ПРИЛОЖЕНИЕ 3

JBIS journal of the british interplanetary society

INTERSTELLAR STUDIES

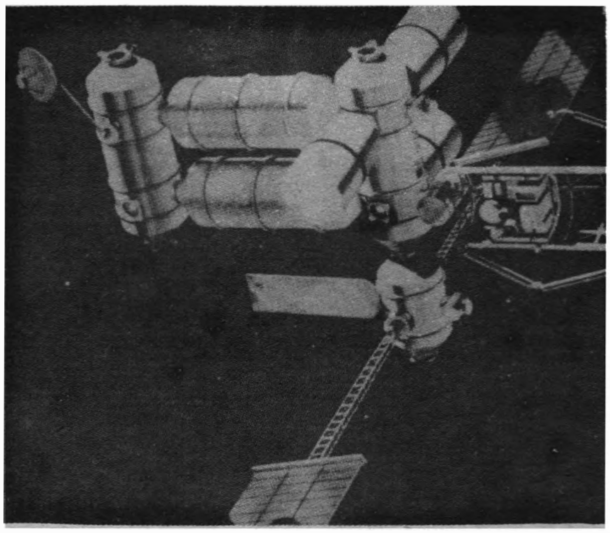
VOLUME 38 No. 3 MARCH 1985

PUBLISHED MONTHLY in LONDON

ISSN 0007-084X

SPACE STATION PLANS

The US Space Station is the next major manned space project of the western world, with initial operations in orbit expected in the early 1990's. Plans for participation are being considered by most European countries, including the UK. Our Society, which has long advocated permanent manned bases in space, will contribute further to the discussions by providing updated reviews at a one-day symposium. The date is 17 April 1985, the venue HQ. A provisional list of papers to be presented by a panel of international speakers will include the following:



1. **'European Space Station Overview,' by F. Longhurst (ESA).**
2. **'Space Station Platform - Overview,' by Dr. R.C. Parkinson (BAe).**
3. **'User Requirements for Space Stations,' by I. Franklin (BAe).**
4. **'Space Station Pressure Compartment,' by Prof. Valleriani (Aeritalia).**
5. **'Application of Propulsion Modules to Space Station Infrastructure,' by D. Gilmour (BAe).**
6. **'Orbital Replacement Units for Space Stations,' (Provisional).**
7. **'Assembly and Maintenance of Space Stations,' (Provisional).**
8. **'European Overview of the Space Station Proposals,' by R. Gibson.**

The Symposium will be held in the Society's Conference Room, 27/29 South Lambeth Road, London SW8 1SZ, England on 17 April, 9.30 a.m. to 5.30 p.m. The registration fee is £15 (non-members £17). Forms are now available from the Executive Secretary at the above address. The places remaining are limited so early application is advised.

1985 SUBSCRIPTION FEES

There is good news for all members: fees for 1985 will remain unchanged from 1984 in spite of rising costs.

Direct Debit Scheme

Our old Bankers Order system has been phased out. Direct Debit slips are now available from the Executive Secretary but, since they will not come into operation until 1986, a separate remittance for 1985 will have to be made.

Amounts payable for the calendar year January-December 1985 are as follows:

RATES

Members	Sterling	US Dollars
Under the age of 18 years	£16.00	$26.00
Between 18 and 20	£18.00	$30.00
21 years of age and over	£21.00	$36.00
Fellows	£23.00	$40.00

Age Allowance

A reduction of £4.00 ($6.00) is allowed to members of every grade over the age of 65 years on 1 January 1985.

JBIS and *Space Education*

The additional subscription payable for *JBIS*, where required as well as *Spaceflight*, is £20.00 ($34.00). For *Space Education*, it is £4.00 ($6.00).

Methods of Payment

Europe

(a) Please pay in sterling with a cheque which shows a UK address, where it can be paid.

(b) Cheques drawn in sterling payable at a bank in Europe must include £2.00 to defray charges and collection costs. Eurocheques have no charges *only* if the account number is written on the back.

(c) Banks which remit directly to the Society must be told to see that the sum is transmitted *free of deductions.*

(d) Remittances from Europe are best made by GIRO. Our GIRO account number is 53 330 4008.

USA and CANADA

(a) US dollar cheques can be drawn on a Bank which gives an address in the United States or in the UK. US dollar cheques drawn elsewhere need to be increased by $8.00 to cover collection charges.

