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# Interstellar travel: a review for astronomers

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*Henceforth I spread confident wings to space;*
*I fear no barrier of crystal or of glass;*
*I cleave the heavens and soar to the infinite.*
*And while I rise from my own globe to others*
*And penetrate ever further through the eternal field,*
*That which others saw from afar, I leave far behind me.*

Giordano Bruno (1548–1600), from *De l'infinito universo et mondi*, 1584 (translated by Singer 1968, p. 249).

SUMMARY

A number of proposed methods of rapid ($v \gtrsim 0{\cdot}1\ c$) interstellar travel are discussed, including pulsed fusion and antimatter powered rockets, laser pushed lightsails, and interstellar ramjets. Lower velocity 'world ships' are also briefly considered. The scale of the undertaking, from both a technological and an economic perspective, is such that it is unlikely to be realized for several centuries. However, the great increase in astronomical knowledge that will result from a programme of interstellar exploration means that astronomers have a vested interest in the dream becoming a reality.

## 1 INTRODUCTION

All astronomers should want to go to the stars, for it seems clear that the Universe cannot be fully understood by way of observations made from the surface of the Earth or its immediate vicinity. In its long history, astronomy has discovered much about the Universe that will never be contradicted: the planets do orbit the solar system barycentre, and not the earth; the stars are gravitationally bound spheres of gas undergoing nuclear fusion, and not holes in the sky through which we see the lights of heaven; the sizes, temperatures, distances and chemical compositions of the stars are also known, at least approximately; the stars are collected together into galaxies. All this, and so much more, we have discovered by interpreting observations made from the Earth with the aid of reliable physics. The crystal spheres will not return. But we should not let our advances blind us to the fact that there must be a limit to the amount of information that can be squeezed out of light by all conceivable spectroscopic, photometric and interferometric means. We cannot, surely, learn everything there is to know by these means alone.

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In support of this view let us consider the history of solar system exploration. Optical astronomy had pretty much achieved all it could with the planets before the space age. It had discovered some facts that will never be disputed: the orbital elements were all known to high precision; it was known which planets were gaseous and which were not; the major satellites were identified. But all this pales almost into insignificance when compared with the knowledge that has accumulated over the last couple of decades. Dancing images in the telescope have been transformed into worlds. Data have become available that could never have been obtained telescopically from the surface of the Earth (consider, for example, the structure of the lunar regolith determined by the *Apollo* seismic experiments). The whole paradigm of solar system science has been irrevocably changed.

It is clear that if interstellar travel ever becomes a practical undertaking, then the main-stream of astronomy will undergo a similar enrichment. Consider the advantages of taking thermometers, magnetometers, mass-spectrometers, gravimeters, seismometers, microscopes, and all the other paraphernalia of experimental science, to objects that today can only be observed telescopically. Consider the advantages to stellar theory to be able to resolve spatially, to the same degree that we can the Sun, stars of all spectral types. Consider the theory of comparative planetology on a galactic scale that would result from visits to other planetary systems. Will we ever know for sure that Cygnus X-1 does, in fact, contain a black hole (and indeed whether such objects exist at all) until it becomes possible to go there and look?

These are some of the scientific reasons for wanting to go to the stars, but there are also important human reasons. Presumably the total number of people who receive a chance of life, and the survival time of our species itself, would increase enormously if colonization of even a small part of the galaxy proved possible. As pointed out by Shepherd (1952) 'humanity dispersed over many worlds would appear to be more secure than humanity crowded on one single planet'. At the very least, the resulting cultural diversity would provide an exciting alternative to Fukuyama's (1989) view of 'the end of history'. These considerations would seem to make interstellar travel a socially desirable goal. Readers who are interested in the social consequences of interstellar travel are referred to the interesting book on the subject edited by Finney & Jones (1985).

## 2 THE *PIONEER* AND *VOYAGER* INTERSTELLAR SPACECRAFT

There are already four spacecraft on hyperbolic trajectories that will take them out of the solar system and into interstellar space. These are *Pioneer 10* and *11* (launched in 1972 and 1973) and *Voyager 1* and *2* (launched in 1977), the interstellar trajectories of which have been described in detail by Cesarone, Sergeyevsky & Kerridge (1984). These four spacecraft have asymptotic heliocentric velocities (i.e. heliocentric velocities at infinity) in the range 10–17 km $s^{-1}$. However, as 10 km $s^{-1}$ corresponds to $10^{-5}$ pc $yr^{-1}$, it is clear that much higher velocities will be required if scientific data from interstellar spacecraft are to be returned to Earth on time-scales of interest to human society. We should point out, however, that even the very low velocities achieved to date may suffice for some proposed schemes of interstellar colonization (to which we will return briefly in Section 8), and are certainly sufficient for a programme of directed panspermia such as that described by Crick (1981).

The rest of this paper is a review of some of the methods of propulsion that might make it possible to travel interstellar distances on a time-scale of decades (i.e. velocities $\gtrsim 0{\cdot}1\ c$). There is little here that is original, most of it has been culled from what is now a rather extensive literature. My aim is to draw the attention of astronomers to some ideas that have been floating around the astronautical community for many years, and to convince some of my more sceptical colleagues that interstellar travel is a subject worthy of serious scientific debate. The concepts discussed here are necessarily selective, reflecting the author's own interests and knowledge, and a number of interesting ideas have been omitted altogether. The reader who wishes to dig deeper is referred to the extensive bibliography of interstellar travel and communication compiled by Mallove *et al.* (1980), and updated by Paprotny, Lehmann & Prytz (1984, 1986, 1987).

## 3 THE DAEDALUS PROJECT

There has been, to date, only one detailed engineering study of a starship design. This is the Daedalus Project carried out between 1973 and 1978 by a small group of scientists and engineers working, in their spare time, under the auspices of the British Interplanetary Society. The aim was to design an automatic vehicle capable of travelling to Barnard's star (the next closest to the Sun after the $\alpha$ Centauri system, and for which, at that time, there seemed good circumstantial evidence for a planetary system) with a flight-time of about 50 years (the original plan was for 40 years, but this was subsequently relaxed). This requires a cruising speed of about 12 per cent of the speed of light, which was to be achieved with currently available technology or a reasonable extrapolation thereof. If the same mission profile was adopted for a flight to the $\alpha$ Centauri system the flight-time would be 36 years. The payload was to have a mass of 450 tonnes, and the only propulsion system capable of satisfying these criteria was found to be one based on nuclear fusion.

The vehicle that evolved from this study consisted of two stages, both of which were to utilize the fusion of deuterium and $^3$He for propulsion, these particular isotopes being chosen in order to minimize the flux of neutrons. Pellets of these isotopes are injected into a reaction chamber where they are heated and compressed to the point of thermonuclear ignition by relativistic electron beams. The resulting plasma is constrained by a magnetic field in such a way that it can escape in only one direction and therefore acts as a rocket exhaust. Full details of this propulsion system, and a review of its historical origins, are given by Martin & Bond (1978) and Bond & Martin (1978a); see also Martin & Bond (1979). Table 1 lists some characteristics of the two stages (Bond & Martin 1978b; Strong & Bond 1978).

Following the acceleration phase, the coast velocity of the remainder of the second stage (the empty fuel tanks having been discarded) and the payload would be 12·2 per cent of the speed of light. There seems little doubt that

TABLE I

*Daedalus vehicle specifications*

| | First stage | Second stage |
|---|---|---|
| Length (m) | 140 | 110 |
| Diameter (inc. propellant tanks) (m) | 190 | 80 |
| Stage mass at cut-off (tonnes) | 1690 | 980 |
| Propellant mass (tonnes) | 46000 | 4000 |
| Propellant | D, $^3$He | D, $^3$He |
| Thrust (N) | $7.5 \times 10^6$ | $6.3 \times 10^5$ |
| Burn duration (yr) | 2.05 | 1.76 |

pulsed fusion propulsion systems, which may follow naturally from present inertial fusion research (but see the discussion by Reupke 1985), would be capable of achieving these very high velocities. Notice, however, the quantity of fuel that is required and the size of the vehicle necessary to accommodate it all (Table 1). Moreover, $^3$He is a very rare isotope, and the Daedalus study concluded that it would be necessary to 'mine' the helium-rich atmosphere of Jupiter (Parkinson 1978); this would also be the logical place to obtain the deuterium. A recent review of the Daedalus project, including a discussion of points which have arisen since the publication of the original work, has been given by Bond & Martin (1986).

