larger quantity of, not hydrogen, but atoms of uranium. The antimatter mixture ratio in this latter case is 9.26×10^{-7} (derived from the data given in table 1 on p.411), and the exhaust velocity given of 140 km/s is then close to the value of 118 km/s which would be predicted by equation (v) above, notwithstanding the fact that matter of a very high atomic number is envisaged in Morgan's design, in place of the hydrogen propellant assumed in the derivation of equation (v).

According to Morgan, the collision cross-section of the pions and muons, produced by the annihilation reaction, with other hydrogen nuclei in the reaction chamber is so small that they would have to travel several kilometres before striking a nucleus when the propellant is at standard atmospheric density. The implication is that unless this is taken into account in the engine design, the annihilation products will all escape into space without having heated any of the hydrogen intended as reaction mass.

Morgan's proposed solutions are to confine the plasma for 7 milliseconds in order to give time for the energy to be distributed among all the particles in the reaction chamber, and additionally to use a propellant of the highest possible atomic number in order to maximise the interactions at each nucleus, and even heat the plasma further with some fission energy. But evidently, although he does not say so, all the neutral pions produced will be incapable of confinement and will therefore be lost, as also will all the neutrons liberated from nuclei in the propellant. Nor does he discuss the reduction in exhaust velocity inevitable when exhaust particles of higher mass are used.

Clearly much work remains to be done before the use of antimatter as an energy source can be fully understood, let alone put to practical use. The present study shall assume the validity of the antimatter mixture ratio equation derived earlier in this chapter (and agreeing with Cassenti's formula), and that it is indeed applicable to antiprotons reacting with a larger mass of hydrogen propellant. But in any future revision, these questions will need to be readdressed.

6. *Grasping the antimatter nettle*

Storage options

One of the barriers to the practical use of antimatter for storing the immense power of the stars in a compact form, for subsequent large-scale power production or high energy rocket propulsion, is the problem of how to store it in quantity.

Bulk antimatter may consist of either charged particles or neutral ones. Neutral antiatoms of antihydrogen were first made at CERN in 1995 (Frank Close, p.93) – coincidentally the same year as the first confirmed discoveries of exoplanets orbiting sunlike stars. Antiatoms of atomic weight greater than one have not yet been made, and nor are they expected to become available in the near future.

From the necessity of keeping antimatter apart from matter until it is time to release its energy, it follows that *charged* antiparticles must be used, in order that they can be confined and controlled with electric and magnetic fields. But from the necessity of confining a large number of antiparticles in a small volume in order to obtain a macroscopic amount of energy from them, it follows that *neutral* antiparticles must be used, otherwise their mutual electrostatic repulsion will overcome any realistic external field and they will fly apart out of their containment volume. The solution usually offered is therefore to use a mixture of charged and neutral antiparticles condensed together into the solid state, so that the charged antiparticles can be used to control the neutral ones.

At first sight, one might imagine that antiprotons could be stored safely in a box made of normal matter, provided that they were kept at a very low temperature. Antiprotons will annihilate on contact with protons or neutrons, but not with electrons. Passing antiprotons through a cloud of cold electrons is in fact the procedure used by the Antiproton Accumulator at CERN for slowing them down so that they may be captured (Close, p.84-86).

Since each atomic nucleus of normal matter is surrounded by a cloud of electrons, the possibility suggests itself that the negatively charged electrons may shield the positive nucleus from the negative antiproton, provided that the antiproton does not have sufficient energy to overcome the potential barrier raised by the electron cloud, either to penetrate it directly, or to slip through by quantum tunnelling.

But unfortunately the electron shield is almost certainly insufficient for this purpose. As explained by Richard R. Zito (p.417), the electron cloud around a nucleus is normally spherically symmetrical, hence its centre of charge is at precisely the same point as that of the nucleus. The net electrostatic field outside the atom is then zero and an antiproton in the vicinity feels no force. It it wanders closer, its own electrostatic force tends to repel the electron cloud, partly exposing the nucleus, and a small net attraction arises, leading the antiproton onwards to its destruction.

Clearly, in a box designed to hold a large number of antiprotons (this author envisaged a large crystal lattice with antiprotons wandering harmlessly (!) through the interstices) an equal number of electrons would need to be removed in order to maintain zero overall charge, thus exposing the positively charged nuclei even further.

In his paper Zito offers the suggestion that electron clouds may be modified by an external magnetic field in such a way as to present a more effective barrier. He states that antiprotons may be stored safely in a container lined with frozen hydrogen (frozen nitrogen is suggested as an alternative) maintained at a temperature of less than 0.77 K, so long as the lining is kept in a 2p0 population inversion by the magnetic field.

Most authors, however, prefer to envisage the manufacture of solid antihydrogen (Forward, p.393-394; Morgan, p.406-407; O'Neill, p.123). This involves the complexities of cooling neutral antihydrogen atoms down through three phase transitions while keeping them in complete isolation from normal matter of any kind.

Pellets of antihydrogen ice in storage would consist mostly of neutral antiatoms. Ionising a pellet by irradiating it with ultraviolet light and removing the positrons with an electric field (Morgan, p.407) would give the pellet as a whole a small net negative charge, sufficient to allow it to be moved around by electromagnetic fields and prevent it sticking to other pellets, but not so great as to cause it to break apart. The pellets could be fed one by one into an auxiliary reaction chamber where they would be gently ionised and evaporated, allowing small bursts of antiprotons to be fed into the main combustion chamber. The reaction would proceed in a series of explosive pulses, like a car's internal combustion engine, rather than continuously, like a chemical rocket.

A suitable storage tank might look like a macroscopic crystal lattice, with weakly charged pellets of antihydrogen ice being marshalled and levitated among a three-dimensional array of electrodes. Control should be straightforward, since each pellet's position could be monitored visually by illuminating it with low intensity microwaves (Morgan, p.407). The storage system could be thoroughly tested beforehand using pellets of ordinary hydrogen ice with all the electrical potentials reversed.

Most of the antiprotons are accompanied by a positron. If these too were employed in the main combustion chamber, the ensuing electron-positron annihilations would generate gamma rays which would be harder for the propellant to absorb than the pions from the proton-antiproton reaction, as well as being insensitive to the magnetic nozzle. The positrons are therefore useless for propulsion. Morgan, however (p.408), describes a design in which, while the antiprotons are guided to the engine, their corresponding positrons (which carry 1836 times less mass-energy) are guided to an auxiliary electrical generator.

The reaction in which pure antiprotons are mixed with hydrogen appears to be the best for rocket propulsion purposes. No gamma rays are produced from electron-positron annihilations. There are no heavy nuclei, so no neutrons are produced.

Protection from cosmic radiation

Another antimatter storage issue which must be addressed is the question of whether a chain reaction of annihilations could be set off by the galactic cosmic ray bombardment to which all space vehicles are subject.

Considering first a tank of normal liquid hydrogen, it is clear that the contents will be heated as they absorb the kinetic energy of incoming cosmic ray particles. The rate of heating is however extremely slow, and would pose no difficulty for maintaining the hydrogen in the liquid state over periods of decades of flight.

If stored antimatter is subject to the same bombardment, each incident particle will not only deposit its kinetic energy in that antimatter, but will also mutually annihilate with one or more antiparticles. A cosmic ray proton will destroy a stored antiproton; a heavier nucleus will liquidate as many antiprotons as its own complement of protons and neutrons. The annihilation energy will contribute to heating up the mass of antimatter, potentially to a dangerous level.

But the kinetic energies of cosmic ray particles are very high, comparable with the annihilation energies of their masses. A proton or heavier nucleus hitting the starship at 94.3% of the speed of light (relativistic $\gamma = 3$) has a kinetic energy of $mc^2 (\gamma - 1)$ equal to the annihilation energy of $2mc^2$ it would release, and such a speed is typical of galactic cosmic ray particles. There will therefore be significant additional heating of the antimatter supply relative to normal hydrogen, but not by a large factor, perhaps just a multiple of two.

Exposure to cosmic ray bombardment will gradually erode the supply of antimatter, in contrast to normal hydrogen, which absorbs the incoming particles without change. But, providing a catastrophic explosion was avoided, the rate of erosion of any macroscopic antimatter supply would still be extremely low.

For the present, it is assumed that, with active cooling, a starship's antimatter supply can be maintained indefinitely without dedicated full shielding, but that it will still be preferable to use the hydrogen propellant as partial shielding in order to reduce the requirement for active cooling while those propellants are still in their tanks.

This critical design question needs to be returned to when more precise knowledge about interstellar cosmic ray spectra and more detailed designs for large-scale antimatter storage systems have become available.

Antimatter and antigravity

According to Professor Close, it is not yet known whether antimatter falls or rises under the force of gravity (p.92).

If antimatter has an antigravity property, then it will be slightly more difficult to store in quantity. A vehicle in orbit around the Sun or a planet feels a force which continuously curves its trajectory downwards. But its antimatter supply would feel an opposite force trying to curve its trajectory upwards. It would then not be enough to merely hold the antimatter in suspension within its tank, but would also be necessary to counteract its constant drift towards the upper wall of that tank.

In deep space this problem would go away, as the further one recedes from any nearby stars or planets, the closer one approaches a condition of freedom from any gravitational acceleration (though complete freedom is never achieved: on a timescale of millions of years one's orbital motion about the centre of mass of the Galaxy would become appreciable).

But if antimatter obeys a law of antigravity, could this not be used directly for propulsion – taking off from a planet, for example? Perhaps if a vehicle had a mass of 50 tonnes and carried a mass of antimatter which we would now have to express as *minus* 50 tonnes, then while its net *inertial* mass might still be 100 tonnes, its net *gravitational* mass would be zero (assuming that an antimatter storage factor of less than one could be achieved).

If it was situated on the surface it would immediately fly off into space in a straight line, obeying Newton's first law and feeling no net force from the planet, just as Cavor's sphere, coated with the gravitationally opaque substance cavorite, does in H. G. Wells's classic *The First Men in the Moon*. But since the planet itself is rotating, from the point of view of somebody standing nearby on the surface the ship would fly straight upwards. Keeping it on the ground would entail anchoring it with a cable strong enough to hold the 100 tonne ship against the centrifugal accelerations of the planet's axial and orbital rotations.

If the ship then cast off its anchor and at the same time dropped one tonne of matter ballast, its trajectory would no longer be a straight line, but would curve gently upwards as it experienced an acceleration away from the planet of 1.01% of the local acceleration of gravity, now having a net gravitational mass of 49 – 50 = –1 tonne, but an inertial mass of 99 tonnes.

Or would it?

In a footnote, Close adds that if Einstein's theory of gravity (known as General Relativity) is still applicable in a situation involving both matter and antimatter (which was unknown when he first formulated the theory), then antimatter should fall downwards under gravity just as matter does. But I would suggest an alternative interpretation: if Einstein is still correct, then the identity between inertial mass and gravitational mass characteristic of normal matter will still hold for antimatter. This may come about in one of two ways: antiparticles may have the same masses and fall under gravity in the same way as their corresponding particles, in which case there is no more to be said. Or antiparticles may have negative gravitational mass *and* negative inertial mass.

This latter concept has certain implications. A negative inertial mass may be taken to mean that, as a force is applied, its direction is reversed. If therefore antiparticles had negative inertial mass, it would follow that they had *the same* electric charge as their corresponding particles: an antiproton would have positive charge, just like a proton, and so on. But their response to an applied electric or magnetic field would be in the opposite direction, creating the impression that their charge was opposite (a concept already familiar and therefore more readily adopted), when in fact their charge was the same and it was their inertial mass that was opposite (a novel and unfamiliar concept).

In this case, a vehicle weighing 50 tonnes which loaded –50 tonnes of antimatter would (so long as it could prevent the two from coming into contact) have zero net gravitational mass *and* zero net inertial mass. It would be as massless as a photon (which seems intrinsically implausible). If situated on the surface of a planet it would immediately fly off into space in a straight line, unless it was anchored to the ground, as before. But this time, the slenderest of threads would be sufficient to hold it on the ground. And dropping one tonne of ballast (or one microgram, or any other amount) would cause it to accelerate away with an additional acceleration equal and opposite to that imparted by the local gravity field.

Such ease of movement would contrast with the internal stresses as the matter and antimatter composing the vehicle pressed against one another via electric fields with a force equal to their respective weights on that planet. The tiniest slip, and the vehicle would explode with the release of 9×10^{21} J, or 2 million megatons worth of bombs.

A gravitational repulsion between matter and antimatter would not affect the annihilation process. A proton and an antiproton annihilate when the electrostatic attraction of their opposite charges forces them together (or, equivalently, when the electrostatic force between their identical positive charges combined with their opposite masses forces them together). Since the electrostatic force between particles is many orders of magnitude stronger than their mutual gravitational force, both forces depending upon the distance according to the same inverse square law, the electrostatic attraction dominates at all distances over any gravitational repulsion.

However, the concept of negative inertial mass introduces a complication. A proton would have to respond to, not only the positive (repulsive) charge of a nearby antiproton, but also its negative (force-reversing) inertial mass, in order for the net mutual force between them to be one of attraction. This is not a fatal objection – the formula for the electric force between two bodies of inertial masses I_1 and I_2 would just need to be multiplied by a factor $I_1I_2/\sqrt{(I_1^2I_2^2)}$ to extract a positive or negative sign, and for particles of the same type this factor would always be unity.

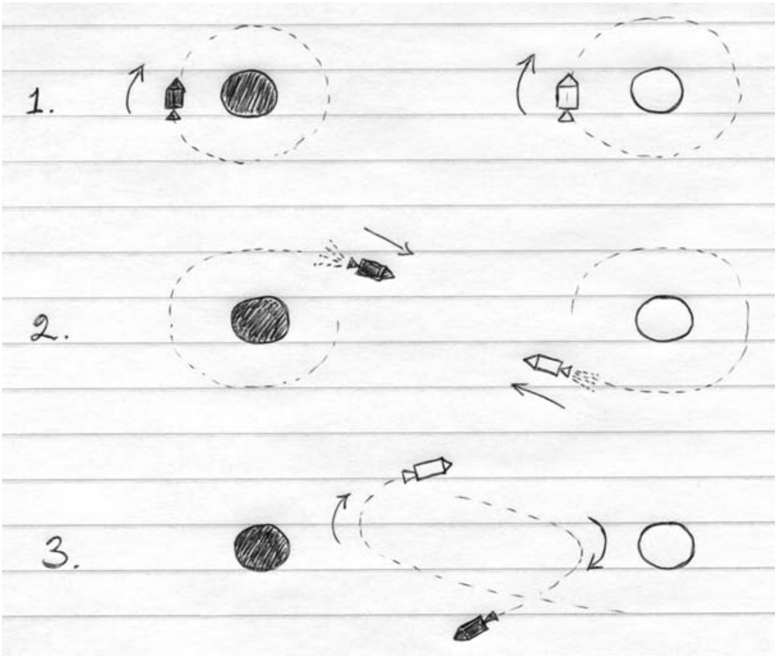
In this way, when two antiprotons or two positrons meet, the force between them is reversed twice, in other words it would still be a mutual repulsion, and the behaviour of large-scale objects composed of antimatter would be indistinguishable from that of the same objects in the matter universe. But an extra degree of complexity is introduced into the theory of these interactions.

It may be both more physically plausible and more theoretically economical to stay with the opposite electrostatic charge on antiparticles, and instead to revise Einstein's General Relativity to the extent of giving antiparticles negative gravitational mass but positive inertial mass, as was suggested above. The calculations of vehicle performance in chapter 8 are based on this assumption.