(b) US dollar notes are accepted.

(c) US or Canadian money orders can only be accepted if *expressed in Sterling.* Internal money orders from these countries i.e. those expressed payable in dollars will be returned as they cannot be cashed in the UK.

(d) Canadian bank remittances may easily be made in sterling drawn on their UK agents. If payment is made in Canadian dollars the current exchange rate may be used, plus the addition of 8 Canadian dollars to cover exchange and collection charges.

JBIS journal of the british interplanetary society

INTERSTELLAR STUDIES

EDITOR: DR. A. R. MARTIN
Editorial Office: The British Interplanetary Society, 27/29 South Lambeth Road, London, SW8 1SZ, England. (Tel: 01-735 3160).

VOLUME 38 No. 3 MARCH 1985

CONTENTS PAGE

Printed by Unwin Brothers Ltd., at the Gresham Press, Old Woking, and Published by the British Interplanetary Society Ltd., (No. 402498). Registered Office: 27/29 South Lambeth Road, London, SW8 1SZ, England.

NGC 4753, in Virgo. A peculiar type SO galaxy, with irregular absorption bands.

Kitt Peak National Observatory

Journal of the British Interplanetary Society, Vol. 38, pp. 99-105, 1985.

CAN POPULATION GROW FOREVER?

PAUL BIRCH
51 Highland Drive, Bushey Heath, Herts., WD2 3HH, England.

Even advocates of space colonisation commonly assume that in the long term population growth must cease. This belief is examined and rejected. A strategy is outlined that would permit mankind to grow in population, knowledge and power forever. Certain difficulties that may arise in the far future of the Universe are considered and possible solutions put forward. It is shown that although an open universe does not succumb to the 'heat-death' the decay of very distant matter before mankind can reach it may be a problem.

1. INTRODUCTION

Thomas Malthus (1766-1835) enunciated the doctrine that populations grow geometrically whereas production grows at most linearly, so that the time must come when there is insufficient food, or coal, or steel for all [1-3]. The notion that population growth is inevitable, leading ultimately to disaster – economic collapse, starvation, extinction – we now call Malthusian.

This doctrine carried little weight with Victorian economists, for the predicted catastrophe quite failed to materialise. It was largely forgotten. But in the past few decades there has been a resurgence of concern about global population growth, an increased awareness of the so-called "Third World" and a widespread loss of faith in technology.

The Neo-Malthusian doctrine claims that resources are finite, that reserves are nearly exhausted and that the world population must be controlled at any cost. This goes beyond what Malthus wrote both in its pessimism and its harsh demands, which are now disseminated with a moral fervour not far from fanaticism. Exemplifying this new trend are a number of influential books [4-6] notable more for emotional rhetoric than for rigorous argument.

These works have been so successful as propaganda, however, that their ideas of the "limits to growth," the "dwindling reserves of non-renewable resources," the "population explosion" and the need for "zero population growth" (ZPG) are today accepted by the majority of people in the industrialised world. Their philosophy pervades the educational establishment, literature and the media; and millions of pounds are being spent on discouraging people from having children. Only a few brave voices [7] now resist this doctrine of doom.

Space activists are well aware of the potential of the industrialisation of space to solve many problems on Earth: Solar Power Satellites to provide energy, asteroid mining to provide raw materials, orbital factories to cure pollution, and so on and so on. They see the idea that there is "Only One Earth" [8] as absurd. These issues have been examined at length elsewhere [9-11] and need not be further enlarged upon.

However, even advocates of space colonisation have often absorbed, perhaps unwittingly, elements of the Malthusian ethos. Whilst claiming that "the end is not yet" they still accept the ultimate necessity for ZPG or that resources are finite [12-15]. Space colonisation, it is said, cannot "solve the population problem," since an advanced civilisation would still have to "control" its population. All too often, it is only argued that the use of resources from space can delay their eventual exhaustion.

A fundamental fallacy of the Neo-Malthusian school of thought lies in the claim that "natural resources are finite," for which there is not the slightest evidence (it is usually held to be "obvious"). On the contrary, what historical and scientific evidence we possess suggests that resources are *not* finite in any meaningful way, either physically or operationally. Throughout human history available resources and reserves have grown faster than the population, still do so today and can be expected to continue to do so in the future.