Daedalus was to make an undecelerated fly-by of the Barnard's star system, it being quite impractical to *launch* a vehicle capable of *decelerating* a 450 tonne payload from 12 per cent of the speed of light with the same propulsion system. A number of small sub-probes were therefore to be deployed prior to the encounter so as to pass close to as many interesting objects (e.g. planets) as possible during the few hours of the encounter itself. Results from these probes would be transmitted to the main vehicle and thence to Earth. During the coast phase *in situ* measurements would be made of the local interstellar medium, and the very long baseline built up between Daedalus and Earth would be used to greatly extend the parallactic distance scale. These are important astronomical observations that could be performed by any interstellar vehicle in flight.

Before leaving the Daedalus concept and moving on to other ideas, we will consider the effect of interstellar matter on the vehicle. This was examined in detail by Martin (1978) who found that, owing to their much greater kinetic energy, the interstellar grains are considerably more destructive than gas-phase atoms. At the Daedalus velocity an interstellar grain with a mass of $10^{-16}$ kg has a kinetic energy of about 0.07 J and, upon collision, is capable of producing temperatures of order $10^{12}$ K local to the point of impact (Benedikt 1961; where, owing to the supersonic nature of the impact, it has been assumed that the kinetic energy is contained within a volume comparable to that of the particle). These high temperatures will lead to evaporation of material from the vehicle and some form of shielding will be required. Ideal shield materials should have a low density, so as to minimize the shield mass, but large latent and specific heat capacities, so as to minimize the loss of material due to collisional heating. Martin concluded that beryllium, boron and graphite were the best available candidates. Clearly, the rate at which material is lost from the shield depends strongly on the mass and flux of in-coming particles. For a beryllium shield and a dust space density of $1{\cdot}6 \times 10^{-24}$ kg m$^{-3}$ (probably appropriate for the solar neighbourhood which has a hydrogen atom density of about $0{\cdot}1$ cm$^{-3}$ (Cox & Reynolds 1987), assuming the dust particle size distribution of Draine & Lee (1984)) Martin's analysis (cf. his eqn (5)) implies a total mass loss of $1{\cdot}6$ kg m$^{-2}$ over the whole flight. This may be considered as an upper limit because, as pointed out by Powell (1975), much of the vapourized material will recondense onto the shield before it can escape into space. It is interesting to note that this last effect becomes more efficient at higher velocities.

## 4 ANTIMATTER DRIVES

There are, of course, potentially useful nuclear propulsion systems other than the Daedalus concept. For example, one could imagine rockets based on continuous, rather than pulsed fusion. It is also possible to envisage fission powered rockets, although, as fission is less efficient in converting mass into energy, it would appear that the performance of a fission rocket will always be lower than one driven by fusion (on the practical side, however, it may be that a fission rocket would be easier to build, at least in the near future). We will not dwell on the relative merits of different nuclear propulsion concepts here (the interested reader is referred to the bibliographies referenced in Section 2), but will instead consider the potential performance of the most efficient possible rocket. The most efficient rocket fuel we can imagine would consist of a mixture of matter and antimatter, as their mutual annihilation leads to a 100 per cent conversion of mass into energy.

In order to use antimatter as a fuel it will be necessary to produce macroscopic quantities of it and to store it in a compact form. This will entail producing large quantities of antiprotons, combining these with positrons to produce antihydrogen atoms, combining pairs of these to form an antihydrogen molecular gas and, finally, condensing this gas into blocks of solid antihydrogen! Needless to say, there will be many problems involved in achieving all this in practice. The problems that arise in the route from antiprotons to solid antihydrogen, together with some proposed solutions, have been discussed by, among others, Forward (1982), Mitchell (1988), Stwalley (1988) and Michaelis & Bingham (1988), and will not be reiterated here. For the sake of argument, we will take the optimistic view that if sufficient antiprotons can be produced, technical solutions will be found to the problems of producing solid antihydrogen in macroscopic quantities. We note that, as it is a diamagnetic material, antihydrogen ice may, in principle, be contained in a magnetic bottle, without the need for it to come into contact with normal matter (e.g. Forward 1982).

At the present time, antiprotons are produced by impacting a beam of relativistic protons into a heavy metal target. The kinetic energy of the protons in the beam goes into the formation of a large number of nuclear particles, some of which are antiprotons. The new antiproton collector (ACOL) at CERN is currently able to collect about $10^{12}$ antiprotons per day from the target (von Egidy 1987; see also the *CERN Courier*, **29** 13 (1989) for updated information on the performance of ACOL). If ACOL were to run continuously, this rate of collection would yield about $6 \times 10^{-7}$ mg of antimatter per year. Several studies (e.g. Larson 1988) have been carried out in order to establish the technical requirements of an antiproton factory capable of producing 1 mg $yr^{-1}$ (i.e. $2 \times 10^{13}$ antiprotons per sec). Although not an easy undertaking, it appears that foreseeable technology may be capable of achieving this rate of antiproton production. We will now consider the quantities of antimatter required for some typical interstellar missions.

Although 100 per cent of the annihilated mass is eventually converted into energy (in the form of γ-rays and neutrinos) not all of this energy is released in a useful form. When a proton, $p$, and antiproton, $\bar{p}$, annihilate a number of charged and neutral pions are produced, i.e.

$$p + \bar{p} \rightarrow n\pi^+ + n\pi^- + m\pi^0,$$

such that, *on average*, $2n + m \sim 5$ (e.g. Vandermeulen 1972). In addition, charged and neutral kaons are produced in about 1 per cent of cases, but these will be neglected here. The neutral pions decay with a mean life of $8{\cdot}3 \times 10^{-17}$ sec into 2 γ-rays. The charged pions decay into muons and neutrinos

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu,$$

with a mean life of 26 nsec in the frame of the particle (Aguilar-Benitez *et al.* 1982). In the rest frame this is extended to about 70 nsec owing to time dilation, during which time the pions would travel about 20 m in free space. The muons decay into electrons, positrons and neutrinos according to the reaction

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu},$$

with a mean life of 2·2 μsec, during which they would cover a distance of about 2 km if unconstrained. Finally, if still physically associated, the electrons and positrons would annihilate to produce γ-rays.

A brief review of possible engine designs for the utilization of the matter–antimatter annihilation products has been given by Morgan (1988). Basically, there are two ways in which the energy released by these reactions could be used to drive a rocket.

(1) The charged annihilation products could be channelled into one direction by a magnetic field thereby producing thrust (much as the expanding plasma in the Daedalus engines was channelled into one direction). A maximum field strength of about 50 T is required if collimation is to be achieved within a space of about $\frac{1}{2}$ m (Morgan 1982). Smaller fields would be required for a larger engine. Of course, the energy carried by the neutral pions, γ-rays and neutrinos would be lost from the system. For applications requiring a very high exhaust velocity such a design is ideal, as the charged pions will have a velocity very close to that of light. On the other hand, the thrust would be low owing to the necessarily small quantity of ejected mass.

(2) The annihilation products could be used to heat a much larger quantity of working fluid, which would then be expelled to produce thrust.

This proves to be a more efficient use of antimatter, and will be considered in detail below.