This author is not qualified to present such a revision of General Relativity in full mathematical detail (fortunately for the patience of the reader). But one can see how such a scheme would work in terms of a simple picture which is often used to illustrate the fundamental concept of curved spacetime. The reader is asked to consider a thin sheet of soft rubber, stretched like a drumhead, and sitting in some terrestrial laboratory. A massive object such as a cricket ball, when placed in the centre of this sheet, sinks down a short distance, distorting the surface into a downwards-pointing, wide-angled conical shape. This represents the curvature of spacetime by the Sun. If a marble to represent Earth is placed on the slope, it will naturally fall straight into the Sun, but if, as it is being placed on the stretched rubber, it is given a flick of the right amount at right angles to the slope, then it will orbit the Sun in a circle by virtue of moving in the straightest possible line in that direction through its conical spacetime.

In this simplistic model (which represents four-dimensional spacetime by a two-dimensional surface), the real gravity of Earth is used to create the gravitational forces on the simulated spacetime surface. If antiparticles obey an antigravity law, in this model they will need to be represented by bodies which fall upwards in Earth's real field. Perhaps the entire model could be placed under water, and antisuns and antiplanets represented by hollow spheres filled with air and placed on the lower surface of the rubber skin. Then (ignoring the resistance of the water – no model is perfect!) an antisun will distort the rubber surface into an upwards-pointing cone, a gravitational hill to the Sun's valley, and an antiplanet will orbit it in the same way as before, only rolling around the underside of the rubber sheet rather than its upper side.

Then an antiplanet placed near the Sun, or a planet placed near the antisun, will, regardless of what motion it is given, experience a repulsive force due to the combination of the local curvature of spacetime and its own physical nature: whether it is a heavy ball released onto the rubber surface or a buoyant one released under it. In other words, a spacecraft can orbit a planet, and an antispacecraft can orbit an antiplanet. But if the two spacecraft try to exchange places, they cannot orbit the other planet, but are deflected away from it, as illustrated in the following diagram:



In general, the force of gravity between two bodies of gravitational masses M_1 and M_2 a distance r apart is GM_1M_2/r^2, where G is the universal gravitational constant. If M_1 and M_2 are both positive (normal matter), then there is attraction. If they are both negative (antimatter?), then there is still attraction. Only if one gravitational mass is positive and the other negative does the sign of the force change, and a gravitational repulsion occur.

Mass would thus resemble electric charge in having two forms: positive and negative. But whereas electricity obeys the law that like charges repel, opposite charges attract, gravitation would obey the opposite law: like gravitational charges attract, opposite charges repel. Thus on a large scale matter and antimatter would tend to move away from each other to occupy different regions of the universe, which may help to explain why there does not appear to be any free antimatter in our part of the universe. The observed lack of any signs of free antimatter in our local universe may even be taken as evidence in support of the view that antimatter does indeed have negative gravitational mass.

So far as space propulsion is concerned, the antigravity property of antimatter – if confirmed by laboratory tests – would not be of significant help. Neutralising the mass of a vehicle would require an equal and opposite mass of antimatter, and the addition of more antimatter would accelerate that vehicle away from the Solar System. But, as the previous chapter has shown, acceleration to a fair fraction of light speed can be done on an antimatter budget of less than one per cent of a vehicle's mass.

Given the high cost of antimatter, conventional rocket propulsion is therefore vastly cheaper, as well as enabling acceleration and deceleration in any chosen directions to be carried out at any chosen points in space, rather than having to rely on interactions with nearby massive astronomical bodies. Furthermore, it may not even be possible to contain a mass of antimatter in a container made of matter which weighs less than its contents.

As noted above, storage of antimatter would be rendered more delicate when in proximity to a star or planet, which will certainly be the case for the large-scale antimatter power industry envisaged in chapter 10.

It remains to be seen, however, whether antimatter's gravitational mass really is positive or negative. For this, the laboratory synthesis of antimatter in the form of condensed particles weighing a significant fraction of a gram is awaited.

7. Alternative propulsion concepts

Nuclear fusion

The nuclear pulse fusion engine was the power plant of the Daedalus starship study, and was investigated in considerable technical detail by Alan Bond and Tony Martin in the *Daedalus Report*. Its fuels were deuterium and helium-3, and the calculated exhaust velocity was 10,000 km/s. Since this is 3% of the speed of light, such an engine is just about capable of driving a fast interstellar starship, though the mass ratio has to be rather high (it was 36.6 for Daedalus) and the energy efficiency consequently sub-optimal (36%, against a theoretical maximum of 65%).

Chang Díaz is pioneering another approach to nuclear fusion through the VASIMR electric engine. In its present form the power input is achieved by generating radio waves, in a process known as ion cyclotron resonance heating, necessitating either large solar arrays or a nuclear reactor to provide the 10 MW of power needed. Maximum exhaust velocity currently envisaged is 300 km/s at a plasma temperature of 10^7 K (*Scientific American*, Nov. 2000, p.72-79).

But the fact that the engine contains a high-temperature plasma, which it uses to create thrust by directing it with a magnetic nozzle, means that it could be developed towards using fusion energy as its power source. Chang Díaz anticipates that such a vehicle would have 10 to 100 GW at its disposal.

If exhaust velocity is scaled to the square root of the engine power, then this implies an exhaust velocity of up to 30,000 km/s, 10% of light speed. This would certainly be extremely useful for starship propulsion.

A variant of the magnetoplasma rocket might use antimatter to induce fusion reactions, with most of the energy coming from the fusion rather than the annihilation. This option is currently under investigation by the Icarus team.

Again, the present study has assumed large-scale use of antimatter for generation of electric power (discussed in more detail in chapter 10). If this becomes a reality, then it may be easier to use it as an alternative source of power for an electric magnetoplasma rocket than to use it directly for thrust.

Beamed energy light-sail

If antimatter production, storage and release still proves to be impractical after another thousand years or so of research, there is, however, another option for taking advantage of the immense power resources of the Sun and the stars, and that is not to store solar energy but to use it directly when required. This involves converting some of that power into a laser or microwave beam, which is directed towards a vehicle. The ship captures the energy and uses it directly as thrust against a solar sail, or as a source of electricity to run a magnetoplasma engine.

Because the ship does not need to carry or accelerate perhaps thousands of tonnes of rocket propellants, this concept sounds at first seductively appealing. All the fuel is left at home and just beamed up as pure energy whenever required (which would take careful coordination when communications between the ship and the Solar System were subject to a time lag of several years).

Such a ship may carry a light-sail which is driven by photon pressure from a laser beam. Since the pressure of light is small, the light-sail would need to be large, perhaps hundreds or up to a thousand kilometres across. But the drawback is that most of the energy of the transmitted beam stays in the beam after being reflected.

Let P = power, E = energy, and suffixes b, s relate these to the beam and the ship respectively. The ship has mass m and velocity v relative to the Solar System. From Technical Note 5–2 in the *Starflight Handbook* (p.75), the gain in the ship's momentum $m\,\Delta v$ after complete reflection of a beam containing energy ΔE_b is:

$$m\,\Delta v = 2\,\Delta E_b\,/c$$

The ship's gain in energy is:

$$\begin{aligned}\Delta E_s &= 0.5\,m\,(v + \Delta v)^2 - 0.5\,m\,v^2\\ &= m\,v\,\Delta v + 0.5\,m\,(\Delta v)^2\\ &= (2\,v\,\Delta E_b)/c + (2/m)(\Delta E_b/c)^2\end{aligned}$$

The power transferred to the ship is:

$$\begin{aligned}P_s &= (\mathrm{d}/\mathrm{dt})\Delta E_s\\ &= 2\,P_b\,(v/c) + (2/mc^2)(\mathrm{d}/\mathrm{dt})(\Delta E_b)^2\\ &= 2\,P_b\,(v/c) + (4\,\Delta E_b/mc^2)\,P_b\end{aligned}$$

Substituting $2\,\Delta E_b = mc\,\Delta v$:

$$P_s = 2\,P_b\,(v/c) + 2\,P_b\,(\Delta v/c)$$

The power transferred to the ship is a fraction of the power beamed to the ship is then:

$$P_s/P_b = 2(v + \Delta v)/c$$

The instantaneous efficiency at any one moment, when Δv is infinitesimal, is:

$$P_s/P_b = 2v/c \qquad \text{(i)}$$

The efficiency of beamed energy propulsion of a ship using a light-sail therefore depends on the velocity of that ship relative to the source of the beam.

When $v = 0$, virtually none of the beam power is added to the kinetic energy of the ship.

When v = 30 km/s = 0.0001c the efficiency is 0.02%.

When v = 3000 km/s = 0.01c the efficiency is 2%, and so on.

Clearly, equation (i) is not valid for large values of v. A relativistic analysis (left as an exercise for the reader) produces the following result, using $\beta = v/c$:

$$P_s/P_b = 2\beta/(1+\beta) \qquad \text{(ii)}$$

Equation (ii) has the efficiency approach 100% as β approaches unity, but an efficiency of exactly 100% is physically impossible.

What do these results tell us about the reflected beam? Clearly, at low velocities the reflected beam contains almost as much energy as it did when it was first transmitted. But as the relative velocity between the light-sail and the Solar System-based laser increases, so the reflected beam is increasingly red-shifted as it loses an increasing amount of energy to the ship.

At non-relativistic speeds the acceleration of the ship is $2P_b/mc$ and at constant power its velocity therefore increases linearly. The net energy efficiency over a period of acceleration, starting at velocity v_1 and ending at v_2, is therefore equal to $(v_2 - v_1)/c$. Thus accelerating a ship to one tenth of the speed of light would require ten times its final kinetic energy to be broadcast towards it. Since a rocket with a high exhaust velocity ends up with around 30% to a maximum of 65% of its rocket energy transmitted to the payload, this means that below mission velocities of 0.3 to 0.65c the conventional rocket is actually more energy-efficient.

There is a way around this, which is for the station in the Solar System to recapture the reflected beam from the light-sail and recycle the energy in it. Whether the reflected beam is still sufficiently well collimated for recapture is the critical question.

Beamed energy rocket

The other way to use a laser or microwave beam is if the ship carries a tank of reaction mass such as ordinary hydrogen, but no means to energise it. If such a beamed energy rocket can draw energy from the beam, it can use that energy to heat the hydrogen, perhaps with some kind of magnetoplasma rocket such as Chang Díaz's VASIMR, and thus create rocket exhaust. Again, the potential drawbacks of this technique are in the very large size of the antenna needed on the ship to intercept the beam, and in the possibly low conversion efficiencies from beamed power to rocket power and thus to kinetic energy of the payload.

The exhaust velocity of such a vehicle (*Starflight Handbook*, Technical Note 5–6, p.85) is:

$$v_e = \sqrt{(2\varepsilon P_b/\phi)}$$

where ε is the efficiency with which the power in the beam is converted to kinetic energy in the exhaust, and φ is the flow rate of the propellant. The concept was described by A. A. Jackson and Daniel Whitmire in 1978.

Combinations of propulsion methods

The light-sail concept does not adapt very easily to deceleration at the target star. A system is needed in which the light-sail splits into two, one of which, consisting of the outer annular section of the sail, intercepts the beam and reflects it back onto the inner sail, to which the ship is still attached (*Starflight Handbook*, p.78-80). The outer sail must then continue to accelerate, while the inner sail and payload decelerate. Quite apart from the difficulties of collimating a laser beam over a distance of at least four light-years, this technique suffers from greater energy losses than before: much of the beam energy goes into accelerating the outer sail, which is counterproductive because it reduces the beam energy which finally reaches the decelerating inner sail by increasing the red-shift of the reflected beam.

A concept offered by Robert Forward and Philip Norem to utilise light-sailing for both acceleration and deceleration appears to be unworkable (*Starflight Handbook*, p.72-77). After accelerating by laser light pressure up to its cruise speed, a ship extends about 5 million kilometres of cables which are charged up to 800,000 volts by emitting electrons into space. The charged ship then executes a huge turn, driven by the Lorentz force caused by the interaction of its electrostatic charge with the interstellar magnetic field. After turning through more than 180° on a circle whose radius is on the order of a light-year, the vehicle is now approaching its target star from the opposite direction to the Solar System. It neutralises its electric charge, and when the laser beam from the Sun is switched on again it now acts to decelerate the vehicle.

Unfortunately, the figures given in the *Starflight Handbook* suggest that the interstellar magnetic field is about four orders of magnitude too weak to achieve the trajectory shown. An equation for the radius of the turning-circle is given in Technical Note 5–3 (p.76); inserting the values for mass, velocity, charge and magnetic flux density given in the text produce a value of 1.28 light-years, which would work nicely. But then one realises that the figure given for galactic magnetic flux density (p.123-124) is expressed in gauss, the CGS unit, whereas the other values are in MKS units. Converting the magnetic flux density to tesla, the radius of the turning circle now works out at 12,800 light-years, making the detour much too long to contemplate.

But another combination of propulsion methods might, however, be worth further investigation. The beamed energy light-sail is most suitable for acceleration, and furthermore when a substantial speed has already been attained by other means. On the other hand, the beamed energy rocket does not adapt so easily to acceleration, since the beam has to pass through the vehicle's exhaust plasma stream in order to reach its antenna. This suggests a system in which a vehicle carries hydrogen propellant and a multi-kilometre-sized sail which can act as either a light-sail or an antenna.

The vehicle is accelerated from rest by a fusion rocket first stage. With an exhaust velocity of 0.03*c* as calculated in the *Daedalus Report* and a mass ratio of 4.9 for maximum energy efficiency, the fusion stage gets it up to a modest speed of 0.05*c*.

The vehicle (now only 20% of its launch mass) now discards its fusion engine, unfurls a light-sail and is further accelerated by the photon pressure of a laser beam generated at a power station in the inner Solar System. If its final cruising speed when the beam is switched off is 0.15*c*, the energy efficiency of this second propulsive stage is 10%; if the vehicle is accelerated to 0.25*c*, the energy efficiency goes up to 20% while the actual expenditure of energy is increased by just 50%.

At the end of the unpowered cruise, deceleration is accomplished by switching on a beam from the Solar System again. The ship switches its sail to antenna mode and the beamed energy is used to heat its onboard hydrogen propellant. Since the exhaust stream is directed away from the Solar System faster than the ship itself is travelling, it does not interfere with the incoming beam at all.

Solar sailing

Solar sailing has much in common with laser beam-riding as a method of reaching the stars, with the added attraction of using sunlight in its natural state (e.g. *Starflight Handbook*, ch.6). Unfortunately the pressure of sunlight on a solar light-sail only produces significant acceleration when the vehicle is very close to the Sun or another star. The accelerations required to reach a high cruising speed in the short time of solar proximity are too severe for the human body to withstand, and the maximum speed attainable by a manned vehicle in this way is limited to about 0.003*c* (p.101), stretching out the voyage to Proxima Centauri to well over a millennium.

Magnetic parachutes

Deceleration at an interstellar destination by magnetic parachute is a theoretically attractive option. Vehicles returning to Earth from orbit always decelerate by friction with the atmosphere, rather than carrying the reaction mass required for a rocket powered descent. Wouldn't it be most economical to enter a solar system in a similar way, extending a magnetic sail and using the local stellar field as a braking medium?

Unfortunately, while this concept seems viable in principle, the decelerations achievable are extremely low. A design by Robert Zubrin and Dana Andrews would generate 70 N of thrust, which would decelerate a 1000 tonne vehicle at only 7 millionths of a gravity. The *Starflight Handbook* describes a magnetic scoop (p.135) which would take two decades to decelerate a vehicle from 0.2*c* to 0.001*c*. Meanwhile a paper by C. Cattell et alia casts doubt on the technology, which is in any case of dubious utility for a fast interstellar crossing.