The economic effects of population growth are considered in Ref. 7, which, although considering space colonisation only in passing, gives a clear picture of the interesting and generally positive link between population growth and the availability of resources.

A somewhat different objection to indefinite population growth is that migration would be too costly or too slow, even if enough new territory could be found. In the field of interstellar colonisation Ref. 16 purported to show that exponential population growth must cease, because of the limited speed of migration possible from a growing sphere of influence. This idea has been used by CETI supporters as a rationalisation of the Fermi Paradox ("if extraterrestrials exist, where are they?" [17-18].

In this paper we shall argue that such considerations are misguided, and that there is every reason to believe in the potential for indefinite population growth.

2. LIMITS TO POPULATION GROWTH

In the past much population growth has been linked with technological innovations allowing greater population densities. It has been argued that there is a limit to this process, and this is surely plausible, since human beings as we know them require at least $\sim$100kg of mass and $\sim$100W of power to exist. We shall not be arguing in this paper for an ever-growing population density, but on the contrary will generally consider an ever-increasing mass and power per capita.

(However, it should be pointed out that if consciousness obeys the Biological Scaling Hypothesis of Ref. 19 it may in fact become possible to overcome the population density limit and embody persons with arbitrarily low mass and power requirements).

2.1 Velocity-Limited Population Growth

Consider a process of one-dimensional migration (a primitive tribe spreading along a river valley) where the average velocity of migration cannot exceed a value v and the population per unit length ρ is constant. The population at

late times will be:

$$P = \rho v t \quad (1)$$

Initially, when the population is less than given in Eq. (1), a period of exponential growth is possible, such that:

$$P = P_o \exp(\alpha t) \quad (2)$$

which can only continue until:

$$P_o \exp(\alpha t) = \rho v t \quad (3)$$

To put this into perspective, we note that, using typical values of $P_o=2$, $\alpha=0.02 yr^{-1}$, $\rho=1 m^{-1}$ and $v=0.01 ms^{-1}$, then the period of exponential growth is nearly 1000 yr. Such a tribe would by then have grown to ~300 million strong, over some 300,000 km of river valley.

It would appear that historically the maximum velocity of migration has not in itself limited population growth.

2.2 Migration in More Than One Dimension

Clearly migrations have not been restricted to one-dimensional river valleys, but have also crossed plains and seas. For such 2-D migration the long-term velocity-limited growth is quadratic:

$$P = \rho (vt)^2 \quad (4)$$

and exponential growth ends when:

$$P_o \exp(\alpha t) = \rho (vt)^2 \quad (5)$$

Using the same values as in Section 2.1 (but with $\rho=10^{-4} m^{-2}$ in 2-D) we obtain a final population $\sim 2 \times 10^{13}$ after 1500 yr of exponential growth, a large increase upon the 1-D case.

In the 3-D colonisation of interstellar space the limiting growth curve is cubic:

$$P = 4\pi/3 . \rho (vt)^3 \quad (6)$$

and exponential growth ends when:

$$P_o \exp(\alpha t) = 4\pi/3 . \rho (vt)^3 \quad (7)$$

Typical values that have been suggested as appropriate are $P_o \sim 10^{10}$, $v \sim 0.1$ ly/yr and $\rho \sim 10^{13} ly^{-3}$ (conservatively assuming a population $\sim 10^{15}$ per solar system), leading to a population $\sim 6 \times 10^{19}$ after about 1100 yr when the sphere of influence is about 110 ly in radius. Even if we put v=1 ly/yr and $\rho=10^{20} ly^{-3}$ exponential expansion ends after about 2400 yr and 2400 ly, although only a small fraction of the Galaxy has then been reached.

It would therefore appear that Ref. 16 is correct and that exponential growth must cease before the Galaxy is colonised. But we have argued too quickly and made several unwarrented assumptions.

First, we have assumed that the migration velocity is constant, but historically this velocity has increased with population growth and technological advance, a trend which we expect to continue. If the migration velocity obeys

$$v = v(t) = v_o \exp(\nu t) \quad (8)$$

then a population growth rate of $\alpha=3\nu$ is sustainable indefinitely. It may be objected that v cannot exceed the velocity of light and that Eq. (8) is therefore invalid, but we shall see in Section 3 that, for migration at least, the velocity of light barrier is illusory; this is quite apart from any possibility of FTL travel [20].