About 40 per cent of the initial rest mass energy is accounted for by the kinetic energy of the charged pions (e.g. Vulpetti 1986) and it is this energy which could, in principle, be transferred to a working fluid (although it may be possible to design an engine which makes use of at least some of the $\gamma$-rays from the $\pi^0$ decay, thereby increasing the efficiency somewhat (Vulpetti 1986)). Of course, it will be necessary to contain the relativistic pions within a relatively small volume so that they transfer their kinetic energy to the working fluid before they decay. Several possible confinement geometries are possible. For example, the pions could be constrained magnetically in a volume containing the working fluid, requiring a field strength of about 10 T for a 1-m diameter reaction chamber (e.g. Morgan 1982). Alternatively, they could interact directly with a liquid or solid propellant, in which their mean free paths will be substantially reduced (Vulpetti 1986). Finally, they could be used to heat a solid surface, past which the working fluid flows on its way to the rocket nozzle (Morgan 1988 and references therein). Note that the latter ('heat exchanger') concept is similar to NASA's now abandoned *NERVA* engine, where the working fluid flowed through the core of a fission reactor.

Regardless of exactly how the annihilation energy is passed to the working fluid, we can derive an expression for the quantity of antimatter required to achieve a particular mission. This derivation has been given previously by Shepherd (1952) and Dipprey (1975), but as it is instructive (and as I have met with disbelief when quoting the end result without a derivation) it will be repeated here.

The Rocket Equation relates the mass ratio, $R$ (initial mass to final mass), of a rocket to its exhaust velocity, $v_e$, and the velocity, $\Delta v$, gained by the rocket during its flight. We have

$$R = e^{\Delta v/v_e}. \tag{1}$$

For an antimatter rocket, the initial mass is equal to the sum of the empty vehicle mass (i.e. payload plus engine, tankage, etc.), the mass of reaction fluid and the mass to be annihilated (both matter and antimatter); the final mass is just the empty vehicle mass. As the mass to be annihilated is small compared to the other masses, this may be neglected and we have

$$R = \frac{M_{\rm veh} + M_{\rm rf}}{M_{\rm veh}}, \tag{2}$$

where $M_{\rm veh}$ is the empty vehicle mass and $M_{\rm rf}$ is the mass of reaction fluid carried. Thus, we have that

$$M_{\rm rf} = M_{\rm veh}(e^{\Delta v/v_e} - 1). \tag{3}$$

Now, let the efficiency with which rest-mass energy is converted into exhaust kinetic energy be $\varepsilon$. We have

$$M_{\rm en} c^2 \varepsilon = \tfrac{1}{2} M_{\rm rf} v_e^2, \tag{4}$$

where $M_{en}$ is the annihilated mass. Substituting for $M_{rf}$ from eqn (3) gives

$$M_{en} = \frac{K}{x^2}(e^x - 1), \tag{5}$$

where $K = M_{veh}\Delta v^2/2\varepsilon c^2$ is a constant for any given mission, and $x = \Delta v/v_e$. It is easy to show that, for a given $K$, $M_{en}$ is minimized when $x = 1{\cdot}59$. Thus, for any mission the annihilated mass required is a minimum when the mass ratio, $R$, is given by

$$R = e^{1{\cdot}59} = 4{\cdot}9. \tag{6}$$

Thus, the optimum mass of reaction fluid is 3·9 times the empty vehicle mass.

The mass of antimatter is 0·5 $M_{en}$, so from eqn (5) we have that

$$M_a = \frac{K}{2}\frac{1}{(1{\cdot}59)^2}(e^{1{\cdot}59} - 1) = 0{\cdot}772\, K. \tag{7}$$

On substituting back for $K$ this gives the minimum amount of antimatter required for any mission

$$M_a = \frac{0{\cdot}39}{\varepsilon} M_{veh}\left(\frac{\Delta v}{c}\right)^2. \tag{8}$$

Thus, if we take $\varepsilon \sim 0{\cdot}4$ (i.e. the fraction of the total mass-energy released as the kinetic energy of the charged pions) we finally obtain

$$M_a \sim M_{veh} \times \left(\frac{\Delta v}{c}\right)^2. \tag{9}$$

It follows from eqns (6) and (9) that if we wished to achieve a velocity increment of 0·1 $c$, we would require 10 kg of antimatter, and 3·9 tonnes of reaction fluid, for each tonne of empty vehicle mass.

As the empty vehicle mass includes the engine and the rocket structure, in addition to the scientific payload, these must be taken into account when considering the quantity of antimatter required for a particular mission. We will assume that $M_{veh} = M_{eng} + M_{struc} + M_{pl}$ (i.e. the sum of the engine, structural and payload masses), and will further assume that the structure mass is a constant fraction, $\zeta$, of the mass of reaction fluid (i.e. $M_{struc} = \zeta M_{rf}$). It is difficult to estimate a plausible mass of an interstellar antimatter engine; however, because it is likely to include equipment for the generation of powerful magnetic fields and for the cryogenic confinement of antimatter, as well as at least some radiation shielding, it seems clear that several tonnes will be involved. For the sake of argument, we will assume an engine mass of 20 tonnes (which may be wildly optimistic) and, following Cassenti (1982), we will assume that the structural mass is 5 per cent of the mass of reaction fluid, i.e. $\zeta = 0{\cdot}05$.

Suppose we wish to accelerate a nominal 1 tonne payload to 10 per cent of the speed of light. Equation (6) (rearranged so as to include the engine and structural masses) shows that we will require 102 tonnes of reaction fluid, and eqn (9) tells us that we require 260 kg of antimatter. (Note that most of this is required to accelerate the relatively large engine mass, so there is actually little to be gained in having a payload mass small compared to the engine mass. On the other hand, payloads more massive than the engine will dominate the economics, for example the Daedalus mission ($M_{pl}$ = 450 tonnes, $\Delta v = 0{\cdot}12\ c$) would require 2280 tonnes of reaction fluid and 8·4 tonnes of antimatter.) If we wished to bring the 1-tonne payload to rest from its cruise velocity of 0·1 $c$, we would require a first stage capable of accelerating to 0·1 $c$ all that is necessary for the deceleration phase. Assuming that the same engine is used, we find that 620 tonnes of reaction fluid and 1·6 tonnes of antimatter are required for the acceleration phase. Note that the total quantity of reaction fluid needed to accelerate a 1-tonne payload to 0·1 $c$ and bring it to rest again (722 tonnes) is comparable to the quantity of liquid propellant ($\sim$706 tonnes; Gatland 1981, p. 202) required by the space shuttle to achieve Earth orbit!

Thus, it is clear that, even for a comparatively modest interstellar mission, the mass of antimatter required will be of the order of several hundred kilograms. We saw above that a production rate of $\sim$1 mg yr$^{-1}$ is about the highest to which current techniques might aspire, a figure which is itself orders of magnitude larger than anything that has yet been achieved in practice. Nevertheless, in order to gain some insight into what will be required to produce kilograms of antimatter per year, consider an antihydrogen factory based on a 100 TW proton beam (cf. Forward 1982). There would be enough raw energy in such a beam to create 1 g of antiprotons per sec. However, antiproton production is very inefficient, partly because of the inevitable production of less massive particles, and partly because existing techniques can only collect a small fraction of the antiprotons created at the target. The figures given by Goldman (1988) imply an overall efficiency in converting primary proton beam energy into antiproton rest mass of about $10^{-7}$, which includes Goldman's estimate of $10^{-3}$ for the highest *collection* efficiency possible with existing techniques. As we are considering a dedicated antiproton factory (as opposed to the present machines designed for physics experiments) which will be constructed (if at all) many decades in the future, let us assume that the collection efficiency could be increased to about $10^{-1}$, such that the overall efficiency rises to $10^{-5}$. Such a facility would then be capable of producing about 0·3 kg of antiprotons per yr, still too little to be of much use for rapid interstellar travel (although certainly enough to revolutionize travel around the solar system). However, it may be that, as our knowledge of particle physics increases, ways will be found to suppress the formation of less massive particles at the expense of antiprotons, thereby increasing the efficiency still further. In this respect, it is interesting that Baldin *et al.* (1988) have reported that the ratio of antiprotons to pions produced by collision of a carbon nucleus with a copper target is sixty times higher than that produced by proton collisions with the same energy per nucleon. A further efficiency increase of this order would enable our hypothetical accelerator to produce 18 kg of antiprotons per yr, and greater production could be achieved by multiplying the number of factories. Finally, we note that Christopoulos *et al.* (1988) have examined the possibility of antiproton production using lasers rather than particle beams, and find that this technique may be very much more efficient (they estimate by up to a factor of $10^6$!). Further work is clearly required on this concept because, at first sight, it appears to offer the potential for a vastly higher rate of antimatter production than considered above.