Zero-point energy

This concept was used in Buzz Aldrin and John Barnes's novel *Encounter with Tiber* (see p.385 and 399 for details).

It sounds attractive. The Heisenberg uncertainty principle reveals that a vacuum is not really empty at all, but bubbling with energy as virtual particles briefly materialise out of nothing and then vanish again. Could this energy be used to drive a laser which generates unlimited thrust for starship propulsion?

The big problem with the concept is that it violates the law of conservation of energy.

Certainly, in some cases it is possible to grab energy out of seemingly empty space to drive our machines, thus apparently getting energy for nothing. Sailing ships can tap into this sort of energy, and be propelled without fuel for as long as the wind blows. They can do this because the universe came into being in a state wildly out of thermodynamic equilibrium. For the next several trillion years the potential energy in the stars will continue to be released, causing natural flows of radiation through planetary biospheres which humans and other species can use to drive their metabolisms and their machines.

The question is therefore whether there is an analogous natural flow of energy from one place to another in the vacuum. Suppose, for example, that our universe had been created with its two different sides in the fourth spatial dimension having different potential energies. Then one would expect energy in some form to leak across the infinitesimal four-dimensional width of our universe as the potentials tended to equalise, and a suitably designed machine could get a free ride off some of this energy as it passed through. But the proponents of zero-point energy do not seem to be saying anything like this.

Insofar as zero-point energy is an outcome of quantum mechanics, then the rules are clear: energy can be borrowed out of nowhere – this is the basis of the quantum tunnelling effect – but it has to be paid back, and the more energy you borrow, the sooner it has to be repaid!

The product of energy and time must be no greater than Planck's constant over 2π, thus one joule can only be borrowed for up to about 10^{-34} of a second. This would be hopeless for driving even a paper dart across the room, let alone a starship to Proxima Centauri.

If a pair of virtual particles are created just on the event horizon of a black hole, and one falls into the hole while the other remains free, then while the particles must now continue to exist, since they cannot get back together to annihilate again, the energy for their creation has to come out of the black hole. So even in this case there's no free lunch. Or launch.

The December 1997 *Scientific American* published an investigation into claims that free energy could be extracted from the quantum vacuum, and their staff writer's conclusion was that zero-point energy was up there with cold fusion and astral projection in the realms of fringe science, if not outright fraudulent pseudo-science.

"Certainly, there should be room for far-out, potentially revolutionary ideas", he wrote. But "it may be best to keep in mind the old caveat emptor: if it sounds too good to be true, it probably is."

Wormholes/warps in spacetime

These are the basis of numerous works of science fiction, notably *Star Trek* and its spinoff series. Concepts of stretching and bunching up the spacetime around a vehicle to get it from A to B while it remains stationary within an isolated bubble of spacetime are currently under study by physicists. They must be regarded as being at present highly speculative. Furthermore, early theoretical results suggest that such a technology is unlikely to be competitive with conventional rocket propulsion in terms of energy consumption. This concept need not detain us further here.

8. *Vehicle configuration*

To summarise the design criteria arrived at so far:

(1) Preferred main propulsion by hydrogen-antiproton magnetoplasma rocket for both acceleration and deceleration (introduced in chapter 5).

(2) Proportion of antimatter to matter determined by maximum energy efficiency due to expected high cost of antimatter, leading to antimatter mixture ratio $\alpha = 0.00945$ (ch.5).

(3) Crew and passengers to total 100 individuals, requiring ~60 m^3 of habitable volume per person, artificial gravity of around one third Earth normal, and full protection against galactic cosmic rays (ch.2-3).

(4) Landing craft and processing equipment to be carried for effective exploration and resource extraction at destination (ch.4).

(5) Hydrogen tankage taken as weighing 5% of contents (ch.5).

(6) Antiproton storage, cooling and feed system taken as weighing ten times contents (highly speculative) (ch.5).

(7) First stage hydrogen and antimatter tanks discarded during cruise, but first stage engine re-used for second stage burn (ch.3).

The size of the ship is set by the payload mass required, and that in turn by criterion (3) above concerning the number of people carried, the habitable volume assigned per person, and the consequent demand for radiation shielding.

Speed and acceleration

A cruising speed of $0.1c$ is chosen, whence the total propulsive ΔV required is $0.2c$. The initial acceleration will be 0.2 m s^{-2}.

The rationale behind the $0.1c$ cruising speed is that it is the minimum speed that will allow a crossing to a handful of nearby stars within a human lifetime (in future centuries the human lifespan may be extended, but at present it is impossible to predict when or by how much). The Alpha Centauri triple star system is brought within a 50-year journey time; fortuitously, our nearest interstellar neighbour also contains the nearest closely sunlike star. To reach the next nearest sunlike star (whether F, G or K spectral type) requires a voyage of over a century; thus a ship travelling at this speed is close to the notional dividing-line between a fast starship and a slow multi-generation ship.

Assuming that the Solar System civilisation which builds Wayland ships is continuing to experience economic growth and technological progress, which seems certain, then a 0.1*c* cruising speed is probably close to the minimum acceptable for the first manned starships. (Marshall Savage earlier came to the same conclusion, p.316)

A vehicle that took 100 years to make the crossing to Alpha Centauri (at around 0.04*c*) would be vulnerable to being overtaken by one which took only 50 years and was built say 30 years later, using next-generation technologies. The necessary size of the Solar System civilisation at this time, and its widely scattered nature, make the scenario of rival power centres competing for the prestige of the first manned arrival at another star perfectly plausible.

While a 50-year crossing is in principle vulnerable to being overtaken in the same way, the time for a competitor to react is reduced in proportion such that rival starship builders are using essentially the same generation of technology, as were America and the Soviet Union in the 1960s Moon race. This type of competition is independent of the crossing time, and therefore does not influence it.

Pressing this argument to its logical conclusion, the speed of starships seems likely to increase as more distant targets are attempted, particularly if those stars have some special attraction, such as a terrestrial planet with signs of life in its spectrum. On the other hand, as the technologies for interstellar travel mature, so the prospects for ever faster speeds will diminish, unless a revolution in the understanding of physics comes to the starship builders' aid. For the present purpose, imagining the first manned starship is enough of a challenge without speculating as to what might be achieved by later generations, and the cruising speed of 0.1*c* will be sufficient in this study.

Turning now to acceleration, the time taken for a rocket vehicle with mass ratio R, exhaust velocity v_e and initial acceleration a_i to reach its final velocity is:

$$T = \frac{v_e}{a_i} \left(1 - \frac{1}{R} \right)$$

In the present case, $R = 4.9$ for maximum energy efficiency. Although the final velocity is zero, this entails first an acceleration to 0.1*c* and then a matching deceleration. The total ΔV of 0.2*c* therefore requires $v_e = 0.1258c$, whence, for a single-stage vehicle:

$$T = (3.0038 \times 10^7 / a_i) \text{ seconds} = (0.9518 / a_i) \text{ years}$$

A range of possible values is shown in the following table. They span the range of practical possibilities for a voyage made by a first-generation manned starship whose unpowered cruise phase will last from ~43 years (to Alpha Centauri) to ~119 years (to Tau Ceti) or more.

Initial acceleration	*Earth gravities*	*Time of powered flight*	*Final acceleration*
0.01 m s^{-2}	0.001	95.2 years	0.049 m s^{-2}
0.05 m s^{-2}	0.005	19.0 years	0.245 m s^{-2}
0.10 m s^{-2}	0.01	9.5 years	0.49 m s^{-2}
0.20 m s^{-2}	0.02	4.8 years	0.98 m s^{-2}
0.30 m s^{-2}	0.03	3.2 years	1.47 m s^{-2}
0.40 m s^{-2}	0.04	2.4 years	1.96 m s^{-2}
0.50 m s^{-2}	0.05	1.9 years	2.45 m s^{-2}
1.00 m s^{-2}	0.1	0.95 years	4.90 m s^{-2}

These figures demonstrate, unsurprisingly, that low accelerations add very significantly to the total journey time, while high accelerations add little, but in addition they usefully offer specific values for "low" and "high".

While a high acceleration is more desirable, a low one is more physically plausible, given experience to date with high specific impulse but low thrust ion and magnetoplasma thrusters – a recent example is the European Space Agency's Smart-1 lunar probe, whose solar powered Hall effect ion thruster using xenon propellant provided a thrust of only 68 mN, hence an acceleration at its launch mass of 367 kg of 0.0002 m s^{-2}. Smart-1 took over 12 months (Sept. 2003 to Nov. 2004) to reach the Moon, starting from a geostationary transfer orbit – not a good advertisement for low-thrust propulsion, but the "smart" feature of its mission was not the ion engine, but the fact that it piggy-backed on the launch of two commercial communications satellites.

The present study assumes that a combination of extremely high energy and moderately high thrust is technically possible, such that the time spent on acceleration and deceleration is within the range of 5-10% of the total journey time, leading to a working figure for the initial acceleration of 0.2 m s^{-2}, rising to about 1 m s^{-2} by the time of orbital insertion at the target system.

This requires an engine thrust of 0.2 × initial mass, thus 2×10^6 N per 10,000 tonnes mass at Solar System departure.

Pressurised accommodation

The habitable volume of the ship consists of five spherical modules arranged in the form of a cross, with one module on the starship's centreline connected to four outlying ones on supporting arms at 90° intervals. The arms are mounted on a circular turntable which can rotate freely on a frictionless magnetic cushion in order to provide artificial gravity. The central sphere is for zero-gravity use.

All five modules have in common:

- 9 metres internal radius;
- 3054 m^3 internal volume, divided into six decks;
- 300 tonnes basic mass (assuming 10 m^3 per tonne typical of present-day space station modules);
- an additional allowance of 100 tonnes for supporting spin arm and internal fixtures and fittings.

The equations for centrifugal acceleration are:

$$a = \omega^2 r \qquad \text{and} \qquad P = 2\pi / \omega$$

where a = acceleration, r = length of spin arm, ω = rotation rate (radians/second), and P = period of rotation. Spin arms 75 metres long and a rotation rate of twice per minute are chosen to generate one third of Earth normal gravity. It may be assumed that this gravity level will be familiar to many of the starship's occupants.

Two gravity modules are equipped with full carbon-based (polyethylene, cellulose or similar) radiation shielding, weighing 7000 tonnes apiece. These provide the permanent accommodation for crew and passengers during the interstellar voyage. The space allowance is 60 m^3 per person, including private, public, machinery and storage spaces. (100 m^3 per person would be preferable, being the space allowance experienced on the Skylab and Mir stations, but limited access to zero-gravity space will also be offered.)

The other pair of gravity modules are without shielding. They are not used during the voyage, except as storage space. But they are surrounded by a vacant compartment 5 metres deep which is to be filled with locally obtained water shielding after arrival, doubling the gravity accommodation available.

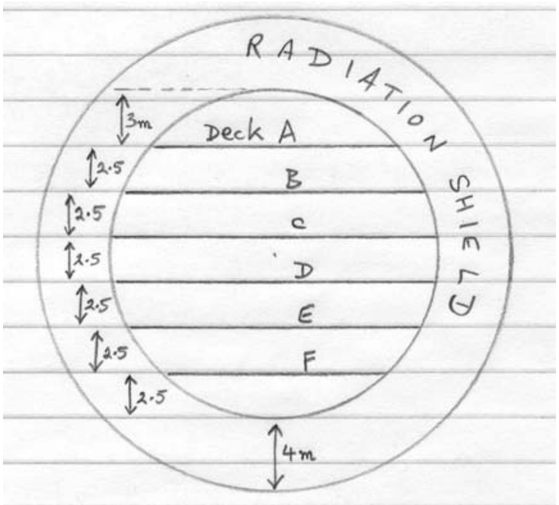
The zero-gravity module is likewise without dedicated shielding. It may be accessed during the voyage for zero-gravity experience, but time spent here is rationed in order to avoid taking a harmful dose of radiation. It is partially protected by the second stage hydrogen propellant tanks, which reduce but do not eliminate the cosmic ray bombardment because they do not completely surround it. Again, this module is fitted with an empty exterior compartment for water shielding to be added after arrival.

Two independent functional habitable modules during the voyage should be regarded as the absolute minimum number for reasons of redundancy, symmetry of the rotating structure, and enabling of social variety.

The zero-gravity module is essential to maintain zero-gravity skills and entertainments, and for access to the wardens, the landing craft, and instruments and equipment mounted externally.

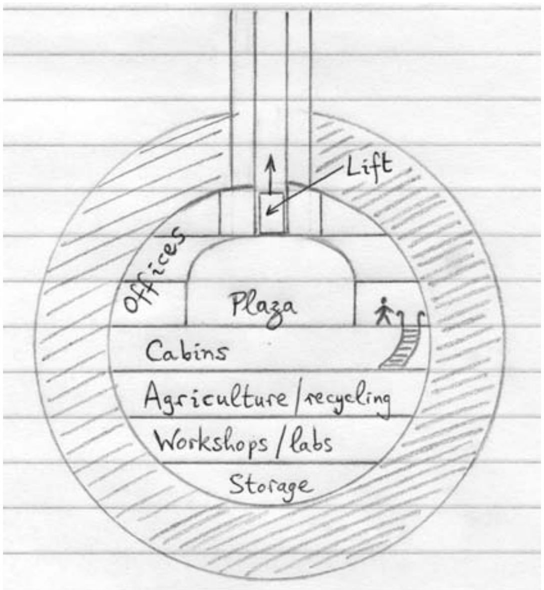
The addition of two gravity modules for use after arrival is not strictly necessary, but it is relatively cheap, it allows the star travellers to look forward to expanding their quarters, it allows their population to grow en route, and the arrangement of four arms on the rotating structure gives it greater stability than with just two.

There is room in each of the pressurised spheres for six decks, 2.5 metres from floor to ceiling, plus additional storage space beneath the lowest deck:



Deck	*Floor area*
A	141 m^2
B	216 m^2
C	251 m^2
D	247 m^2
E	204 m^2
F	122 m^2

If six decks are fitted in their entirety, the total floor area in each sphere is 1181 m^2. With 50 occupants to a sphere, they enjoy over 20 m^2 per person, though this includes machinery, storage and agricultural spaces as well as living and working space. A possible interior arrangement might be as follows.



In this concept of the interior design, deck A has 100 m^2 of office space surrounding a circular concourse, in the centre of which are the lifts for access up the spin arms to the zero-gravity parts of the vehicle.

Decks B and C have between them 310 m^2 of floor space for offices, shops, restaurants and a doctor's surgery, surrounding an open circular plaza 10 metres wide with a 5 metre ceiling height. The perimeter of one of these decks could be kept clear as a 50 metre circular jogging track.

Deck D has 247 m^2 of space for personal cabins arranged in two concentric rings, sufficient for 3 m^2 per person plus 97 m^2 of shared corridors, toilets and bathrooms. There is not sufficient space for en suite facilities in individual cabins. A partition wall may be removed if two single cabins are being combined into one for a married couple, and replaced if a couple are breaking up.

Deck E has 204 m^2 of space for food production in highly efficient algal farms, with waste decomposition and recycling equipment, and the laundry.

Deck F adds 122 m^2 for workshops, laboratories and small-scale manufacturing facilities. This area is supplemented by an underfloor machinery and storage space, which also accommodates the emergency batteries.

Buffers of essential consumables such as water and oxygen may be stored outside the pressure sphere itself, in the 4 metre thick radiation shield.