Second, we have assumed that the dimensionality is constant (and equal to three), but historically the dimensionality of migration has increased with population growth and technological advance, a trend which we expect to continue. It is speculative, but not unreasonable, to extrapolate beyond a dimensionality of three for the future. This may be possible, even in 3-space, if the topology is suitably complex, and black holes may provide this topological complexity (compare this with the effective dimensionality approaching two of the tributaries and distributaries of a nominally 1-D river valley).

2.3 Continued Exponential Growth in Velocity-Limited Migration

Even in the power term phase of population growth limited by the velocity of migration it remains possible for exponential growth to continue for part of the population.

A simple linear picture, in which each colony founds the next colony in line, is adequate for modelling the radial progression of the colonisation front after the initial phase of exponential growth.

Let the population growth rate in each colony follow:

$$\alpha_i = \alpha(1 - P_i/P_{max}) \quad (9)$$

where P_i is the population of the i-th colony, P_{max} the maximum population per colony and α the free growth rate. Then the population of each colony will grow exponentially initially and approach the maximum value [illegible] a standard S-curve.

It will be seen that the border colonies are [illegible] the exponential growth phase where both the growth [illegible] and emigration rates are high. Only [illegible] the growth rate gradually [illegible] but never reaching [illegible] population growth. [illegible] to note that in such a scenario population [illegible] necessary for the pioneer families [illegible] front, only in the long-settled regions [illegible]. In the case of interstellar colonisation each colony [illegible] exponentially for about 1500 yr. A similar [illegible] occurred during the frontier days of America.

It is therefore apparent that even if migration [illegible]-limited, enforced ZPG, with its radical social implications, is unnecessary, improbable and undesirable. The argument that colonisation of the Galaxy will cease as a result of the social change of ZPG, so purportedly resolving the Fermi Paradox [17], is thus seen to be flawed; and the conclusions of the Hart-Viewing chauvinists [21-23], that extraterrestrial intelligent beings do not exist, are upheld. It is because of this that I implicitly assume the uniqueness of mankind; however, if in fact ETI exist the main conclusions of this paper can be readily adapted.

3. STRATEGY FOR INDEFINITE POPULATION GROWTH

In this section we shall derive a relativistic strategy, which is not "velocity limited," for indefinite population growth. It will not make use of hypothetical new physics (such as FTL travel) and will permit net per capita industrial growth, so that wealth will increase along with population.

3.1 Euclidean Space-Time

We begin by considering a static universe of constant energy

density in Euclidean (flat) space-time; this will give a good description for colonisation out to about the Hubble radius (~3 Gpc), but thereafter a more sophisticated analysis will be needed.

We assume that the population grows exponentially and encompasses a volume V at a given time t. In order to emigrate to a new world it is necessary to travel, on average, a distance $d \sim V^{1/3}$, in a constant (or at most logarithmically increasing) length of time as experienced by the migrant.

Thus the journey time must be carried out at a Lorentz factor $\gamma \propto d$, such that the elapsed time on board is $\tau \sim d/\gamma c$. This means that the proper speed $\sim \gamma c$ is unlimited.

To the rest of the Universe the migration wave travels at the speed of light (close enough), but subjectively or 'historically' the effective speed is γc and ever-increasing. The energy consumed is proportional to the Lorentz factor and the proper speed.

For a population P, population density ρ and historic time t:

$$P = P_o \exp(\alpha t) \quad (10)$$

$$\rho = \rho_o \exp(-\beta t) \quad (11)$$

$$V = P/\rho = (P_o/\rho_o) \exp((\alpha+\beta)t) \quad (12)$$

$$\gamma \propto d \propto V^{1/3} \propto \exp((\alpha+\beta)t/3) \quad (13)$$

The emigration rate per unit volume is proportional to the population density, so the power density requirement is given by:

$$P \propto \rho \propto \gamma \propto \exp(((\alpha+\beta)/3-\beta)t) \quad (14)$$

But if the power density is held constant we obtain:

$$\beta = \alpha/2 \quad (15)$$

This strategy will allow continuous population growth with $P \propto \exp(\alpha t)$, $\rho \propto P^{-1/2}$, $V \propto P^{3/2}$ and $\gamma \propto d \propto P^{1/2}$. If we equate industry with power consumption the industrial growth rate is 3/2 times the population growth rate (gross) and 1/2 (net per capital). In economic terms this is not hard to achieve, since typically the industrial growth rate is about twice the population growth rate.