The power required for antimatter production is placed in perspective when we realize that the present-day electrical generating capacity of the whole world is approximately 1 TW (*The World in Figures*, Economist Newspaper Ltd, 4th edn, 1984). Of course, any form of interstellar travel will be energy intensive; if a material object has to be accelerated to a significant fraction of the speed of light, its kinetic energy must come from somewhere. Clearly, however, it is not, and may never be, practical to generate the required energy at the surface of the Earth. From an astronomical perspective, however, 1 TW is a very small amount of power: about $2{\cdot}6 \times 10^{-15}\, L_\odot$. At the Earth's distance from the Sun, 100 TW ($2{\cdot}6 \times 10^{-13}\, L_\odot$) would be intercepted by a collector 270 km on a side (of course, this neglects the inefficiencies involved in converting sunlight to beam energy, which would require either a larger collector or one built closer to the Sun). Thus, we see that the sun is the obvious, and perhaps the only, energy source for this (and other) proposed methods of interstellar travel.

Having discussed the performance of the most efficient possible rocket, we now turn to proposed methods of interstellar transport which rely on principles other than that of the rocket.

## 5 LIGHT SAILS

Photons carry a momentum given by $h\nu/c$, where $h$ is Planck's constant, $\nu$ is the frequency of the light and $c$ is the speed of light. It follows, therefore, that a beam of light could, in principle, be used to accelerate a space vehicle, and it has long been recognized that spacecraft deploying large reflective surfaces ('sails') would be able to utilize the momentum carried by sunlight as a means of getting around the inner solar system. In order for the method to be adapted to interstellar flight, however, it will be necessary to arrange for a powerful unidirectional beam of light (as produced by a laser, for example) in order to avoid the inverse-square dependence of the intensity of sunlight with distance. This method of interstellar propulsion was first proposed by Forward (1962), and subsequently considered by, among others, Marx (1966), Redding (1967; who corrects an error in Marx's paper), Moeckel (1972) and Forward (1984a, b).

If we are interested in using photon pressure to accelerate a vehicle to a significant fraction of the speed of light in a few years, a very intense beam of light will be required. For a perfectly reflecting surface, the acceleration resulting from the change of momentum of the incident photons is given by:

$$a = \frac{2P}{Mc}, \tag{10}$$

where $P$ is the power in the beam (the product of the number of photons striking the sail per unit time and their energy) and $M$ is the mass of the vehicle. For example, if we wanted to send a 450 tonne payload to Barnard's star in 50 yr (the nominal Daedalus mission) we would require a constant acceleration of 0·045 m sec$^{-2}$, corresponding to a radiated power of $3 \times 10^{12}$ W.

Of course, in practice many other considerations enter into the designing of an interstellar light sail in addition to the total power required to produce a given acceleration. Foremost among these are (i) the requirement that the incident power be distributed over a sufficiently large area to prevent structural damage, (ii) the fact that even a perfectly collimated beam will diverge as a result of diffraction. Both of these considerations will result in the need for a very large reflective area, i.e. a light sail, even though one is not required by a simple application of eqn (10).

By considering the equilibrium between the incoming power $P$ and the energy radiated by the sail (from both surfaces) it can easily be shown that the vehicle acceleration and the temperature of the sail are related by

$$a = \frac{2(1+\eta)\sigma\varepsilon T^4}{c}\frac{A}{\alpha M}, \tag{11}$$

where $\sigma$ is Stefan's constant, $\varepsilon$, $\eta$, $\alpha$ are the sail emissivity, reflectance and absorptance, respectively, $T$ is the temperature of the sail, $A$ is the sail area, and $M$ is the total vehicle mass (payload plus sail). (In deriving eqn (11) we have substituted $(1+\eta)$ for the factor 2 in eqn (10) in order to allow for the fact that not all the incident radiation is reflected. This has resulted in a slightly different expression from eqn (5) of Forward (1984a), as he chose to allow for less than perfect reflection by multiplying eqn (10) by a factor $\eta$; this gives a physically incorrect result for $\eta = 0$, although as $\eta \rightarrow 1$ the two expressions converge. In reality, the situation is more complicated than assumed here as some light will pass through the (very thin) sail, and account must also be taken of light re-emitted by the sail; Forward (1989) has given a detailed analysis which considers these effects.)

The sail must be supported in some way, so we can write $M = M_{\mathrm{pl}} + M_{\mathrm{sup}} + M_{\mathrm{sail}}$, where $M_{\mathrm{pl}}$ is the payload mass, $M_{\mathrm{sup}}$ is the mass of the sail support and $M_{\mathrm{sail}}$ is the sail mass (i.e. the mass of the reflective surface). If we assume that the support mass is some constant fraction, $\zeta$, of the sail mass, we can write $M = M_{\mathrm{pl}} + (1+\zeta)M_{\mathrm{sail}}$ where, for a sail of thickness $t$ and density $\rho$, $M_{\mathrm{sail}} = \rho A t$. We can therefore rewrite eqn (11) as

$$a = \frac{2(1+\eta)\sigma\varepsilon T^4}{c}\frac{A}{\alpha\, M_{\mathrm{pl}} + (1+\zeta)\rho A t}. \tag{12}$$

It is interesting to note that as $A \rightarrow \infty$, the last term on the right-hand side of eqn (12) tends to $[(1+\zeta)\rho t]^{-1}$, so the maximum possible acceleration (i.e. that given by an infinitely large sail) at temperature $T$ is given by

$$a_{\max} = \frac{2(1+\eta)\sigma\varepsilon T^4}{c}\frac{1}{\alpha\,(1+\zeta)\rho t}. \tag{13}$$

The sail thickness must be chosen to maximize the acceleration and the efficiency, i.e. minimize the amount of light that passes through the sail and the energy absorbed by the sail. These considerations led Forward (1984a) to conclude that the thickness should be chosen such that the ratio $\eta^2/\alpha t$ is

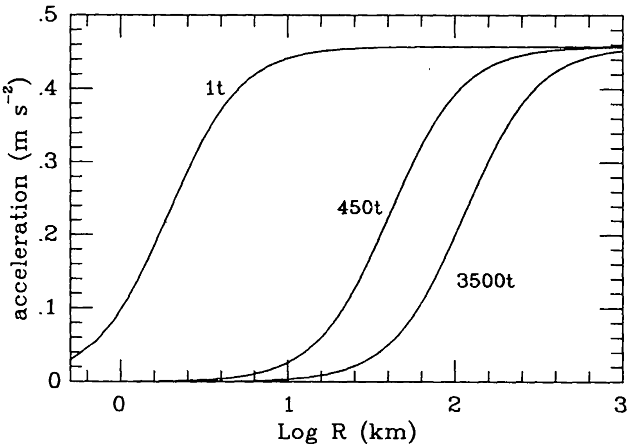


FIG. 1. The variation of light sail acceleration with sail radius, for payloads of 1, 450, and 3500 tonnes. These curves are appropriate for the 16-nm thick aluminium sail discussed in the text, operating at a temperature of 600 K and assuming $\zeta = 1$.