It would be possible to build transparencies into the radiation shield by installing sections in transparent plastic, glass or water. But it is more likely that exterior views would be captured on camera, after which they could be viewed anywhere on board without the need to go to a window.

At a reasonable electrical allowance of 10 kW per person, the two occupied gravity spheres would require 1 MW of continuous electric power, thus an energy consumption of 3×10^{13} J/year. Assuming that antimatter is used to generate electrical power, this corresponds to the consumption of 0.3 grams of antimatter per year (plus an allowance for the energy conversion inefficiency). In comparison with the energy requirement for propulsion, this is a trivial additional energy demand.

The reader may have noticed that no mention has been made of any kind of control room or ship's bridge. Projecting current developments in fly-by-wire into the future, it seems clear that all human controlling of the vehicle will be carried out in a virtual control room. The ship's commander and officers will have instant access to this online virtual space at all times and wherever they may physically be in the vehicle.

Computer terminals with keyboards and screens will probably no longer be necessary, as developments in mobile phone technology together with improved scientific understanding of how the brain works seem likely to converge to enable wireless networked digital systems to be directly hard-wired into the brain.

Having gained a clearer impression of the accommodation to be installed, it is now possible to consider the vehicle as a whole.

Overall vehicle proportions

The payload amounts to:

5 habitable modules @ 400 tonnes:	2,000 tonnes
2 radiation shields @ 7000 tonnes:	14,000 tonnes
Landing vehicles:	~ 1,000 tonnes
Resource extraction equipment:	~ 1,000 tonnes
Total:	18,000 tonnes

This is six times the payload in the outline design sketched in chapter 3. For consistency with that earlier analysis, the payload should be matched with 12,000 tonnes of engines, support structure and second stage tankage, for a mass on arrival of 30,000 tonnes.

It should be borne in mind that the resulting apparently generous allowance for engine and structural mass needs to include power generation for the engine's magnetic nozzle and for electrical power demand throughout the voyage, with perhaps an auxiliary antimatter supply, or alternatively a nuclear fusion power plant. This mass must also include much of the complex and power-hungry antimatter feed system, and the attitude control system. The main engine thrust needs to be uprated in proportion with the sixfold payload increase in order to maintain reasonable levels of acceleration, and this again increases its mass in proportion.

Given a mass ratio $R = \sqrt{4.9}$ for the deceleration phase for maximum energy efficiency, the propellant masses work out as:

Second stage hydrogen:	36,067.0 tonnes
Second stage hydrogen tanks:	1,803.4 tonnes
Second stage antimatter:	340.8 tonnes
Second stage antimatter tanks:	3,408.3 tonnes
Engine and supporting structure:	~ 6,000.0 tonnes
Design margin:	788.3 tonnes

Whence:

Total mass at second stage ignition:	66,407.8 tonnes
Total mass at second stage burnout:	30,000.0 tonnes

Note that, while the mass ratio here is $\sqrt{4.9} = 2.21$, the antimatter mixture ratio assumes a mass ratio of 4.9. This is correct: optimum energy efficiency depends upon the complete voyage, but the sizing of the propellant quantities for each stage depends only upon that stage.

Jettisoning the first stage tankage before the second stage burn may, however, change the value of overall mass ratio for optimum energy efficiency, but that difference is not expected to be large, and is not calculated here.

The mass ratio for the first stage burn is again $\sqrt{4.9}$, producing the following results for the first stage:

First stage hydrogen:	96,624.0 tonnes
First stage hydrogen tanks:	4,831.2 tonnes
First stage antimatter:	913.1 tonnes
First stage antimatter tanks:	9130.9 tonnes

Whence:

Total mass at first stage ignition:	177,907.0 tonnes
Total mass at first stage burnout:	80,369.9 tonnes

The total antimatter cost is 340.8 + 913.1 = 1253.9 tonnes.

With a total payload of 18,000 tonnes, of which 14,000 tonnes is radiation shielding, 4000/1253.9 = 3.19 tonnes of non-shielding payload are being transported per tonne of antimatter (which is greater than the figure produced in chapter 3, option (2), because here the shielding forms a smaller proportion of the gross payload).

The energy cost is $2 \times 1{,}253{,}900 \times c^2 = 2.26 \times 10^{23}$ joules = 7152 TW year, or about seven centuries of global energy consumption at the early 21st-century rate of 10 TW.

The condition of initial acceleration = 0.2 m s^{-2} arrived at above requires an engine thrust of 35.6×10^6 N, which is about the same as that of the Saturn V moonrocket at liftoff. The propellant flow rate is thrust divided by exhaust velocity, thus 0.94 kg s^{-1}, of which about 931 grams/sec is hydrogen, 9 grams/sec is antimatter.

The tank volumes required (for the present treating antimatter as normal liquid hydrogen with a density of 71 kg m^{-3}; the actual tank volumes required for antimatter will be a multiple of this) are:

First stage hydrogen:	1,361,000 m^3
Second stage hydrogen:	508,000 m^3
First stage antimatter:	12,860 m^3
Second stage antimatter:	4,800 m^3

Overall vehicle design

The Wayland vehicle is constructed around a longitudinal box truss some 400 metres long, with hexagonal cross-section, just wide enough to accommodate the 9 m radius zero-gravity sphere with its 5 m deep water jacket. (See accompanying figures.)

The hydrogen propellant tanks consist of stretched toroids which fit like a sleeve over the longitudinal truss. Additional, smaller, cylindrical tanks are fitted inside the truss, and have a cross-sectional area of 615 m^2. Notably these include the antimatter storage areas, which receive partial cosmic ray protection from the surrounding tanks. But as those tanks are drained in the course of running the engine, the antimatter may need active cooling to dissipate the heat of cosmic ray impacts, as discussed in chapter 6.

The volume allocated to antimatter storage is about four times the volume required by the same mass of liquid hydrogen; if this turns out to be insufficient the truss and main tanks could be stretched further to increase the volume available.

There is space within the vertices of the hexagonal truss for up to six propellant, antimatter and general cabling ducts around 1 metre wide to pass alongside large modules and tanks fitted snugly within the truss.

About halfway along the truss are mounted two turntables. One of these carries the four gravity modules, as described above. The other carries a secondary rotating ring with a pressurised compartment and docking hatches.

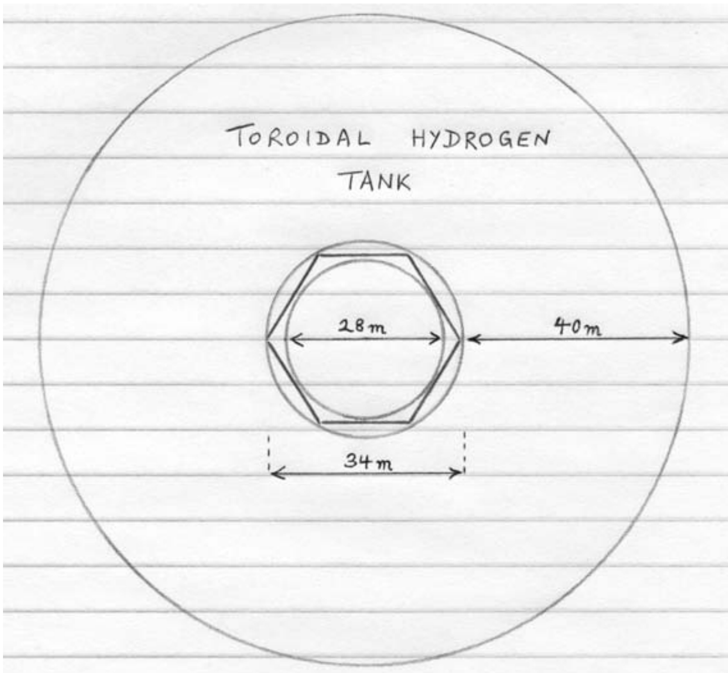
Access between the gravity modules and the pressurised central aisle of the vehicle is achieved via a lift compartment which runs up and down inside each of the spin arms. At its outer limit of travel, a hatch in the side of the lift docks with a matching one in the gravity sphere, allowing some of the occupants of that sphere to board the lift. At its inner limit of travel, the same hatch docks with a matching one in the secondary ring while it is rotating at the same rate as the main turntable. Individuals may then transfer between the lift and the pressurised compartment in the secondary ring. Closing the hatch and undocking from the lift, the secondary ring is then despun and docks with a different hatch to a compartment rigidly attached to the structural core of the vehicle. Personnel may then pass through this hatch and into the central aisle.

Once in the non-rotating part of the vehicle, the star travellers enjoy pressurised access through the central aisle to their exploration/transport vehicles, to the zero-gravity sphere, and to spacesuit rooms and airlocks giving access to the exterior of the vehicle, if this is required. Normally, external maintenance is carried out by remotely operated “wardens” (a term originated in the Daedalus study), which are small free-flying robotic inspection and repair vehicles, but it is by no means excluded that direct personal intervention by an astronaut may be required in the case of a problem with external equipment, and the skills and accessories for working outside the vehicle in a spacesuit need in any case to be maintained. This will not, however, be a frequent pastime due to the high radiation environment outside the ship.

The first stage tanks are all located at the front of the vehicle, requiring about 200 metres of hydrogen and antimatter ducts in order to communicate with the engine at the rear. This layout follows from the assumptions that maximum economy is achieved when the first stage tankage is jettisoned when empty, but the same engine is used for both first and second stage propulsion. The drained first stage tankage is however left in place for the duration of the cruise, and a dust shield mounted on the front protects the rest of the vehicle from impacts with grains of interstellar dust.

When it is time to begin the deceleration phase, the unwanted tankage is detached and allowed to drift ahead of the rest of the vehicle. The slimmed-down vehicle is rotated through 180° so that the main engine now points in the direction of travel, and the second stage burn begun. This time no dust shield is necessary as protection is provided by the exhaust plume, which vaporises any dust particles encountered in the line of travel.

On arrival, when the ship is lightest, the engine thrust which gave only 0.2 m s^{-2} at the start of the first stage burn now produces 1.2 m s^{-2} of acceleration, and this higher level, while still mild, is more appropriate for manoeuvering into orbit around a planet, or from one planet to another. The vehicle with its second stage tankage intact may be partially refuelled using local resources and enjoy an afterlife as an interplanetary transport, though it will be many years before it becomes possible to replenish all but the tiniest fraction of its antimatter supply. In this mode of operation, however, its engine would probably be run at a much lower antimatter mixture ratio.



Cross-section through toroidal hydrogen tanks. The first and second stage tanks are the same width. Within the hexagonal box truss is room for a spherical pressurised accommodation module, additional cylindrical hydrogen tankage or the antimatter storage space, having a maximum diameter of 28 metres.

Auxiliary landing vehicles

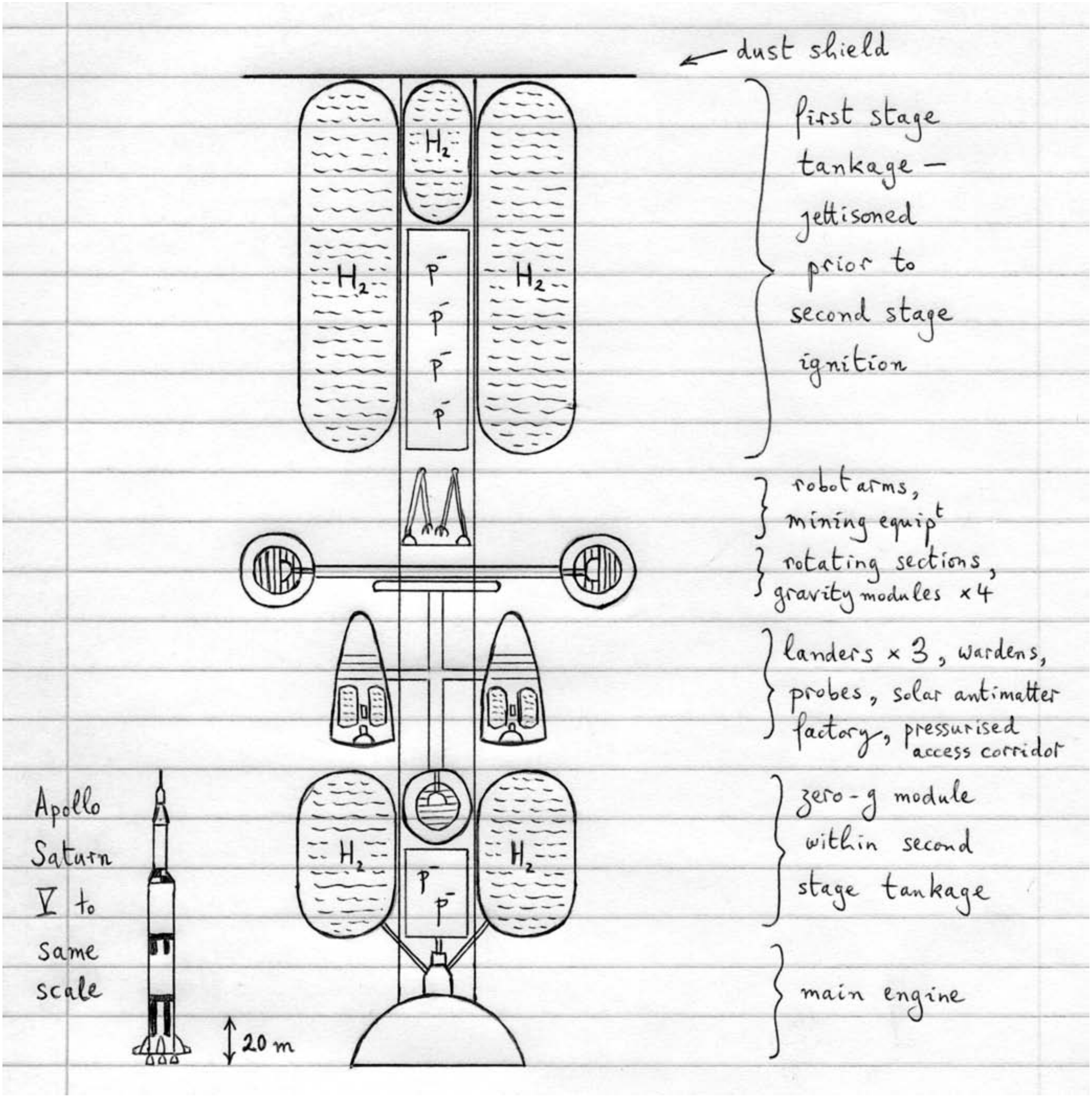
Three manned landing vehicles for local exploration and transport are carried. The design chosen is a broad-based conical airframe for aerobraking in a planetary atmosphere, similar in outline to the DC-X test vehicle of the late 1990s. They remain in an upright position for landing, after extending footpads. They are not designed for level aerodynamic flight, but for direct transport between orbit and the surface of a planet, which may or may not have an appreciable atmosphere.

The landers are roughly twice the size of the Space Shuttle orbiter: 150 tonnes mass (unfuelled), length 50 metres, width 25 metres at the base. Their propulsion uses a less powerful version of the hydrogen-antimatter magnetoplasma rocket. As already noted in chapter 4, such engines are likely to be in widespread use in the Solar System before the more powerful starship prime mover is developed. Landers such as these are therefore likely to be well established vehicles and will not add to development costs for the first interstellar flights.

The landers carry 50 tonnes of hydrogen propellant in two cylindrical tanks of 352 m^3 each (length 12 m, radius 3.4 m). The mass ratio is 200/150 = 1.33. For a total ΔV of 100 km/s before needing to refuel, the exhaust velocity needs to be 350 km/s. The antimatter mixture ratio equation (equation (v) of ch.5) gives $\alpha = 8.0 \times 10^{-7}$, and the 50 tonnes of hydrogen therefore need to be energised with 40 grams of antimatter.