The emigration rate per capita is here $(\alpha+\beta)=3\alpha/2$ and the total emigration per unit volume is $(\alpha+\beta)\rho_o/\beta=3\rho_o$. Thus the material resources required per unit volume over all time remains finite.

Suppose the total available energy per unit volume to be limited, such that the available power density decreases exponentially:

$$p = p_o \exp(-\epsilon t) \quad (16)$$

We may put:

$$(\alpha+\beta)/3-\beta=-\epsilon<0 \quad (17)$$

Typically, however $\alpha \sim \beta \sim 10\text{yr}^{-1}$ whereas $\epsilon \leq 10^{-10}\text{yr}^{-1}$ for astronomical power sources; hence:

$$\beta=\alpha/2+3\epsilon/2 \simeq \alpha/2 \quad (18)$$

That is, a very slight additional decrease in population density allows exponential growth to continue, even though the total energy density be finite and decreasing exponentially, perhaps through a process such as proton decay [24].

3.2 Open Universe

In an open universe the geometry of space-time is hyperbolic. In the standard models the universe is infinite in extent and will expand forever [25]. There is evidence that our universe is of this type [26].

For colonisation beyond the Hubble radius (redshift z= 1) the expansion of the universe becomes most important. If the cosmic time is ξ the proper distance to a galaxy is [19]:

$$d \sim \psi \exp(\xi) \quad (19)$$

where ψ is a normalised angular distance parameter related to the curvature of space-time. The number of galaxies within this distance scales as [19]:

$$N \sim \exp(2\psi) \quad (20)$$

If the galaxies were mutually at rest it would take a time $d/c \sim \psi \exp(\xi)$ to reach such a galaxy, but because of their mutual recession we find that this time is increased by a factor $\sim \exp(\psi)$. Thus the Lorentz factor required for the migrants' journey:

$$\gamma \sim \psi \exp(\psi) \exp(\xi) \quad (21)$$

The term $\exp(\xi)$ is the time elapsed from the origin of the universe in Hubble periods, which scales as t at late times. We have:

$$\gamma \sim \ell n N . N^{1/2} . t \quad (22)$$

Since $N \sim \exp((\alpha+\beta)t)$ for exponential population growth:

$$\gamma \sim t^2 \exp((\alpha+\beta)t/2) \quad (23)$$

The required power density is therefore:

$$p \sim \rho\gamma \sim t^2 \exp((\alpha-\beta)t/2) \quad (24)$$

For constant or slowly decreasing power density, noting that the exponential outweighs any power term, we obtain:

$$\beta \simeq \alpha \quad (25)$$

This strategy allows for continuous growth with $P \propto \exp(\alpha t)$, $\rho \propto P^{-1}$, $N \propto P^2$, $\psi \propto t$ and $\gamma \propto t^2 P$ at late times. The emigration rate per capita is 2α and the total emigration per unit initial volume ρ_o. The total energy required per unit initial volume (at cosmic times ξ_o) $\sim \int t^2 \exp((\alpha-\beta)t/2)dt$ which converges provided that $\beta-\alpha=\epsilon>0$; thus both material and energy requirements per galaxy remain finite over all times. The gross industrial growth rate for this strategy is twice the population growth rate.

3.3 Closed Universe

It may be that the universe is actually closed and finite. The strategy given above would then only work for a limited time, until the whole universe had been filled up.

We may speculate as to how further expansion might then be made possible. For example, General Relativity apparently predicts that traversing the ergosphere of a large rotating black hole may bring one into another universe containing a copy of the black hole [28]; repeated passes through the black hole would give access to an infinite series of universes. It may even be that we shall eventually be able to create universes at will, merely by collecting stars together into a black hole. If something of the sort is true, then the

TABLE 1. Timescales for Astronomical Processes (from Refs. 19 and 27).