maximized. Forward discusses a number of possible sail materials and finds aluminium to be the most appropriate, for which the optimum thickness is 16 nm assuming a wavelength of 650 nm for the incident light. Finally, we note that, for a thin sail, the maximum operating temperature is far below the melting temperature because of a tendency for thin films to agglomerate into droplets. It appears that the maximum safe temperature for an aluminium sail would be about 600 K (Forward 1984a, and references therein). Thus, in what follows we will follow Forward and adopt values appropriate to a thin aluminium sail: $\varepsilon = 0{\cdot}06$, $\eta = 0{\cdot}82$, $\alpha = 0{\cdot}135$, $t = 16$ nm, $\rho = 2700$ kg m$^{-3}$, $T = 600$ K. For the case where $\zeta = 1$ (total structural mass equals sail mass), eqn (13) then gives

$$a_{max} = 0{\cdot}46 \text{ m sec}^{-2}. \tag{14}$$

Figure 1 shows solutions to eqn (12) for payload masses of 1 tonne, 450 tonnes (i.e. the nominal Daedalus payload) and 3500 tonnes (as might be appropriate for a manned mission, e.g. Forward 1984b). As follows from eqn (14), all of these curves tend to a maximum acceleration of 0·46 m sec$^{-2}$, but the vehicles with lighter payloads require much smaller sails in order to approach this limit.

The power required to achieve a given acceleration can be obtained from eqn (10), taking into account the size (and hence mass) of sail required (and again substituting $(1+\eta)$ for the factor 2). For example, if we wanted to send a 450 tonne payload on a flyby mission to $\alpha$ Centauri in 36 years (i.e. as could be achieved by the Daedalus vehicle) we would require a continuous acceleration of about 0·06 m sec$^{-2}$. Equations (10) and (12) show that we would require a sail diameter of 32 km (with a mass of 34 tonnes, excluding structural support) and a total transmitted power of $5{\cdot}1 \times 10^{12}$ W. The final velocity at $\alpha$ Centauri would be 23 per cent of the speed of light. The same mission flown with 1 tonne and 3500 tonne payloads would require sail diameters of 1·5 and 88 km, and transmitted powers of $1{\cdot}2 \times 10^{10}$ and $4{\cdot}0 \times 10^{13}$ W, respectively. Note that we have here neglected the Doppler effect, which will result in the power having to be increased gradually as the vehicle velocity increases. However, for the velocities of interest here, this is a relatively small effect, requiring a power increase of ~20 per cent over the duration of the mission.

Since diffraction will lead to divergence of the beam, very large transmitting apertures will be required. The diameter of the central peak in the Airy disk formed at a distance $s$ from a circular aperture of diameter $D$ is given by the familiar relation

$$d = 2{\cdot}44 s\lambda/D, \tag{15}$$

where $\lambda$ is the wavelength of light employed. For $\lambda = 650$ nm, it follows that aperture diameters of 42000, 2000 and 720 km would be required to produce beam diameters equal to the sail diameters of the 1 tonne, 450 tonne and 3500 tonne payload missions at the distance of the nearest star. Shorter wavelengths would result in smaller apertures; however, Forward (1984a) has suggested that a practical choice of laser may force the use of longer wavelengths ($\lambda \sim 1$ $\mu$m).

Another way to reduce the size of the transmitting aperture would be to employ higher accelerations, and cease power transmission when the vehicle has travelled some fraction of its total flight path. For example, the same 36-year flight to the nearest star could be achieved with an initial acceleration of 0·35 m sec$^{-2}$ lasting for 3·3 years, by which time the velocity would be 12 per cent of the speed of light (the same as envisaged for the Daedalus vehicle) and the spacecraft would be 0·06 pc from the solar system. The sail diameter, total vehicle mass, transmitted power and transmitting aperture diameters required for each of the three payloads considered above are summarized in Table II.

TABLE II

*Vehicle parameters for the three light sail missions discussed in the text*

| Payload (tonnes) | Sail diameter (km) | Total vehicle mass (tonnes) | Power (TW) | Transmitter diameter (km) |
|---|---|---|---|---|
| 1 | 6·9 | 4·2 | 0·24 | 440 |
| 450 | 147 | 1920 | 110 | 21 |
| 3500 | 410 | 14900 | 860 | 7·4 |

It appears that the transmitting apertures required are much larger than could plausibly be constructed for a single laser, and Forward (1984a) has advocated the construction of a Fresnel zone lens of the appropriate size. This lens would be stationed in the outer solar system and would collect the individual beams from a number of separate lasers situated in the inner solar system. It is also clear that very large power levels are required, typically many TW for all but the most modest missions. As in the case of antimatter drives, it appears that this energy must ultimately come from the Sun.

Although, at first sight, light sails appear only capable of accelerating a payload, Forward (1984a, b) has demonstrated (in principle) a method of light sail deceleration. The method involves splitting the sail into two concentric circles. When the vehicle approaches its destination, the outer annulus is detached and moved ahead of the inner sail to which the payload is attached. The latter is turned around so that the two reflective surfaces face each other, and the light beam is reflected from the large annulus onto the inner sail, thereby decelerating it. Of course, in order for this manoeuvre to work efficiently, the beam will have to be no larger than the outer annular sail at the distance of the target. This will require a very large transmitting aperture.

Before leaving interstellar light sails, we must briefly consider the effect of interstellar material on the sail. Considering that $1{\cdot}6$ kg m$^{-2}$ was found to be eroded from the Daedalus dust shield over its $1{\cdot}8$ pc flight to Barnard's star, and that a 16-nm thick aluminium sail would have a surface density of only $4{\cdot}3\times10^{-5}$ kg m$^{-2}$, the prospects for interstellar light sails would at first sight appear hopeless. However, Forward (1986) has argued that as the sail is so thin (much thinner than the $\sim 0{\cdot}1$ $\mu$m diameter of interstellar grains) the grains will pass straight through the sail, creating a hole only about as big as themselves, and depositing little of their kinetic energy in the sail. If we follow this assumption, and further assume a grain number density of $10^{-13}$ cm$^{-3}$ (estimated from a gas density of $0{\cdot}1$ atoms cm$^{-3}$ and a gas/dust number ratio of $10^{12}$) and a grain radius of $0{\cdot}1$ $\mu$m, the fraction of the surface converted into holes is $\sim 10^{-4}\times d$, where $d$ is the distance travelled in pc. Since we have shown above that, in order to minimize transmitter size, the acceleration phase would be best restricted to within less than a pc of the sun, interstellar grains would appear not to be a significant problem, *provided* that they only create holes as large as themselves. Presumably, this assumption could be tested in the laboratory.

Finally, we note that the total *mass* of interstellar gas is about 100 times that of the dust (Spitzer 1978, p. 7). Thus, the interstellar gas, tenuous though it is, will exert a drag on the necessarily large light sails. We can estimate the importance of this by considering the retarding force on the sail due to collisions between it and the interstellar gas. The retarding force is proportional to the sail area, the density of interstellar matter, and the square of the vehicle velocity, so the larger sails experience a larger force. However, since the total mass is also (approximately) proportional to the sail area, the retardation itself is essentially independent of this parameter. For each of the three missions listed in Table 2 (which have a cruise velocity of $0{\cdot}12\ c$) we find a retardation of $\sim 1{\cdot}9\times10^{-3}$ m sec$^{-2}$, assuming a hydrogen atom number density of $0{\cdot}1$ cm$^{-3}$. Although small, this is not negligible, and it would make sense to discard the sail after the acceleration phase.