A maximum thrust of 400 tonnes, i.e. 4×10^6 N, would allow takeoffs from planets whose surface gravity was a little greater than Earth's, and would require a maximum propellant flow of 11.5 kg/s of hydrogen together with 9.2 mg/s of antimatter. Normally a lower thrust level would be used.

This concept is based on one described in Aldrin and Barnes (p.222, 300, 350-351). Although a work of science fiction, many of the concepts in this novel appear to be workable (others, such as the zero-point energy laser which generates energy in defiance of the law of conservation of energy, are clearly not).



Plan of the complete Wayland starship. Length overall is 400 metres.
Maximum width over the dust shield and the gravity turntable is 160 metres.
An Apollo-Saturn V moonrocket, with the same maximum engine thrust,
is shown to scale for comparison.

Antimatter production facility

A critical task on arrival will be to set up a local source of power for prolonged exploration and construction. This will naturally take the form of a solar powered antimatter factory, a miniature version of those in the inner Solar System which power the home civilisation (described in more detail in ch.10).

A reasonable early level of production might be 100 grams of antimatter per year, thus allowing two landers to be refuelled (40 g each) plus 20 g for power production for industrial processing and general maintenance of life aboard the starship. The latter quantity provides 3.6×10^{15} J of energy per year, thus a power level of 114 MW.

The total energy input required to manufacture 100 g of antimatter (under the assumption of 1% efficiency adopted in ch.10) is 0.2 (kg matter and antimatter) × 9 × 10^{16} (speed of light squared) × 50 (efficiency of matter production = efficiency of antimatter production = 1%) = 9×10^{17} J = 28.5 GW years.

At a solar irradiance of 9.0 kW/m^{-2} (typical of the value used in the Solar System at the orbit of Mercury), a solar array with an area of 3.2 km^2 is required to gather the energy, thus for example a square array would be 1.78 km on a side. With a mass of 10 kg/kW of output power (energy being output from the array at an efficiency of 25%), the total mass of the array would be about 71,000 tonnes. This is significantly greater than the 1,000 tonnes allowed above for the total of resource extraction and processing equipment to be carried.

In comparison, the antimatter production and storage unit should be fairly light, being a small version of units which have been in use in the Solar System for many centuries. The strategy must clearly be to manufacture the solar array after arrival, using local resources. This should be done at the same time as water for additional radiation shielding is being loaded.

Then, while the main vehicle is conducting initial close-up exploration of the inner planetary system, the antimatter production unit can be manoeuvering itself into a close heliocentric orbit and commencing energy gathering. Together with the array and the factory, one or more small ferry vehicles will be needed to convey the antimatter out to where the starship is based; alternatively, and more economically, one of the landers may be employed in this role at occasional intervals.

9. *Interstellar trajectories and precursors*

Trajectories

A starship using onboard rocket propulsion has a three-phase journey: acceleration to cruising speed, unpowered cruise at virtually constant speed, and deceleration at the destination star.

Assuming constant engine thrust, the trajectory of an accelerating or decelerating rocket vehicle depends upon three variables:

- the exhaust velocity v_e,
- the initial acceleration a_i (equal to the engine thrust divided by the vehicle mass at ignition),
- and the mass ratio R (the initial mass of the vehicle divided by its final mass at the end of the propulsive engine burn).

The mass ratio and exhaust velocity are related to the final velocity by the classical rocket equation $\Delta V = v_e \ln R$. Although a relativistic correction must be applied when speeds close to the speed of light are involved, that correction is only small at 10% of that speed, and the present analysis ignores relativistic effects.

The equations for the time taken T for a powered phase of flight using rocket propulsion, and for the distance travelled S during that phase, may easily be derived, and are as follows:

$$T = \frac{v_e}{a_i} \left(1 - \frac{1}{R} \right)$$

$$S = \frac{v_e^2}{a_i} \left(1 - \frac{1}{R} - \frac{\ln R}{R} \right)$$

For the Wayland Mk I a cruising speed of $0.1c$ has been assumed, together with an exhaust velocity of $0.1258c$ for maximum energy efficiency and an initial acceleration of 0.2 m s^{-2}. The mass ratio for the acceleration phase is 2.214.

After the first stage tankage has been jettisoned, the initial acceleration for the second stage is 0.5361 m s^{-2} and the second stage mass ratio is again 2.214.

Regardless of the destination, the distances travelled and times spent in powered flight, first accelerating and then decelerating, are therefore:

	Distance travelled	*Time taken*
First stage (acceleration):	0.142 light-years	3.279 years
Second stage (deceleration):	0.053 light-years	1.223 years
Total under power:	0.195 light-years	4.502 years

The total duration of a one-way interstellar voyage to a star which lies D light-years from the Sun is then $10\,D + 2.55$ years. All but 4.5 years of this trip time is spent in unpowered cruise. The trip times to a number of nearby stars are as follows:

Destination	*Distance travelled*	*Voyage duration*
Proxima Centauri	4.242 light-years	44.97 years
Alpha Centauri A-B	4.365 light-years	46.20 years
Barnard's Star	5.963 light-years	62.18 years
Sirius A-B	8.583 light-years	88.38 years
Epsilon Eridani	10.522 light-years	107.77 years
Procyon A-B	11.402 light-years	116.57 years
61 Cygni A-B	11.403 light-years	116.58 years
Epsilon Indi	11.824 light-years	120.79 years
Tau Ceti	11.887 light-years	121.42 years

In general, the following stars are within range of Wayland:

Within 50 years flight time:

Alpha Centauri A-B-C (sunlike G star, cooler K star, red dwarf).

Within 50-100 years:

The next six closest systems, containing:

- six red dwarfs
- Sirius A-B (hot A star and white dwarf).

Within 100-125 years:

The next eleven closest systems, containing:

- eleven red dwarfs
- four K stars (Epsilon Eridani, 61 Cygni A-B, Epsilon Indi)
- one G star (Tau Ceti – the second closest sunlike G star)
- Procyon A-B (hot F star and white dwarf).

Precursors

In chapter 2, it was argued that future star travellers will not be dependent upon finding earthlike planets at their destination. To them, life on Earth will be like outdoor life in north-east Africa may seem to us today: a fascinating study in the origin of the species, but never a lifestyle that the more sophisticated branches of that species would want to emulate, except in the form of a brief research expedition or camping holiday.

The human exodus from Africa and colonisation of the rest of the planet has already taken us a long way from our origins. Most of us now live in cities, surrounded on all sides by the products of human engineering. We live in artificial buildings, surrounded by manufactured furniture, computers, books and televisions, and eat and drink the mass-produced products of industrial agriculture, brought to us by global packaging and distribution. We enjoy heating in the winter and air conditioning in the summer, and most of our transport is undertaken in engine-driven metal vehicles. Much of our lives is lived in the glare or the soft glow of artificial lighting.

Life in a space colony will merely complete the transition from the hunter-gatherer-scavenger-beachcomber lifestyle of the earliest members of our species to the newly emerging techno-lifestyle. We are already most of the way through this transition. In many ways, the space colony will be scarcely distinguishable from the modern city. A shopping mall on Earth, an industrial park, a doctor's surgery, a housing estate, a bedroom – these may seem superficially identical to their counterparts a billion kilometres away on the other side of the Solar System. People's working lives will require the same technical qualifications, the food will taste very similar, the pubs will be designed for comfortable nostalgia, and the media will be rerunning the same films, game shows and news clips ad nauseam.

If, therefore, we find an Earth analogue in orbit around another star, we will certainly want to visit its surface and explore its history and its biosphere. But our homes will remain in orbit, where we have material resources, mobility, solar power and room to expand, and are free from the vicissitudes of planetary weather.

The likelihood that closely earthlike planets may be exceedingly rare is therefore not in the least a problem. A starship which fails to find one at its destination will not regard its mission as a failure. Its mission will rather be to create earthlike habitats in space using the local asteroidal resources.

But it seems unlikely that sufficiently detailed information about bodies in the 100 km to 100 metre size range can be obtained remotely, from telescopes in the Solar System or in another nearby planetary system. This leads us to presume that each Wayland departure will be preceded by a robotic precursor mission in order to make a detailed survey of local resources and establish that sufficient material of all the main types – icy volatiles, stony silicates and metals – is available, and where it is located.

In order to get a robotic probe out to an interstellar target in a reasonable period of time, a high speed no less than that of Wayland itself is required, and hence a high exhaust velocity if rocket propulsion is used. But given that the main difference between an interplanetary vehicle and a starship is the extremely high exhaust velocity of the latter, and hence the development of an engine with a very much higher antimatter mixture ratio, it is an interesting question whether a robotic probe can act as an intermediate developmental step for the Wayland propulsion system.

Unfortunately there is very little room for manoeuvre. At maximum energy efficiency, the mass ratio $R = 4.9$ and the velocity ratio $\Delta V / v_e = 1.59$. Suppose that for a given mission ΔV the exhaust velocity were lowered by a factor of ten: the mass ratio would have to increase to an impossible 8,000,000. Even just halving the exhaust velocity makes the mass ratio shoot up to an only marginally practical 24.

Could nature help to reduce the propulsion burden on an early probe? Proxima Centauri, at 4.242 light-years = 40.16×10^{12} km, is the nearest known destination beyond our Solar System, but might others be discovered? Faint brown dwarfs and rogue planets are believed to wander the depths of interstellar space, and it is perfectly possible that one or more of them may be discovered, using infra-red space telescopes such as ESA's Herschel and NASA's Webb, at only a fraction of the distance of Proxima. If a brown dwarf were to be located just 0.1 light-years = 10^{12} km away, a vehicle capable of just one tenth the speed of Wayland could fly to it in a decade. But the energy output of a brown dwarf or rogue planet would be so small as to render it unattractive as a target for permanent human settlement.

What velocities might be in use in the Solar System when Wayland is under development? In the next chapter a fast interplanetary passenger liner is described, with a cruising speed of around 250 km/s, equivalent to one AU per week. The difference between such a vehicle's interplanetary round trip velocity of 1000 km/s and the one-way interstellar velocity of 60,000 km/s (0.1c acceleration followed by 0.1c deceleration) is a factor of about 60, which applies equally to the exhaust velocity required at any given mass ratio. Unless trip times for the earliest probes of several centuries become acceptable – which seems unlikely in view of the arguments presented in the previous chapter – this 60-fold increase in velocity, hence 3600-fold increase in energy consumption, must be mastered in a single technological leap. This is a consequence of brute astronomical reality: the stars are separated by distances five orders of magnitude greater than are the planets in the Solar System.

Is it possible to bridge the velocity abyss with even faster transport within the Solar System? Among the inner planets, certainly, one AU per week is extravagantly fast, and it seems unlikely that the demand will arise for anything faster, particularly when remembering that each doubling of speed raises the energy cost fourfold.

From the region of Earth out to Neptune, however, a distance of 30 AU, would take 7 or 8 months on such a fast interplanetary ship, and destinations in the Kuiper belt might take a year or more. This is not to say that a means of more rapid transport over a distance of 30 to 100 AU will ever be put into service. But in the event of large-scale colonisation of the Kuiper belt it remains possible that a market for a super-fast interplanetary vehicle will arise, and that the inhabitants of Earth and the Kuiper belt will be wealthy enough to bear the 64-fold increase in energy cost of a vehicle which travels say eight times faster, thus an interplanetary cruising speed of 2000 km/s, or 1.2 AU per day, and a total mission ΔV from one refuelling in the inner Solar System to the next of 8000 km/s. Such a vessel would cover the trip from Earth out to Neptune and the inner edge of the Kuiper belt in a month or so, provided that its engine thrust was sufficient to drive it up to cruising speed in a few days (2.4 days at one gravity acceleration, 4.7 days at half a gravity).

If this super-fast interplanetary transport became available, flying at speeds eight times faster than the regular passenger liner for use out as far as Saturn, it would nicely bridge the technological gulf between interplanetary and interstellar flight, as another eightfold increase in speed, and hence of exhaust velocity, would bring it up to the performance level required for Wayland.

But this speculation is dependent on how easy or difficult antimatter engines prove to be to uprate in practice, as well as on the wealth distribution in a cosmopolitan civilisation a million times more populous than the primitive global village society of today (see next chapter). It might equally be the case that the super-fast transport is first made possible as a spinoff from the starship programme, which has to bear all the development costs for an engine capable of going beyond a mission ΔV of 1000 km/s.

A precursor robotic probe cannot, therefore, offer much help in bridging the performance gap between interplanetary and interstellar propulsion. This must be achieved within the Solar System (perhaps with the help of any yet to be discovered nearby brown dwarfs). But the probe certainly does offer a halfway house in terms of energy consumption, and perhaps two halfway houses.

Any probe and any manned vehicle have two fundamental differences: the probe is lighter, no more than tens of tonnes rather than the tens of thousands of tonnes envisaged for Wayland, and the probe can endure much greater accelerations.

Taking the first of these differences, a precursor probe in the region of 30 tonnes mass on arrival but based on Wayland's antimatter propulsion technology is perfectly conceivable. While its electronics and sensors will be miniaturised further compared with present-day planetary probes, the nature of its mission imposes substantial energy requirements for transport around the target system and radio or laser transmission of data back to the Solar System.

Dividing all the structural and propellant quantities of Wayland by 1000 gives an antimatter budget of 1.25 tonnes per probe, corresponding to an energy consumption of 7.15 TW years. This is equivalent to three voyages of the fast interplanetary liner described in the next chapter, and is therefore eminently affordable.

Even before extremely high energy antimatter engines are available, small probes may be sent. In 1985 Robert Forward proposed an interstellar probe called Starwisp, supposed to weigh a total of only 20 grams (*Starflight Handbook*, p.81-83). A structural mass of 16 grams was allowed for a cobweb-like mesh of fine wires forming a disk one kilometre across, and the remaining 4 grams allocated to a payload of microcircuitry. This would be accelerated at up to 115 gravities by the relatively modest power in the microwave beam of a 10 GW power satellite, and would reach 0.2*c* in a few days.

Probes such as this, taking full advantage of miniaturisation and also of their tolerance of high accelerations, may give us our first close-up look at another planetary system, though possibly with limited capabilities. The principal purpose of such a probe will be to gather data about the asteroidal matter in a system – tiny bodies which are impossible to detect individually or categorise spectroscopically from a multi-light-year distance away. For this task, a telescope with a few inches of aperture would normally be indispensable, putting the payload up into the range of kilograms rather than grams, unless some sort of interferometer can be engineered into the microcircuitry. A sizeable solar array will also be needed to give the probe both electric power and mobility, whether by light-sailing or solar-electric ion propulsion.

It is conceivable that the same gossamer film of fine wires might serve as a sail for acceleration on a microwave or laser beam, a solar sail for use after arrival, a solar array for electric power, a telescope for surveying the target system and an antenna for relaying its findings back to the Solar System. Such a probe might have a mass of only a few kilograms. But a question remains as to how they would be decelerated. Given the purpose of their mission, an active lifetime in orbit at their target star of some years will be required.

Later probes, which have the equally important purpose of validating the main propulsion system for the manned Waylands to follow, are likely to be much heavier if there are limitations on scaling down the engine size.

The development roadmap might therefore be as follows:

(1) A fleet of fast (250 km/s cruising speed) passenger liners gradually develops to serve a broad commercial market within the Solar System.