Astronomical Process	Astronomical Duration-yrs	Historical Time from Present-yrs
Main sequence star formation and evolution	10^{11}	3300
Formation of stellar black holes	10^{11}	3300
Low mass stars cool down	10^{14}	3700
Planets detached from stars	10^{15}	3800
Stars detached from galaxies	10^{19}	4300
Formation of galactic black holes	$\lesssim 10^{20}$	$\lesssim 4400$
Decay of orbits by gravitational radiation	10^{20}	4400
Proton decay	10^{31}	5600
Decay of stellar black holes	10^{64}	9400
Matter loses structural strength (cold flow)*	10^{65}	9600
Decay of galactic black holes	10^{97}	13200
Positronium formation and decay	$\gtrsim 10^{116}$	$\gtrsim 15400$
Quantum tunneling of nuclei to iron *	10^{1500}	175000
Quantum tunneling of matter into black holes	$10^{10^{26}}$	1.2×10^{28}

* if nucleons are stable (protons do not decay)

effective extent and dimensionality of space-time would be infinite (or, more strictly, indefinite).

We may also note that in an open universe of infinite extent and marked inhomogeneity there may exist large relatively dense regions that appear from within as closed universes [29]; such regions would form "bubbles" or "island universes" in a wider sea. By the same token a closed universe might be locally "burst open" [30] to expand forever or give access to a wider universe that may be truly infinite.

It must be emphasised that these suggestions are highly speculative. Nevertheless, they illustrate the fact that even a closed and finite universe may not place any ultimate limits upon mankind.

4. DIFFICULTIES AT LATE TIMES

The simple scenario given in Section 3 encounters certain difficulties at late times, not all of which appear readily solvable at present. Some, such as the construction of relativistic starships, are straightforward technological problems for which outline solutions can be given. Other are more profound.

4.1 Elapsed Cosmic Time in Distant Galaxies

The time taken for a colonist to reach a distant galaxy may be only decades for him, but for the universe a long time will have elapsed. A galaxy at arc parameter ψ can be reached at cosmic time ξ:

$$\xi \sim \psi \tag{26}$$

Since the arc parameter is also proportional to the historical elapsed time t we have:

$$\xi \sim t(\alpha+\beta)/2 \tag{27}$$

If the arrival time, counting from the beginning of the universe, is $T \sim \exp(\xi)$ we find that typically, at times $t >> 50$yr:

$$T \sim 10^{-18}\text{yr} \,.\, \exp(T/50\text{yr}) \tag{28}$$

Thus after a short span of millenia in historical time the colonists may arrive at their destination in a very much older universe. When $T \sim 10^{12}$yr it is likely that most of the stars will be dead, yet this circumstance may be met by colonists within $\sim$3500 years of history.

If no energy sources survive for the colonists' further use then migration will – apparently – have to cease. Although the stars will go out in a comparatively short time, other energy sources – gravitational potential energy, proton decay, black hole evaporation – will last far longer; Table 1 gives timescales for these phenomena, both in cosmic time and our putative historical time.

Whether any form of matter or usable energy (such as dust grains or positronium) can be expected to survive in appreciable quantities forever naturally (without intelligent intervention) is uncertain, but at present it appears unlikely. This may therefore be a fatal flaw in the expansion scenario at late times, and as yet no definite solution has been found. (However, we may note that FTL travel might provide such a solution – and see also Section 5.4).

4.2 Population within Horizon

In the scenario given above the population density falls with time. If we consider a minimum society of a certain number of persons it is apparent that its physical extent must increase with time. The limit to this process is evidently the amount of matter within the causal horizon which even at late times scales only as t^2. Thus the exponential decrease of population density will in due course lead to an arbitrarily low population (less than unity!) within the horizon. (The concept of a causal horizon does assume that there is no FTL travel).

To overcome this limit it would appear that the population density must decrease no faster than t^{-2} at late times. This is likely to necessitate a comparable reduction in emigration and population growth rates, but at no time would the growth rate actually become zero or negative. Growth remains possible within a growing causal horizon.

4.3 Decay of Matter within Horizon

In order for a society to grow in population and power indefinitely the amount of available mass and energy within the horizon must continue to grow. But at late times exponential decay of matter (proton decay, etc.) would become important, since the mass $\sim t^2 \exp(-\epsilon t)$ would eventually tend to zero, and life (at least on our restrictive assumptions) would become impossible.

To avoid this fate we must find ways to store matter and energy stably, or with an increasing decay time $t_{dec} \sim t^r$, $r \geq 1$.