## 6 THE LASER-POWERED INTERSTELLAR ROCKET

Rather than using the momentum of photons to push a light sail towards the stars, it may be possible to use the energy transmitted by a solar system based laser to heat a quantity of inert reaction fluid carried by the spacecraft. A relativistic treatment of such a vehicle has been given by Jackson & Whitmire (1978). Here we give a simple non-relativistic treatment of the laser-powered rocket which follows that given in Section 4 for antimatter rockets. The two cases are similar because, in the antimatter case, the mass of *energy* carried by the vehicle was assumed to be negligible, while in this case the vehicle carries *zero* energy since it all comes from outside. The mass of reaction fluid required by a laser powered spacecraft is therefore given by eqn (3).

If $E$ is the total energy beamed to the vehicle, and this is converted into exhaust kinetic energy with an efficiency $\varepsilon$, we have an expression similar to eqn (4), namely

$$E = \frac{1}{2\varepsilon} M_{\text{rf}} v_e^2. \tag{16}$$

Substituting eqn (3) into eqn (16) gives

$$E = \frac{\Delta v^2}{2\varepsilon} M_{\text{veh}} \frac{1}{x^2}(e^x - 1), \tag{17}$$

where $x = \Delta v / v_e$. As before, $E$ is minimized for $x = 1{\cdot}59$, so the energy required for a particular mission is given by

$$E = 0{\cdot}772 \frac{M_{\text{veh}} \Delta v^2}{\varepsilon}, \tag{18}$$

and the optimum mass ratio is 4·9, as in the antimatter case. Indeed, it follows from the above analysis, that this is the optimum mass ratio for *any* rocket which carries all its reaction mass but none of its energy.

Except for the very lightest payloads, eqn (18) indicates that a laser-driven rocket is a more efficient use of laser energy than a laser-pushed light sail. For example, the total energy required to accelerate the Daedalus 450 tonne payload to 12 per cent of the speed of light by this method (assuming $\varepsilon = 0{\cdot}5$) is $1{\cdot}2 \times 10^{21}$ J (where, as for the antimatter case, I have assumed a 20-tonne engine and a structural mass equal to 5 per cent of the reaction fluid mass, yielding $M_{\text{veh}} = 584$ tonnes). This compares to a total energy of $1{\cdot}1 \times 10^{22}$ J released over the 3·3 yr acceleration phase for the appropriate entry in Table II.

It is also interesting to compare this propulsion system with the antimatter rocket. If the conversion efficiencies of annihilation energy on the one hand, and beamed energy on the other, to exhaust kinetic energy were the same then, clearly, the energy locked in the antimatter in the former case equals half the transmitted power in the latter (compare eqns (4) and (16), remembering that $M_{\text{a}} = 0{\cdot}5\ M_{\text{en}}$ in eqn (4)). Thus, it appears that the laser-powered rocket will always require about twice as much energy as the antimatter rocket. However, recall that the *production* of antimatter is very inefficient (it was speculated in Section 4 that this efficiency might possibly be made to approach $10^{-5}$–$10^{-4}$ in a dedicated antimatter factory), so it is orders of magnitude more efficient to beam the solar energy to a laser-powered rocket than to use it to create antimatter as an intermediate step.

On the other hand, it may not be possible to design an engine that would be able to cope with the very high power levels involved. Also, although a laser-powered rocket dispenses with the need to produce large, very thin, light sails, it still suffers from many of the problems associated with light sailing, in particular the need to maintain a highly collimated beam over interstellar distances.

## 7 THE INTERSTELLAR PELLET STREAM

Singer (1980) has suggested that a stream of electromagnetically launched pellets might be used to transfer momentum to an interstellar vehicle. We see that physically this concept is similar to the laser-pushed light sail, except that material pellets (with a mass of a few g and velocity $\sim 0{\cdot}2\ c$) are used to transfer momentum rather than photons. As with the laser-pushed light sail, the major difficulty appears to be collimation of the pellet stream, although Singer has shown that it may be possible to correct the course of each pellet while in flight; something that is not possible with photons.

The pellet stream concept does not escape from the problems of ambitious in-space engineering as the electromagnetic launcher will probably have to be tens of thousands of kilometres in length in order to achieve the desired pellet velocities. However, if the engineering difficulties of the launcher can be overcome, and pellet collimation maintained, Singer was able to show that this concept offers considerable advantages over both fusion rockets (as no fuel is carried by the vehicle), and laser-pushed light sails (as high-quality optics are not required). As an example of the potential performance of the pellet stream technique, Singer considered its application to the nominal Daedalus mission (cf. his Table 1). In order to accelerate a 450 tonne payload to $0{\cdot}12\ c$ in 3·8 yr, a maximum launcher power of 15 TW is required. This is about half that generated by the Daedalus first stage, and almost an order of magnitude less than required by a laser-pushed light sail operating with the same acceleration distance.

## 8 PEOPLE TO THE STARS?

It seems likely that it will always be more difficult to send people to the stars than machines, and some proposed solutions to this greater problem are discussed in this and the following section. The extent to which manned interstellar travel can be justified from a strictly scientific point of view depends on the speeds that can be attained, and on the degree to which machine intelligence can be perfected. If machines can be produced that are as intelligent, and as versatile, as human specialists, then there may be no scientific justification for sending people at all. If this is not possible, there will eventually be a time when a *scientific* reason for sending people will exist. Moreover, as discussed in the Introduction, many of the motivations for sending people are social rather than purely scientific. There appear to be three ways in which human beings might travel to the stars.

(a) *World ships*. This concept envisions very large vehicles designed to carry a breeding population of human beings over interstellar distances. These vehicles would employ some form of nuclear propulsion to achieve velocities of $\lesssim 10^{-2}\ c$. The travel times would, of course, be very long ($\gtrsim 1000$ yr), the idea being that the remote descendants of the original pioneers would one day arrive at their destination. A recent review of the world ship concept, with references to its historical development, has been given by Martin (1984). As an example of the scale of vehicle considered, Bond & Martin (1984) have considered the construction of a cylindrical vehicle 20 km in diameter and 114 km in length. The cylinder is spun about its long axis so as to provide artificial gravity, and is designed such that its interior surface is as earth-like as possible.

Clearly, the motivation for building such large, slow vehicles, each carrying large numbers of people, could only be a programme of interstellar colonization. From a purely scientific point of view the returns would be very slow in coming, although *ultimately* scientific knowledge would be a major beneficiary of even a very slow expansion of humanity into interstellar space. Interesting moral and social problems arise when one considers the many generations that would be destined to live and die within a world ship before it reached any other stellar system; these are beyond the scope of this review, but have been discussed, for example, by Holmes (1984) and Regis (1985).

(b) *Suspended animation.* We have seen that a number of foreseeable propulsion technologies (e.g. fusion, laser and antimatter drives) may be capable of achieving velocities of 10–20 per cent of the speed of light. These velocities correspond to travel times of several decades for journeys to the nearer stars, and such a significant fraction of a life-span spent in transit is unlikely to be acceptable to a human crew. However, if some way can be found of drastically slowing down human metabolic processes, involving loss of consciousness as well as delayed ageing, there is no reason why travel times of decades would be unacceptable from a human point of view. An interesting review of recent biological/medical work which may have a bearing on suspended animation for spaceflight has been given by Hands (1985). There appears to be no fundamental reason why the human metabolism should not be greatly slowed down for several decades (or even stopped and then re-started?) although the necessary techniques do not exist at present.

(c) *Relativistic time dilation.* If an interstellar vehicle were to travel very close to the speed of light, relativistic time dilation would enable its crew to travel great distances in little time as measured in their frame of reference. An interval of ship-time, $\Delta t_s$, is related to an interval of Earth time, $\Delta t_0$, through the well-known relation:

$$\Delta t_s = \sqrt{\left(1 - \frac{v^2}{c^2}\right)} \times \Delta t_0, \tag{19}$$

where $v$ is the vehicle velocity and $c$ is the speed of light. It follows that as $v$ increases, the passage of time on the vehicle slows down. In the limit $v \to c$ $\Delta t_s \to 0$, and ship-time effectively stops. However, this effect only becomes significant as $v$ becomes close to $c$. For example, $\Delta t_0/\Delta t_s = 2{\cdot}3$, $7{\cdot}1$ and $22{\cdot}4$ for $v = 0{\cdot}9$, $0{\cdot}99$ and $0{\cdot}999\ c$, respectively.