(2) A series of kilogram-sized probes driven by beamed energy afford a first close-up look at nearby stars. By confirming that orbiting asteroidal matter is indeed present, they justify the considerable investments in engine technology to follow.

(3) The liner technology, when mature, is used for a series of large robotic interstellar probes. The cost is dominated by uprating the engine technology (exhaust velocity increased by factor of 60, antimatter mixture ratio increased by factor of 3600).

(4) Once the first probes have returned results and demonstrated the reliability of the uprated engines, manned starships may be built from an adapted liner design with engines enlarged from the probe engine design. The cost is dominated by the antimatter fuel.

(5) Meanwhile a super-fast (2000 km/s cruising speed) interplanetary liner may appear as a spinoff from the interstellar technology, if there is a market for it.

Known extrasolar planets

Among the stars listed above as being within 125 years flight time for Wayland, only one extrasolar planet has so far been identified, orbiting Epsilon Eridani, 10.5 light-years away. It was discovered in 2000.

The age of the star is estimated to be less than 1 billion years. It is a singleton star of K2 spectral type with a luminosity 0.28 that of the Sun. An earthlike orbital environment may therefore be found at around 0.53 AU from the star, though with more infra-red radiation and less ultra-violet than Earth receives.

The mass of the planet is still uncertain, but is somewhat greater than that of Jupiter. The exoplanets.org website gives its distance as 3.42 AU from the star, but its eccentricity as 0.3 ± 0.23, in other words still highly uncertain. Two debris belts have also been detected, one close to 3 AU distance and the other at 20 AU and beyond, corresponding roughly to our main belt and Kuiper belt. If the inner belt is confirmed, then the giant planet's eccentricity must be low, and the system could turn out to be a fair Solar System analogue.

10. *The home front*

The first departure of a manned starship will not resemble the first manned missions to the Moon or Mars.

In the early 21st century, the predominant cultural and political view of space is broadly similar to that of the Middle Ages: space is an unearthly domain which operates on different principles to those of the sublunary sphere. Earth is contaminated by sin, but the heavens are the perfect work of God, still uncorrupted by human greed or pollution.

While the heavens may now be visited, space travellers must first undergo a ritual purification consisting of many years of training. They must purge themselves of base human desires such as the profit motive, and dedicate themselves to the noble pursuit of pure scientific learning. Only then may they be allowed to join the exalted ranks of the elite and mystical knighthood of scientific monks and nuns – the *astronauts*.

Or, in more populist terms: humanity is evilly destroying the Earth through overpopulation, capitalism and technology, and it would be morally wrong for us to travel out into space in order to destroy other planets as well.

It will be clear from what has been said earlier that this popular view of man's place in the universe is incompatible with the starship enterprise. Without large-scale capitalist growth at numerous locations around the Solar System, without permanent and expanding extraterrestrial populations to drive economic and technological growth in space, the resources to build and fuel a vehicle such as Wayland, or even its unmanned precursors such as Daedalus and Icarus, will be unavailable.

The Space Age will not really have arrived until the "astronaut" is an obsolete idea, as outdated as is for us today the concept of an "aeronaut". The aura of specialness, almost of holiness, of having reached up to the sky and touched heaven, surrounding an astronaut – or cosmonaut, or spacionaut, or taikonaut/yuhangyuan, or angkasawan – must vanish, and its place must be taken by a sense of a commonplace activity enjoyed by millions of people. Space must cease to be an arena primarily of national prestige, science and spinoff, and must become primarily a marketplace for personal space exploration ("space tourism"), zero-gravity manufacturing and solar power collection. The motto "take only photos, leave only footprints", with its fine moral sense of leaving the heavens alone, must give way to the motto "get bums onto seats", applied to tickets on any one of dozens of competing spacelines taking visitors to space hotels in orbit and on the Moon.

Whereas today space travel and walking on other worlds is an activity set aside for an anointed elite, the best of the best, the exemplars of physical, moral and academic perfection, the chosen ones who have emerged from an arduous and exacting selection process, in the future it must be opened up to entrepreneurs and financiers, holidaymakers and honeymooners, miners and bulldozer drivers, the overweight and the undereducated, artists, poets, crooks, socialites, the famous, the obscure, and those simply doing their job. Space must, in other words, become the arena of people who are more broadly representative of our species. While the best of the best may still lead, without the most mediocre of the most mediocre to follow in their footsteps the whole enterprise will grind to a juddering halt long before we are in any position to reach for the stars.

Assuming, however, that that position is one day reached, public attitudes to starflight will clearly differ from those of the present-day to interplanetary flight.

It seems most implausible that an analogous quasi-mystical division between our planetary system and extrasolar ones could arise. Many more extrasolar planets will be known of, and in some detail, than are known today. They will be regarded as our planets will be: as natural wonders, certainly, but also as resources and as opportunities. Scientific interest will be keen, but it will be balanced by the practical sense that humanity is an active participant in the evolution of planetary systems, not merely a passive observer. Our interventions will be regarded as a force for praiseworthy creativity, not one of lamentable destruction of pristine purity.

This has to be the case because the future projected here assumes large-scale colonisation of space and of the smaller worlds in our system. Large numbers of people will be living in a completely artificial environment. They will owe their existence to machines that tend to their needs every minute of their lives. The very atoms in their bodies will have been mined, in large part, from extraterrestrial sources. Starflight for them will still be a leap into the unknown. But they will already be there in spirit. Life on a starship and in a new planetary system will be fundamentally similar to their own lives. The personal space allowance during the voyage and in the first years after arrival will be more cramped than the conditions that most people are used to. But the starship could well be closely modelled on a fast interplanetary vehicle which millions of people have experience of.

The first manned voyage to the stars (presumably the Alpha Centauri system) will be much more like a long-range interplanetary cruise than the first Mars flight will be like a cruise in an intercontinental jet airliner.

Energy costs in a Solar System context

When Apollo flew to the Moon, the energy consumption of each Apollo-Saturn vehicle was about 10^{13} J, roughly one ten-millionth of a year's industrial energy budget worldwide. Yet this greatly understates the costs and economic impacts of the programme. The propellants – kerosene, hydrogen, oxygen, hydrazine and dinitrogen tetroxide – were cheap. The real costs were in hardware development, testing and construction, because nothing like an Apollo-Saturn had ever flown before.

But if and when a Wayland flies, it will have a much more extensive heritage in interplanetary vehicles and space colonies. Technologies for closed cycle life support fully independent of Earth will be long mature. Vehicle control, navigation, communications, artificial gravity, radiation protection, power, thermal control, propellant acquisition, planetary landing craft – all will be standard practice with off-the-shelf equipment. So much is guaranteed by the prior existence of a Solar System economy with large, permanent extraterrestrial populations, as argued in chapter 1.

The one major difference between even a very fast interplanetary vehicle and a starship is the immense propulsive demand of the latter. It will need a ΔV capability perhaps 50 to 100 times greater, with a corresponding energy cost 2500 to 10,000 times greater than that of the interplanetary cruiser.

The major unanswerable question at this point is therefore how easily an engine sized for fast interplanetary transport scales up to an interstellar capability. This question would seem to govern the main development cost of a Wayland starship.

The Saturn liner

An exhaust velocity of $v_e = 600$ km/s satisfies the energy efficiency criterion for a total ΔV of 900 to 1000 km/s. This might represent a two-way trip between the inner Solar System (Earth/Moon or Mars) to Saturn and back, with a v_∞ of 200 to 250 km/s at each planetary departure and arrival.

A speed of 250 km/s is equal to one astronomical unit per week. At such high hyperbolic velocities, conventional orbital mechanics makes only minor corrections to trajectories which closely approximate straight lines traversed at constant speed. The journey to Jupiter on such a vehicle would then take around 5 weeks, and to Saturn, 10 weeks.

Having a number of Saturn liners in service is necessary to ensure that if one suffered from engine failure while in transit, another one would be available to chase after it and rescue its passengers. Unless the stricken vessel could be repaired or towed back to safety, it would leave the Solar System for ever, though at a speed of only about $0.001c$ it would make a very poor starship.

Tourism is a plausible motivation for substantial numbers of visitors to Saturn in particular. Space hotels could be constructed in orbit, some actually in the rings using ring material, others in highly inclined, highly elliptical orbits that give the best views of the planet, its ring system and satellites. If this seems over-ambitious, one should ask what Columbus or Vasco da Gama would have made of a modern ocean cruise liner like the enormous *Queen Mary II*. A prosperous, highly automated interplanetary civilisation some centuries ahead may be able to afford recreations which to us today, accustomed to our primitive global village life, seem absurdly extravagant.

The antimatter mixture ratio equation for v_e = 600 km/s gives $\alpha = 2.4 \times 10^{-6}$. A Saturn liner might be constructed along the same lines as Wayland, with the addition of 14,000 tonnes of radiation shielding for its third and fourth gravity modules, and the removal of its landers, exploration probes and mining equipment, for a total payload of 30,000 tonnes. The overall vehicle proportions are then:

Overall payload:	30,000 tonnes
Engine and supporting structure:	~ 6,000 tonnes
Hydrogen propellant:	175,500 tonnes
Hydrogen and antimatter tanks:	~ 9,000 tonnes

Whence:

Total mass at first ignition:	220,500 tonnes
Total mass at final burnout:	45,000 tonnes

Unlike Wayland, none of the tankage is jettisoned, since the vehicle is fully reusable.

The quantity of antimatter required is 421 kg – very little in comparison with the starship. The energy expenditure per round trip is then 7.6×10^{19} J = 2.4 TW years.

With 200 passengers, each passenger needs to pay for the consumption of 12 GW years of energy as well as nearly 900 tonnes of liquid hydrogen. At 5 pence per kW hour the energy cost would be about £5 billion per passenger (hydrogen and other costs are small in comparison). In order for the Saturn liner to be possible, levels of real personal wealth will therefore need to see an increase of at least a factor of 10,000 over present-day levels. Large-scale Solar System development continued over a period of several centuries would make this not an unreasonable prospect.

One Wayland Mk I interstellar voyage (7152 TW years) is equivalent in energy cost to about 3000 round trips of the Saturn liner. A Solar System fleet of 1000 to 1500 interplanetary passenger ships may make that number of trips in a year, conveying half a million or so passengers.

This should be regarded as the minimum precursor activity before the starship becomes a reasonable possibility, in order to ensure that the relevant technologies are fully mature, and to limit the energy cost to a supportable fraction of existing economic activity – for example, if each Wayland is fuelled with antimatter over a ten-year period, the increase in annual production to meet the extra demand will only need to be 10%.

As noted above, the only technology which cannot be developed beforehand by general economic activity within the Solar System is the extremely high energy starship engine, which requires an antimatter mixture ratio of about one part per hundred rather than a few parts per million. This therefore will be the major development burden in uprating a Saturn liner for interstellar operations.

The asteroid tug

Another plausible example of a large-scale space transport economy is the use of a fleet of asteroid tugs.

One of our species' characteristic activities on Earth is the transport of cargo around the globe. Raw materials are shipped from their points of extraction to refineries and factories; manufactured products are trucked by road or rail to wholesalers and retailers. Whole industries revolve around logistics, distribution and delivery.

The Solar System contains the material and energy resources to support vast populations (as already noted in chapter 1), but one reason, perhaps the most fundamental one, why planet Earth is so far the only abode of a biosphere of complex, multicellular life is that these resources are distributed haphazardly, and only on Earth have rocks, metals, ices, energy and gravity come together in the right proportions for life to evolve. The Moon, for example, enjoys the same flux of sunlight as we do, and has a similar rocky crust, but its virtually total lack of water and other volatiles kept it completely lifeless until visitors from another world arrived. There is of course no shortage of water but it is not in the right place: the nearest water in any quantity is on Earth, while huge unclaimed reserves are available in the mid to outer Solar System.

A major focus of future human space activity is therefore likely to be on transporting bulk materials from where they were left by the chaotic processes of planet formation to where they are now needed for the growth of human populations.

The Moon needs large-scale import of ices (water, methane, ammonia and carbon dioxide) if it is to support an expanding biosphere, and its closeness to Earth, the metropolis of the Solar System, suggests that the necessary finance will be forthcoming. Resources could be shipped in from the asteroid belt. But the main belt will need those raw materials for its own development, and meanwhile the proportion of an asteroid which consists of volatiles is greater the further out one goes from the Sun. Lunar development will require ices with as little rocky content as possible. Here we consider transport of asteroids consisting mostly of ices from the Kuiper belt beyond Neptune into the inner Solar System for delivery to the Moon. ("Kuiper" is generally pronounced by English speakers as "Koyper".)

In this concept an antimatter-powered tug fuels in the inner Solar System and flies out to the Kuiper belt, some 30 to 50 AU from the Sun. It captures an icy asteroid and deploys miners which scoop up some of the material of that asteroid for use as reaction mass. The tug first fires its engine at a tangent to cancel the asteroid's rotation, and then drops it into an orbit which reaches in as far as Jupiter. The giant planet's gravity is used to capture the asteroid into a short-period comet orbit, as happens from time to time naturally. Further engine burns, perhaps with additional gravity assists from the inner planets, manoeuvre the asteroid into a near-Earth orbit.

At this point, two options are possible. James Oberg has proposed that such an asteroid or a stolen moon of Saturn may be sent on a "reverse Jupiter swingby" into a retrograde orbit in which it smashes head-on into the Moon, both contributing volatiles and helping to spin the Moon up into an earthlike rotation period (*New Earths*, p.222-233, diagram on p.112). Oberg assures his readers that all the material thrown up by the collision will remain on the Moon and that none of the debris will be flung free to cause damage on Earth, though the Moon itself may have to be evacuated "over a period of several years" (p.226-228).

I find this scenario implausible. The latent heats of fusion and vaporisation for 1 kg of ice amount to 334 + 2270 = 2604 kJ; the energy required to raise its temperature from say –100 °C to zero and from zero to +100 °C is about 211 + 420 = 631 kJ; the total energy required to heat up 1 kg of ice from –100 °C until it is completely vaporised is therefore 3.2×10^6 J. The kinetic energy of 1 kg at lunar escape velocity of 2.38 km/s is 2.8×10^6 J; its kinetic energy at the 60 km/s or so of a head-on smash is 1.8×10^9 J. At even the gentlest possible collision speed from deep space, therefore, much of the ice will be vaporised, but the speed of a head-on collision produces more than 500 times the energy needed to vaporise all the incoming ice completely. The specific heat capacity of steam is about 2 kJ kg^{-1} K^{-1}, thus each further 2×10^6 J that goes into heating the steam raises its temperature by 1000 K.

These facts, combined with the glancing collision geometry necessary to alter the Moon's rate of spin, will ensure that much if not most of the collision debris – steam at thousands of degrees mixed with fragmented rocks and dust excavated from the lunar surface – is blasted back into space at more than lunar escape velocity, with the net results of eroding the Moon rather than adding to it, and creating a space debris hazard for all transport vehicles and infrastructure in cislunar space for millennia to come.

It may also be noted that spinning the Moon up from its present sluggish rotation rate until it matches Earth's day-night cycle would require the accumulated tangential impacts of 6×10^{16} tonnes of material at 60 km/s impact velocity, or thirty times the mass of gases required for a full 1 bar Earth pressure atmosphere, provided that none of this material was lost back into space. However, as we have seen, most of it will be lost, and the goal of spinning up the Moon can hardly be achieved by this method.

The second option is therefore more likely to see practical application: that of manoeuvering the asteroid into a prograde heliocentric orbit closely matching Earth's, from which capture into the Earth-Moon system is possible, perhaps at one of the Earth-Moon Lagrange points. From here, the asteroid's volatiles can be mined at leisure and transported to orbiting space stations or to the lunar surface as required.

Small chunks of a few thousands or tens of thousands of tonnes at a time may be manoeuvred into low lunar orbit, from whence they may be deposited on the surface at an impact velocity of under 1.7 km/s and an impact energy of about half that in the case of impact at escape velocity, thus ensuring that losses by vaporisation, and random secondary impacts elsewhere on the surface, are minimised.

The studies of Richard Vondrak, cited by Oberg (p.223-226), conclude that a mass of only 100,000 tonnes of gas would be sufficient to give the Moon a long-lived atmosphere. Although the surface pressure would still be almost imperceptible, there would be just enough gas present to shield the surface from the solar wind, and to moderate the daily fluctuation in surface temperatures (p.228). Vaporised ices from asteroidal fragments dropped to the surface from low orbit would persist as part of that atmosphere, rather than being swept out by the solar wind and lost to space. If an impact was timed after local sunset, thanks to the Moon's slow rotation much of the ice may survive long enough to be recovered before being evaporated by the rays of the morning sun.

Alternatively, it may be deemed more efficient to carry the asteroidal material down to the surface in rocket vehicles or using some system of tethers and space elevators.

Oberg describes the engineering of an earthlike atmosphere on the Moon. Certainly it is an alluring and romantic prospect to imagine lunar rivers and seas of real water, meadows, forests and blue skies like those of Earth. But in order to construct a breathable lunar atmosphere with say half the surface pressure of Earth, a mass of 10^{15} tonnes of oxygen and nitrogen is required. The oxygen (42%, to match the partial pressure on Earth) must be either imported in some form, or extracted from lunar rocks; the nitrogen (58%) has to be imported. At the same time, a large quantity of water, or at least of hydrogen for combination with lunar oxygen, must also be imported for an earthlike environment, as well as biologically accessible carbon.

The imported materials would take the of form of asteroidal ices – water, ammonia, methane, carbon dioxide – and asteroidal hydrocarbons, which are then processed by genetically engineered microorganisms. This will clearly take a long time, on the order of centuries, and meanwhile the dynamic Solar System economy which we have assumed – and which is indispensable if a lunar terraforming project is to be funded – suggests that there will in any case be large-scale human settlement of the

Moon, even before terraforming has transformed it into a small sister planet of Earth.

A more realistic prospect is therefore that a number of settlements will emerge, consisting of roofed-over pressurised space, and that the emphasis will be on extending this indoor living space.

Lunar buildings for permanent occupation may be referred to as moonscrapers. The key architectural feature of a moonscraper is its flat roof, thick enough to balance the internal pressure, initially consisting simply of a layer of lunar regolith, and later, when more local mining and manufacturing capabilities have been built up, including progressively larger sections of lunar glass. At a density of around 3000 kg m^{-3} a regolith layer 10 metres thick will balance an internal pressure of half an atmosphere; for glass with a density of 2600 kg m^{-3} the corresponding thickness is 12 metres. Under such thick roofs, protection from solar and galactic cosmic radiation is at least as good as on Earth at sea level.

Initially using pre-existing craters as foundations, later moonscrapers will be excavated artificially. On the maria, the circular floor plan would give way to a hexagonal one, allowing progressively larger areas to be continuously roofed over one unit at a time. As external walls became internal ones, some would be knocked down to create larger interior spaces, others maintained for security against a pressure loss.

If the entire Moon were to be progressively roofed over with lunar glass giving an average ceiling height of 50 metres, the mass of gas required to fill that space with a pressure of half an Earth atmosphere would be 10^9 tonnes – one-millionth of the mass required for an atmosphere open to space. However, a mass of 10^{15} tonnes would still need to be applied to balance the pressure, but in the form of locally produced glass or a simple regolith layer rather than the more expensive imported atmospheric gases.

A small moonscraper with a ceiling height of 6 metres and a diameter of 30 metres would require only 2.6 tonnes of atmospheric gases. Thus by starting small and progressing to larger and more numerous lunar buildings, even very small quantities of gases are usable as soon as they are delivered, rather than having to wait until close to a quadrillion tonnes have been imported before any of them can enter human lungs.

The Moon thus gradually acquires a double surface: a lower one consisting of the floors of linked-up moonscrapers, with an air pressure a large fraction of Earth sea-level pressure, perhaps one half, and an upper surface consisting of the outer roofs of those buildings, on which spacecraft can land, and solar power collectors and waste heat radiators set up, subject to only a very thin atmosphere, unbreathable, yet long-lived and substantial enough to moderate surface temperatures and divert the solar wind away from the surface.

Over thousands of years of human occupation the atmospheric gases trapped in the moonscrapers will gradually leak, both outwards into the thin artificial lunar atmosphere and inwards, through the moonscraper floors and into the body of the Moon. Imports from the Kuiper belt will probably continue indefinitely in order to make up these losses. The lunar atmosphere will thus gradually thicken as the millennia pass, not, in this concept, as a deliberate act of terraforming, but as an evolutionary process, gradual and unintended (the moonscrapers will be made as airtight as possible in order to minimise losses).

How long it would take for a breathable lunar atmosphere to accumulate in this way is impossible to predict, but the enormous mass of gas required, being, as was seen above, one million times greater than the mass required to pressurise the entire surface area under a 50 metre high ceiling, suggests that it might take a geological age (for example, if a Moon totally covered in such moonscrapers lost one per cent of its breathing gases to its outer atmosphere per year, the time required would be 100 million years). But if some practical reason for thickening the lunar atmosphere emerged, or if the cost of importing volatiles fell to a very low level, then an earthlike atmosphere might still be created within historical time, and the moonscrapers abandoned or kept in use only as cellars as the population moved to the outer surface.

One major early demand for asteroid tugs therefore arises from the need to source breathing gases, carbon and other volatiles for this incremental colonisation of the Moon, which, due to its proximity to the metropolis of Solar System civilisation, can hardly be avoided.

A robotic tug may have a fully fuelled mass of 200 tonnes. It is propelled by a small hydrogen-antimatter magnetoplasma rocket engine, similar to those employed in Wayland's landing vehicles (chapter 8), whence v_e = 350 km/s, $\alpha = 8.0 \times 10^{-7}$ and the maximum thrust is 4.0×10^6 N.

At the orbit of Mercury (0.4 AU), the heliocentric circular velocity is 47.10 km/s and the parabolic velocity is 66.61 km/s. A ΔV of 40 km/s will therefore put the newly fuelled tug onto a hyperbolic orbit. It takes about 3 years to cruise out to the Kuiper belt, and at 40 AU from the Sun it has a velocity of 56.4 km/s. A ΔV of 56.6 km/s at this point is sufficient to kill its outward plunge and put it into a circular orbit whose velocity is 4.71 km/s. With a little manoeuvering fuel left to rendezvous with a Kuiper belt asteroid and bring its spin under control, the tug's initial propulsion budget of 100 km/s with 50 tonnes of hydrogen propellant is exhausted. Antimatter consumption so far amounts to 40 grams.

A suitable early target may be a 100 metre diameter asteroid with a mass of about one million tonnes – only twice the payload of the world's largest crude oil tankers today. Dropping this object into the inner Solar System requires a ΔV of around 3.7 km/s. The tug, which is still well stocked with antimatter, deploys miners which scoop up ice from the surface of the asteroid for use as reaction mass. If the same antimatter mixture ratio is maintained, the exhaust velocity falls to 196 km/s when water ice rather than hydrogen is used (chapter 5). The mass ratio is then 1.019, and 19,000 tonnes of the asteroid's mass are consumed in the manoeuvre.

With an acceleration of 4×10^{-3} m s^{-2}, 11 days of thrusting change the velocity of the asteroid by the desired amount. Antimatter consumption is 15.2 kg.

The fall to perihelion takes 46 years. There is little for the tug to do during this period, so it detaches itself from the asteroid (leaving a navigation beacon for remote tracking) and goes in search of another one, continuing to fire million-tonne objects into the inner Solar System for as long as its antimatter reserves permit, finally returning itself on a hyperbolic orbit to refuel at the antimatter factories close to the Sun. (O'Neill, p.106, describes a mass driver propelled tug operating in a similar fashion.)

As has been seen, the energy budget for sending the tug flying around the Solar System at hyperbolic speeds is small in comparison with that for manoeuvering its asteroid targets, due to the huge discrepancy in sizes. This ensures that tugs will only visit those asteroids during the relatively brief periods when their active propulsion is required. One such time comes during the Jupiter flyby, when the jovian gravity field is used to capture the asteroid into a short-period comet orbit. (The asteroid will need to be wrapped in a protective layer of tin foil in order to prevent it becoming a real man-made comet.) The nature of planetary flybys is such that small uncertainties in navigation are greatly magnified by the encounter, thus demanding a course correction during the Jupiter flyby for accurate insertion into the heavily trafficked inner Solar System and for rendezvous with the Earth-Moon system.

If the resulting orbit has aphelion at 6 AU and perihelion at Earth's distance from the Sun, then the asteroid's perihelion speed will be 39.0 km/s, requiring deceleration by 9.2 km/s to match Earth's orbital velocity. A further 2 to 3 km/s are required for capture into the Earth-Moon system, probably at an Earth-Moon Lagrange point. For ΔV = 12 km/s, using the same propulsion method as before, the mass ratio is 1.063, requiring consumption of another 62,000 tonnes of the asteroid's substance, and another 49.6 kg of antimatter. The mass finally delivered is then 91.9% of the asteroid's original 10^6 tonnes.

The total antimatter cost is around 65 kg, and the energy cost is then 1.17×10^{19} J = 0.371 TW years. This is equivalent to 1.27×10^{13} J = 3.54×10^6 kW hr per tonne of material delivered, which at a nominal 5 pence per kW hr would come to £177,000 per tonne. While expensive by present-day standards, this may not be an unreasonable cost in a dynamic Solar System economy some centuries ahead, and it is certainly cheaper than current costs for transporting material from the Earth's surface to orbit.

Industrial delivery of asteroidal volatiles to the Moon will clearly take several decades to get under way, given the leisurely descent rate from the Kuiper belt to the inner planets. But once it was in full-scale operation, the delivery of up to ten such asteroids per year could be a practical prospect, allowing human occupation of the entire lunar surface in moonscrapers over a period of about 1000 years. (Here it is assumed that breathing gases refined from carbon dioxide and ammonia ices amount to about one tenth of the total import, about half of which is water ice).

At ten deliveries per year, the antimatter cost is 650 kg per year, equivalent to 1.5 voyages of the Saturn liner. The asteroid tug industry presented here is therefore only one 2000th of the size of the level of passenger liner activity projected in the preceding section of this chapter, and the conclusion may be drawn that it is unlikely to form a major sector of demand for antimatter power.

Energy and population

In chapter 1 it was stated that the most likely starship propulsion technology will be based on the most widespread power technology for general economic use: the starship needs to evolve from the existing industrial base. This study has focused on antimatter as the energy source for the Wayland engine, therefore it has implicitly assumed the prior large-scale use of antimatter for general Solar System industrial and domestic power generation, and for interplanetary transport.

What would a large-scale antimatter economy look like?

The orbit of Mercury offers a suitable location for antimatter factories: close to its solar power source, and close to a source of material with which to build those factories (Mercury itself). At its mean distance of 0.3871 AU from the Sun, the solar flux is 6.67 times greater than it is at Earth, thus about 9.0 kW m^{-2}.

The energy conversion efficiency of a large-scale, highly developed antimatter production industry is impossible to predict at this stage. For the present purely illustrative discussion a 2% efficiency is assumed for conversion of raw solar power into matter (1%) and antimatter (1%). Current methods of manufacturing antimatter are highly inefficient (Close, p.134-135, 147; Savage, p.319). Some authors expect this to greatly improve in the future (Savage, p.319-321, referencing work published in *JBIS*; Professor Close appears to be unaware of this work).

A square solar array in space at Mercury's mean distance from the Sun, 1000 km on each side, has an area of 10^6 km^2, and will therefore power the creation of 1 gram of matter and 1 gram of antimatter per second (180 TW power output). It thus accumulates 30 tonnes of antimatter per year (allowing 5% down time). Radiators in the shade of the solar array are needed to maintain an energy balance by radiating the remaining 8820 TW to space.

The largest customers for this antimatter, in the scenario envisaged in this study, are the interplanetary passenger transport industry, fuelling the Saturn liners described above, but more especially the domestic and industrial electrical power generation industry, particularly in the mid to outer Solar System, where solar power is too diffuse to harvest effectively.

The electrical power situation in the main asteroid belt, centered on the orbit of Ceres, 2.8 AU from the Sun, is a marginal one: sunlight here is 7.8 times weaker than at Earth, requiring solar arrays larger than those near Earth's orbit by the same factor for a given power. This is by no means impossible, but such arrays may well be supplanted by antimatter reactors once a large-scale antimatter industry has come into being, and this will be our assumption here.

The following table shows a range of possible sizes of the electrical power economy and population, assuming that each individual demands an average of 10 kW of power input for domestic and industrial use together, similar to that of people living in present-day developed countries. The population is mostly domiciled in the main asteroid belt, and power is provided solely by the antimatter industry.

Population	*Power demand*	*Energy demand per year*	*Antimatter demand per year*	*Solar array collection area*
10^{10}	10^{14} W	3×10^{21} J	17.5 tonnes	0.584×10^{6} km^2
10^{11}	10^{15} W	3×10^{22} J	175 tonnes	5.84×10^{6} km^2
10^{12}	10^{16} W	3×10^{23} J	1,750 tonnes	58.4×10^{6} km^2
10^{13}	10^{17} W	3×10^{24} J	17,500 tonnes	584×10^{6} km^2
10^{14}	10^{18} W	3×10^{25} J	175,000 tonnes	$5{,}840 \times 10^{6}$ km^2
10^{15}	10^{19} W	3×10^{26} J	1,750,000 tonnes	$58{,}400 \times 10^{6}$ km^2

What mass would be required to build the 58 billion square kilometres of solar arrays in the last line of the table? (Such an area is 114 times the entire surface area of planet Earth.)

Assuming 25% efficiency for basic power production, the power generated is $5.84 \times 10^{10} \times 9 \times 10^{9} \times 0.25 = 1.3 \times 10^{20}$ watts. A realistic modern value for mass per unit output power generated was given by Bob Parkinson at the October 2007 "Three Ways to Mars" talk at the BIS as 50 kg/kW (for both nuclear electric and solar electric power systems), though he added that supporters of electric propulsion claim they can get down to 5 kg/kW. O'Neill (p.83) gives 10 kg/kW for a power satellite based on a Brayton turbine under test at the time of writing in 1976.

Assuming therefore a mass of 10 kg/kW for a large-scale future generation industry, the aggregate mass of solar arrays (whether photovoltaic or turbine-based) comes to 1.3×10^{15} tonnes. The mass of the planet Mercury is 3.3×10^{20} tonnes, so if the bulk of the solar array structure is sourced from there, it will require the use of about four millionths of that planet's mass. The antimatter production units might also be constructed from mercurian metals and silicates. Propellants, however, for lifting the material off the planet and redistributing it around Mercury's orbit, would need to be imported using the asteroid tug described above.

As was noted in chapter 1, estimates of the maximum carrying capacity of the main asteroid belt for human populations are in the region of 10^{15} to 10^{16} people. But once large-scale power generation is independent of the local solar flux, populations are free to migrate further afield, to the trojan asteroids in Jupiter's orbit, the satellites of the giant planets, the centaurs and the Kuiper belt.