In order to illustrate the potential of relativistic time dilation, let us follow an example described by Sagan (1963). Consider a vehicle capable of uniform acceleration, $a$, for the first half of its journey and deceleration at the same rate thereafter. Let $s$ be the total distance travelled. The relativistic expression giving the elapsed ship-time as a function of $a$ (measured in the ship frame) and $s$ has been given by Sänger (1957)

$$t_s = \frac{2c}{a}\cosh^{-1}\left(1 + \frac{as}{2c^2}\right). \tag{20}$$

Following Sagan, Fig. 2 shows the result of solving eqn (20) for $a = 10\ \mathrm{m\ sec^{-2}}$, i.e. for an acceleration equivalent to one Earth gravity.

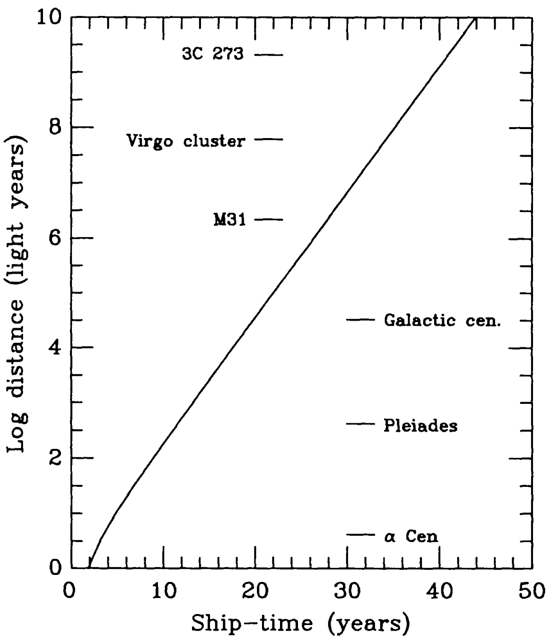


FIG. 2. Distance travelled as a function of ship-time for a vehicle which accelerates at 10 m $sec^{-2}$ for the first half of its journey, and decelerates at the same rate thereafter.

Classically, a vehicle would be moving at about the speed of light after 1 yr's acceleration at 10 m $sec^{-2}$, so it is clear that relativistic effects dominate within the first year. The distances to some well-known astronomical objects are indicated in Fig. 2, and it will be seen that the galactic centre would be reached in about 20 yr ship-time, the Andromeda galaxy in under 30 yr and the quasar 3C 273 in about 40 yr. In fact, such a vehicle would reach the edge of the observable universe (here taken to be $c/H$, where $H$ is Hubble's constant) in only 44 yr as measured by its crew! For the longer journeys considered here, it may still be desirable to employ some form of suspended animation to supplement the effect of time dilation. Of course, the number of years which pass on Earth while these trips are in progress is approximately equal to the distance travelled in light years.

## 9 THE INTERSTELLAR RAMJET

Continuous acceleration for a significant time is difficult to achieve with a rocket because of the very large mass ratios required (resulting from the extra mass of fuel required to accelerate the fuel which has yet to be used; cf. eqn. (1)). Even using antimatter (and ignoring the price!) continuous acceleration for decades at anything like 10 m $sec^{-2}$ would be impossible in practice. In 1960 Bussard proposed a solution whereby an interstellar vehicle would collect its fuel from the interstellar medium using a large scoop. Interstellar protons would then be fed into a fusion reactor and used to produce thrust.

By considering the conservation of energy, Bussard (1960) showed that the acceleration $a_s$ (measured in the frame of the vehicle) is given by

$$a_s = \frac{n m_p c^2 A}{M_s} \alpha\eta, \qquad (21)$$

where $n$ is the number density of interstellar protons of mass $m_p$, $A$ is the area of the scoop, $M_s$ the mass of the vehicle, $\alpha$ is the fraction of the collected mass that is converted into energy, and $\eta$ is the efficiency with which that energy is converted into exhaust kinetic energy. Strictly, eqn (21) is valid only for $\frac{v}{c} \gg \alpha\eta$, but as $\alpha = 0{\cdot}007$ for the proton–proton ($p$–$p$) chain, and $\eta \lesssim 1$, it is appropriate for the velocities of interest here. For a vehicle of mass 3500 tonnes operating in the solar neighbourhood, where $n \sim 0{\cdot}1$ cm$^{-3}$, eqn (21) implies a scoop intake radius of $10^4$ km for $a_s = 10$ m sec$^{-2}$. Of course, such a scoop could not be made of solid materials, and Bussard suggested that it be formed from an electric or magnetic field.

Of course, the use of electromagnetic fields requires the interstellar medium to be ionized, which is not generally the case. Previous studies have assumed that the local interstellar medium is neutral, and that it must be artificially ionized from the vehicle prior to collection, although Whitmire (1975) has drawn attention to physical problems associated with this suggestion. However, there is now evidence that the ionization fraction in the very local interstellar medium is quite large. For example, solar backscatter observations (reviewed by Cox & Reynolds 1987) suggest an ionization fraction of about 0·5–0·7. So, provided a ramjet can be designed to work in such a low density ($n_H \sim 0{\cdot}1$ cm$^{-3}$), artificial ionization may not be necessary (although, as stressed by Cox & Reynolds, further work is required to confirm this high degree of ionization, not least because there appear to be insufficient local ultraviolet sources to account for it).

Unfortunately, even if the local interstellar medium is largely ionized, there are a number of reasons why the performance indicated by eqn (21) is over-optimistic. First, as noted by Bussard (1960), the $p$–$p$ chain is extremely slow, requiring the attainment of very high densities in the reactor if it is to work effectively. However, at high density, bremsstrahlung and synchrotron radiation losses from the plasma will exceed the rate of energy production, and a self-sustaining $p$–$p$ fusion reaction will not be possible (Martin 1973). Indeed, it appears that similar objections hold for the deuterium–deuterium reaction (which is twenty-six orders of magnitude faster than $p$–$p$), and that only for deuterium–tritium fusion (about thirty-one orders of magnitude faster than $p$–$p$) is a self-sustaining reaction possible. There may be ways to overcome the losses in a deuterium reactor (e.g. Glasstone & Lovberg 1960, p. 39), but if the reactor is to burn deuterium, the appropriate number density, $n$, for use in eqn (21) is the number density of interstellar deuterium, requiring a vastly larger intake area for a given acceleration.

Moreover, there are serious problems with a magnetic scoop, which have been discussed in detail by Fishback (1969) and Martin (1973). Firstly, the necessary field geometry (strongest at the reactor entrance) resembles a 'magnetic mirror', and many incoming particles will actually be reflected by the field. Secondly, the particles will gyrate about the field lines, and if they do so with radii larger than the physical radius of the entrance aperture, they will not enter the vehicle. In order to maximize the fraction of incident particles that enter the reactor, Martin (1973) found that the maximum field strength (i.e. that at the entrance to the reactor) must increase as a function of velocity, rising from a few hundred tesla at $v = 10^{-4}c$ to $\sim 10^7$T at $v = 0{\cdot}9\ c$, with still stronger fields being required at higher velocities. (These very strong fields are needed to keep the particle gyration radius smaller than the reactor intake radius, assumed by Martin to be 100 m.) Even with these field strengths the intake fraction is very small, rising from less than $10^{-12}$ at $v = 0{\cdot}4\,c$ to $10^{-8}$ at $0{\cdot}9\,c$. As magnetic field strengths of millions of tesla seem not to be possible from an engineering point of view (owing to the stresses imposed on the magnet) Martin considered the effect of a 'technological limit' of 1000 T for the peak field strength, and found a maximum intake fraction of $1{\cdot}3 \times 10^{-12}$. Clearly, a low intake fraction means that the collecting area has to be increased proportionately. Even if sufficient fuel can be collected, Fishback (1969) has shown that, owing to the finite strength of materials, an interstellar ramjet will be unable to accelerate at 10 m $s^{-2}$ indefinitely, and has produced a modified version of Fig. 2 which illustrates the effect of this limitation.