The question which now needs to be addressed is how small a fraction of the total energy budget of human civilisation the energy cost of a Wayland starship (using 1254 tonnes of antimatter) must become before that ship becomes economically feasible.

Clearly, this question is unanswerable. Many other factors also come into play, and the cultural priorities of civilisations centuries ahead of ours are completely unpredictable. Nevertheless an illustration of what may be possible can be offered, based on analogy with the past.

In 1965, the Apollo programme was at its height. The funding of NASA was $5.2 billion in that year (representing 5.3% of the federal US budget), and about half of this money went to Apollo (NASA: http://history.nasa.gov/Apollomon/Apollo.html). The US GDP for the same year was $712 billion in current (not inflation adjusted) US dollars (Google public data, derived from the World Bank's World Development Indicators). The spending on Apollo therefore peaked at 0.365% of American GDP.

If the cost of Wayland is dominated by the energy cost of each departure, then energy may be used as a rough proxy for dollar cost. This suggests that the starship programme may become economically feasible when each vehicle consumes no more than 0.4% of total annual energy usage, indicating that an aggregate Solar System population of around 200,000 billion is needed. Given priority, the first starships could be despatched at an earlier stage, but this scenario is intended as a realistically conservative one.

Future population growth levels are another imponderable factor. The global growth rate in the late 20th century was about 2% per annum (O'Neill, p.17), but fertility in developed countries has been falling. The fertility levels, lifespans and resulting rates of population growth (or indeed decline) in future space colonies must for the present remain pure guesswork.

In a range of illustrative scenarios, the following table shows different population growth rates projected into the future:

Total human population	*Date, at annual growth rate of …*			
	2%	*1%*	*0.5%*	*0.25%*
6 bn	AD 2000	2000	2000	2000
20 bn	2061	2121	2241	2482
200 bn	2177	2352	2703	3404
2,000 bn	2294	2584	3164	4326
20,000 bn	2410	2815	3626	5249
200,000 bn	2526	3047	4088	6171
2,000,000 bn	2642	3278	4549	7093

The conclusion may therefore be drawn that, if space colonisation becomes a reality and the aggregate human population continues on a trend of sustained growth, and if the primary extraterrestrial technologies of power production are, like the use of antimatter, applicable to starship propulsion, then it is entirely conceivable that a programme of launches of manned starships may be undertaken, probably starting no earlier than 500 years from now.

But if population and hence economic growth in the growing Solar System civilisation is slower than in today's monoglobal society, or if conflicts not anticipated here, or serious problems adapting to life in space, act as a brake on progress, the first passenger-carrying starship launch could be much delayed, to AD 3000 (with 1% growth), 4000 (0.5%) or later than 6000 (0.25%).

Could Wayland fly earlier than AD 2500? It may well be technically feasible to launch the first Waylands at a time when each vehicle consumed the equivalent of a full year's antimatter production for other purposes, even before the population had reached 1000 billion people, thus maybe as early as the year AD 2250.

Technical feasibility is no guarantee that a vehicle will be built, of course, as numerous initiatives to send astronauts to Mars from 1969 onwards have demonstrated. But at the start of this chapter it was argued that public attitudes to the first starflights will be different from the current apathy regarding Mars. A further point in favour of an early start to the programme is that in a dynamic economy, wealth grows faster than population. AD 2250 therefore represents a reasonable estimate of the earliest opportunity to build and fly Wayland ships, with the timespan AD 2500 to 3000 as a more conservative estimate.

Slippage by many centuries or millennia is also possible, if extraterrestrial growth is significantly slower than an average of 1% per annum or if the interplanetary economy goes into a prolonged downturn.

11. *Conclusions and prospects*

Wayland began as a study of a ship to take people to the stars. It quickly ended up as a study of a ship to take large quantities of radiation shielding to the stars.

Each person on board weighs around 150 kg, with clothing and a modest personal baggage allowance. That individual accounts for 8 tonnes of accommodation, and for 32 tonnes of spare accommodation, vehicles and other equipment for use after arrival.

That same person requires 140 tonnes of inert radiation shielding in order to keep him or her self in good health.

The need for a thick protective layer, probably of a polyethylene-derived plastic material, multiplies the cost of the voyage by a factor of 4.5, assuming that all the propulsive parts of the ship are scaled to the payload. Yet given current knowledge of the human body, the levels of galactic cosmic radiation and the impracticality of shielding with electric or magnetic fields, it is a cost that cannot be avoided. The shielding material itself is cheap, as is the extra burden of liquid hydrogen propellant. What drives the cost up is the additional stored energy to whip that hydrogen up into a plasma exhaust stream of particles at 12.6% of the speed of light.

Antimatter has been chosen as the prime power source for Wayland, partly because nuclear fusion has already been investigated in considerable detail in the Daedalus study, and partly because in principle antimatter offers higher performance than fusion. But whether this higher performance can be realised in practice depends on whether it can be stored in a container whose mass is no greater than about ten times the mass of its contents, and on whether its annihilation products can be efficiently harnessed to create rocket thrust at a mixture ratio of up to 1% antimatter. It is acknowledged that the present study has barely scratched the surface of these complex technical questions.

A manned starship is not something that could be built in the next century or two. It demands absolute confidence in the life-support systems of habitable modules that function for many human lifetimes and in which people can live, work, relax and procreate as healthily and as safely as they can on Earth. It demands structures and equipment of unprecedented reliability, and which are either easy to repair or, preferably, self-repairing. It demands everyday familiarity with all kinds of material and energy resources in space, and well-honed techniques for transforming them into functional products. But above all it demands an easy command of flows of energy many orders of magnitude higher than those known today.

Each Wayland vehicle burns up about seven centuries' worth of present-day global energy consumption in a single one-way interstellar crossing. That is not a cost that any social institution in a one-planet civilisation can remotely afford. One is therefore led to anticipate a future multiglobal human civilisation at least a million times more populous than today's monoglobal society, and wealthier than us to a degree and in ways which we can scarcely imagine. Such a civilisation would be further than we are along the path of social, economic and technological growth to an extent analogous to that by which our present-day privileges and capabilities surpass those of the subsistence farming societies of five thousand years ago.

Just as those primitive village communities provided the social matrix out of which grew the great civilisations of antiquity in Mesopotamia, Egypt, Crete, India and China, and later on in Greece, Persia, Rome, Carthage, central America and the Andes, so too our modern primitive global community suggests itself as the bedrock on which high-tech civilisations of the future may be founded to flourish in the new lands of the Moon and Mars and among the asteroids. Yet while this analogy offers us a sense of direction, it can never provide certainty about the future.

The general public view in the West of who we are and where we are going is dominated more by fear of the future than by confidence in our future progress. That fear is based above all on computer models of how the global climate might respond to the carbon dioxide waste emitted by fossil fuel burning – our main source of power for industry and transport. But is also draws on a variety of other human assaults on the natural environment, as forests are logged and other species driven into extinction. The story goes that *Homo sapiens* is out of balance with the rest of nature, and we must curtail our populations and stifle our economies – reducing our "ecological footprint" – in order to avoid some dimly perceived catastrophe in which the natural life-support system of Earth fails to sustain us any longer and our own species too becomes extinct.

Such environmental pessimism, however, seems largely confined to the old heartland of the industrial revolution in Europe and North America. The billions who aspire to an affluent first-world standard of living in South America, Africa and Asia do not share the fashionable guilt of the West, and do not intend to cripple their economic growth for the sake of a climate model whose accuracy over periods of half a century or more has yet to be demonstrated.

The conflict between pessimism and optimism is therefore not so much a struggle for the soul of civilisation as it is a cultural movement which could change the balance of power between East and West. If Western political leaders succeed in reducing their economies to windmill-based societies, then the balance of global power will simply shift to the newly emerging economies of the southern and eastern hemispheres, and growth will continue as before.

However, even in the West, skepticism about disastrous anthropogenic climate change is on the rise, thanks to over-zealousness on the part of the climate alarmists, and to the obscuring of any long-term climatic trends by chaotic short-term fluctuations. Common sense is making itself heard: whatever the climatic future, richer societies will adapt to it better than poorer ones, and meanwhile our understanding of natural climatic cycles on Earth and how they are influenced by cycles of activity on the Sun is at such an early stage that basing draconian economic change on the single factor of greenhouse gases is unlikely to achieve its goals.

Social evolution, like climate, is an intrinsically chaotic, evolutionary process. In both cases the outcome at any future time is the aggregate result of a large number of individual small-scale events – personal economic and cultural choices in the case of society, individual movements of molecules of air and moisture and of quanta of radiation in the climate. Each local event both affects and is affected by all the surrounding ones, and the system as a whole is not amenable to control from any one point. Prediction of future states is intrinsically problematic, unless some dramatic, overpoweringly large-scale phenomenon such as a major asteroid impact intervenes. It is the contention of climate alarmists that anthropogenic carbon dioxide emissions are just such an irresistable intervention in an otherwise stable and predictable system. But given the low concentrations of atmospheric carbon dioxide, both before and after industrial contributions are added in, and given the natural fluctuations in climate over human history, the alarmist view may be doubted.

Ideological movements with an urgent message for mankind have often found themselves unable to control society in accordance with their formula for the future, and the attempt to do so has sometimes in the past had a perverse effect – for example, the Japanese Tokugawa government attempted to isolate Japan from the rest of the world from 1603, but in so doing set up the conditions for Japan's generally successful integration into global society from 1868 onwards; Lenin's Bolshevik party attempted to improve the lot of the Russian people, but in so doing created the nightmare of Soviet Communism which crippled the economy for 70 years, and killed and enslaved millions who might well have prospered under a transformation of tsarism into a constitutional monarchy.

Anyone who advocates a programme such as the extension of human growth and progress into space needs therefore to be very circumspect about what they are calling for, and must reject dogmatic attitudes.

Yet it can still be understood, by anyone who considers the prospects for human civilisation at all, that there is a direction to progress, and that this direction points us towards, firstly a multiglobal civilisation within our local planetary system, and subsequently a society that builds and operates starships, and which over the succeeding millennia develops a flourishing presence over an increasing fraction of the Galaxy.

Wayland is therefore not so much a technological as a political project. It is a reaffirmation of the desirability and value of human growth and progress, and the functional purpose of the industrial liberal democratic capitalist system in the greater scheme of evolution. It offers a specific perspective on how present-day trends lead to a long-term sustainable future:

- Current space exploration efforts must lead to commercial activities serving mass markets, starting with personal space exploration (space tourism), space manufacturing and the industrial use of space resources;
- Even as the explosion of industrial activity on Earth levels off, industrial growth must transfer to space in order to continue with even greater vigour and on a vastly greater resource base than before;
- Even as population growth on Earth begins to level off mid-century, at the same time permanent extraterrestrial populations must come into being that will continue the trend of growth through many more orders of magnitude;
- A stable, high-tech, one-planet democratic civilisation is impossible: we must choose either to continue to grow and spread out in the infinite universe, or to fall into terminal decline on the overcrowded village Earth;
- The human species is not an eternal given fact but a natural work in progress, a new natural experiment in devising forms of life that can leave their planetary cradle, just as they left their watery cradle 400 million years ago, and claim the raw materials of the universe, which now lie unused, for the purposes of life.

Wayland, like Daedalus before it and now Icarus, is intended to contribute towards this perspective on human growth, and to inspire the politicians, engineers, scientists, managers, entrepreneurs, physicians, tourists, artists and poets who find themselves in a position to contribute towards the emerging extraterrestrial civilisation.

Where Wayland can make an especial difference is to humanise the project of going to the stars by examining the possibility that real human beings might one day follow their robot emissaries to the stars. It moves the debate on from science to its ultimate logical outcome: colonisation.

This has been attempted in this study, and it is the author's hope that others will carry it forward to a Wayland Mk II, until eventually down the centuries a real spacecraft, a distant descendant of the primitive sketches begun in the 20th and 21st centuries, will carry our human and post-human descendants to the stars.

References

Aldrin, Buzz, and John Barnes, *Encounter with Tiber* (Hodder & Stoughton, 1996).

Ashworth, S., "Three Ways to Mars", report on the October 2007 BIS meeting, online at http://www.astronist.demon.co.uk/space-age/essays/Three_ways_to_Mars.pdf.

Barry, Patrick L., "Plastic Spaceships" (25 Aug. 2005), http://science.nasa.gov/headlines/y2005/25aug_plasticspaceships.htm (accessed 30 March 2010).

Barton, William, and Michael Capobianco, *Alpha Centauri* (Avon, 1997).

Bond, Alan, "On the Improbability of Intelligent Extraterrestrials", *JBIS* 35 (May 1982), p.195-207.

Bond, Alan, A. R. Martin et alia, *Project Daedalus: The Final Report on the BIS Starship Study* (supplement to *JBIS*, 1978).

Cattell, C., et alia, "Physics and Technology of the Feasibility of Plasma Sails", PSFC/JA-05-26, submitted to the *Journal of Geophysical Research* in September 2005. Online at http://www.psfc.mit.edu/library1/catalog/reports/2000/05ja/05ja026/p5ja026_full.pdf.

Chang Díaz, Franklin R., "The VASIMR Rocket", *Scientific American*, Nov. 2000, p.72-79.

Close, Frank, *Antimatter* (OUP, 2009).

Cohen, Jack, and Ian Stewart, *Evolving the Alien* (Ebury, 2002).

Drake, Frank, and Dava Sobel, *Is Anyone Out There?* (Souvenir, 1992).

European Space Agency, *CDF Study Report: Human Missions to Mars: Overall Architecture Assessment*, section 2.6 on p.39-44, "Radiation environment" (February 2004).

Forward, Robert L., "Antimatter Propulsion", *JBIS* 35 (September 1982), p.391-395.

Hempsell, Mark, and Roger Moses, "The Impact of Radiation Protection on the Design of Space Habitats", IAC-07-A1.5./A1.7.08.

Jackson, A. A., and D. P. Whitmire, "A Laser-Powered Interstellar Rocket", *JBIS* 31 (1978), p.335-337.

Lewis, John S., *Mining the Sky* (Addison-Wesley, 1996).

Mallove, Eugene, and Gregory Matloff, *The Starflight Handbook* (Wiley, 1989).

Mewaldt, R. A., et alia, "The Cosmic Ray Radiation Dose in Interplanetary Space – Present Day and Worst-Case Evaluations", 29th International Cosmic Ray Conference Pune (2005) **00**, 101-104 (accessed online).

Morgan, David L., "Concepts for the Design of an Antimatter Annihilation Rocket", *JBIS* 35 (September 1982), p.405-412.

Oberg, James E., *Mission to Mars* (Stackpole, 1982).
Oberg, James E., *New Earths* (Stackpole, 1981).
O'Neill, Gerard K., et alia, *The High Frontier*, 3rd edn (Space Studies Institute, 2000).
Parker, Eugene N., "Shielding Space Travelers", *Scientific American*, March 2006, p.22-29.
Savage, Marshall, *The Millennial Project* (1992; Little, Brown, 1994).
Zito, Richard R., "The Cryogenic Confinement of Antiprotons for Space Propulsion Systems", *JBIS* 35 (September 1982), p.414-421.
Zubrin, Robert, and Dana G. Andrews, "Magnetic Sails and Interstellar Travel", paper IAF-88-553 (1988).
Zubrin, Robert, and Richard Wagner, *The Case for Mars* (1996; Touchstone, 1997).

Data on volatile liquids/gases from http://encyclopedia.airliquide.com/.
Properties of water (ch.10) from http://www.engineeringtoolbox.com/.
JBIS = Journal of the British Interplanetary Society

Extrasolar planetfall