Some of the problems associated with a magnetic scoop might be overcome by use of electrostatic fields. Possible configurations of electrostatic scoops have been discussed by Matloff & Fennelly (1977), who point out that, for an interstellar ion density of $10^5$ $m^{-3}$, a 20-coulomb charge would have an effective radius of influence of about $2{\cdot}4 \times 10^5$ km. Such a charge could be used to attract ions to the vicinity of the spacecraft, where additional electric or magnetic fields would be used to channel them into the reactor.

The many problems with the 'conventional' ramjet concept have led to a number of suggestions to improve its performance. Some of these are outlined below.

### *Catalytic ramjet*

Whitmire (1975) has suggested that the problems arising from the low cross-section of the *p–p* reaction may be overcome if the ramjet carries a catalyst to assist proton burning. For example, carbon could be used to enable the reactor to utilize the CNO cycle (such as occurs in hot stars), and other catalytic reactions may also be possible. The CNO cycle is about $10^{18}$ times faster than the *p–p* chain, and Whitmire was able to show that a catalytic proton burning ramjet is theoretically capable of maintaining an acceleration of 10 m $sec^{-2}$.

### *Ram-augmented interstellar rocket (RAIR)*

This concept was mentioned in passing by Bussard (1960) and developed (and named) by Bond (1974). The idea is for the vehicle to carry its own source of energy, but for it to collect interstellar gas to use as a reaction fluid. Thus, it would not have to rely on the *p–p* chain, but would still be able to collect most of the mass needed for propulsion from the interstellar medium. Of course, acceleration would only be possible for as long as the fuel lasts.

Bond (1974) found that the *RAIR* reduces the mass ratios required to achieve semi-relativistic velocities ($0{\cdot}5$–$0{\cdot}7\,c$) by several orders of magnitude relative to those of a conventional rocket. For example, for an ideal *RAIR* operating with a mass$\rightarrow$energy efficiency of $\alpha = 0{\cdot}002$ (i.e. appropriate for the burning of hydrogen and lithium) Bond found that a mass ratio of $1{\cdot}2 \times 10^2$ is required to achieve a velocity of $0{\cdot}7\,c$, compared to a mass ratio of $6{\cdot}4 \times 10^4$ for a conventional rocket using the same reaction (note that these values were derived from a simplified non-relativistic analysis, and that for $v = 0{\cdot}7\,c$ the *RAIR* mass ratio would actually be about 60 percent higher, cf. his equation (19)). Thus, although the *RAIR* offers a great reduction in mass ratios over conventional rockets, the mass ratios are numerically still quite large, and this method may not be able to achieve the extreme relativistic velocities needed to exploit time dilation.

Use of antimatter as the fuel reduces the *RAIR* mass ratio considerably. If we assume a mass → energy conversion efficiency of 0·4 (cf. Section 4) then Bond's analysis (his equation (19)) yields a mass ratio of 2 for an ideal *RAIR* with a final velocity of $0{\cdot}7\,c$. Of course, this implies a mass of antimatter equal to that of the empty vehicle, so it may be cheaper to make do with the higher mass ratio of a fusion *RAIR*! Use of antimatter in a *RAIR* has been considered in more detail by Jackson (1980).

The *RAIR* concept still suffers from the problems inherent in the design and construction of a scoop for the interstellar protons. Bond found that an intake radius of several thousand kilometres is required for operation in a region with 1 proton $cm^{-3}$, and this would have to be increased by a factor of about three for operation in the solar neighbourhood (ignoring the scoop inefficiencies discussed by Fishback (1969) and Martin (1973), which actually make matters much worse).

*Laser ramjet*

Whitmire & Jackson (1977) have discussed a vehicle which collects its reaction mass from the interstellar medium, but which derives its energy from a solar system based laser beam. It is therefore similar to the laser-powered rocket discussed in Section 6, but does not carry its reaction mass. Whitmire & Jackson find that such a vehicle makes more efficient use of the laser beam energy than laser-pushed light sails (as does the laser-powered rocket), and that, although the conventional ramjet is more energy efficient at velocities greater than about $0{\cdot}14\,c$, it does avoid the need for *p–p* fusion. However, owing to the Doppler effect, it will not be efficient for such a vehicle to operate at the relativistic velocities needed to exploit time dilation.

*Ramjet runway*

In the conclusion of their laser ramjet paper, Whitmire & Jackson (1977) suggest the possibility of laying down a track of deuterium pellets for later collection by a ramjet. The pellets would be electromagnetically accelerated from the solar system along the route later to be followed by the main vehicle. Provided that accurate collimation can be maintained, this concept would greatly ease the problems associated with large magnetic ramscoops. As pointed out by Whitmire & Jackson, in this case the scoop might even be a physical structure. However, it is not clear that sufficient fuel could be deposited along the runway to achieve a large acceleration and, in any case, acceleration would cease once the vehicle reached the end of the runway. Nevertheless, the concept may be of value for missions which require only semi-relativistic velocities ($\sim 0{\cdot}1\ c$), and its application to such missions has been discussed by Matloff (1979).

## 10 CONCLUSION

It will be clear from the above that neither the technology, nor the economic base, necessary to achieve rapid interstellar flight exists at present, and will not exist for decades or centuries to come. On the other hand, it is also clear that interstellar travel violates no physical law, and is therefore a legitimate technological goal for the distant future. We have already achieved the capability of very slow interstellar travel, and there is no reason to believe that the much higher velocities considered here will forever be out of reach. Indeed, nuclear fusion propelled vehicles, such as Daedalus, may be *technically* possible within the next several decades. However, given the size of the vehicle that must be constructed in space and the quantity of rare isotopes that must be collected, it seems certain that the world economy will not be able to afford such a thing until long after it has become technically feasible.

As all proposed methods of rapid interstellar travel involve large-scale construction activities in space, it seems certain that it will not become economically possible until a large space-based industry, and its associated infrastructure, has been built up for other, more utilitarian, purposes. Parkinson (1974) has considered this question, and concluded that only a truly interplanetary society, exploiting the economic potential of the whole solar system, will have sufficient economic strength to pursue a programme of interstellar exploration. We have seen that many proposed methods of interstellar travel will require the utilization of large quantities of solar energy, and it seems likely that only a competent space-faring society will be able to manage this on the necessary scale. Moreover, as pointed out by Finney (1987), it is likely that only a space-based society will be *psychologically* prepared for interstellar travel, or at least for the grander schemes of interstellar colonization.

I believe that all this has some relevance to the current debate about the scientific justification for an ambitious manned space programme. A number of eminent astronomers and space scientists have argued strongly against manned space programmes such as the Shuttle and the Space Station, because they draw funds away from the development of automatic spacecraft which generally yield a higher scientific return. These arguments have been clearly stated by Van Allen (1986) and, given his underlying assumption that the resources available for the entire civilian space sector will remain constant, they are fairly persuasive. However, by focusing on the very short-term future, these arguments neglect the very considerable long-term scientific benefits that will result from a human expansion into the solar system and beyond. As our knowledge of the Universe will necessarily remain limited as long as our instruments are restricted to the immediate vicinity of the Earth, and as rapid interstellar travel (even by automated probes) will only be possible once an extensive space infrastructure has been developed, I submit that the long-term interests of astronomy are inextricably linked to the human colonization of the solar system. The fact that these developments lie in the future does not, in the author's view, absolve the present generation of astronomers from a responsibility to consider them carefully when drawing up their philosophical and political positions.

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