For black holes the decay time $\sim M^3$, and if we bring together black holes of mass $M \sim t^2$ (a constant fraction of the mass within the horizon) the decay time increases rapidly $\sim t^6$, while the emitted power falls $\sim t^{-4}$. If instead one uses ever more black holes of mass $M \sim t^{1/3}$ then $t_{dec} \sim t$ and the emitted power within the horizon $\sim t$. Between these limits lie a range of possibilities.

4.4 Extraction of Black Hole Energy

Energy may be extracted from black holes either by collecting the power emitted as they decay (a quantum mechanical phenomenon) or by extracting the mutual gravitational energy of coalescing black holes or the rotational energy of a spinning black hole classically.

A black hole of mass M has a temperature $T \sim M^{-1}$, a decay time $t_{dec} \sim M^3$ and an emitted power $P \sim T^4 R^2 \sim M^{-2}$. We can immediately see that if the black hole temperature is not to fall below the background temperature (which scales as t^{-1}) we must have black holes of mass $M \sim t^r$ where $1 \geq r \geq 1/3$.

In order to capture the radiation of the black holes we must surround them with absorbing shells. If we employ a mass M_{cap} for this purpose it must be supported by a pressure $p \sim (M_{cap}/R^2)(M/R^2) \sim M_{cap}/M^3$, which implies a total support energy and mass $\sim M_{cap}$ for $R \sim M$. The amount of capture mass may be estimated in several ways: the number of electrons needed to absorb the black hole radiation is $Ne \sim P/T^3 \sim M$; and a complete shell of dipoles of constant cross-section and length $\sim T^{-1} \sim M$ has a mass $\sim R \sim M$. Thus the total mass required for capturing the radiated power is proportional to the mass of the black hole itself.

However, because of proton decay or other disordering mechanisms the capture mass must be repaired on a fixed timescale and therefore demands a constant specific power. Since $P \sim M^{-2}$, $P/M_{cap} \sim M^{-3}$, so the size of useable black hole is limited (unless a structure requiring repair only on increasing timescales can be found). This is the problem met in Ref. 27.

This problem may be overcome by maintaining two black hole populations; one with mass $M \sim t^{1/3}$ for indefinite storage of mass and energy; another of black holes allowed to decay from the storage mass to a standard mass useable as a power source at constant specific power. But only a decreasing fraction $\sim M^{-1}$ of the stored energy could be used.

We may also generate power by classical (i.e. not quantum mechanical) gravitational interactions. For example, a smaller body orbiting a rotating black hole or a binary pair of black holes will experience accelerations $\sim M/R^2 \sim M^{-1}$ and can extract energy at a specific rate $\sim M^{-1}$ (for a standard velocity $\sim c$). The time taken to extract all the available energy will vary as M^2/M_{sub}, so the subsidiary mass should not be reduced faster than M^{-1}.

If the subsidiary mass were of normal matter it would decay in a fixed time (since the specific power $\sim M^{-1}$), but if it consisted of one or more black holes with $M_{sub} \sim M^{1/3}$ (or greater) there would be enough power for their repair or replacement. The energy extraction would then take a time $\sim M^{5/3} \sim t^{5/9}{}_{dec}$. Since the ultimate extraction to normal matter requires a constant specific power and standard black hole mass, additional stages, utilising smaller and smaller black holes, would be needed. However, the number of stages would grow very slowly $\sim \log\log M$, and although there might be a certain loss at each stage the overall loss would only grow as $\log M$; typically the number of stages would be $\sim (2.1 \log(33+\log(M/Mo))-3.5)$.

This multi-stage classical scheme for the extraction of energy from black holes appears to offer the efficiency and flexibility we desire at all epochs, and to overcome the problems caused by proton decay and other disordering mechanisms.

5. SCENARIOS FOR BLACK HOLE GROWTH

If the thermal radiation of black holes is to be used it will be appropriate to put $t_{dec} \sim t$ and $M \sim t^{1/3}$. More generally we put $M \sim t^r$. The total mass used to create a black hole of mass M we shall call M_T.

Black holes must be brought together over increasing distances $\sim t . \ln M_T$ over a time interval $\sim t$, against the expansion of the universe with redshift $\sim \ln M_T$. A cumulative specific energy $\sim \gamma \sim (\ln M)^2$ is thus required.

5.1 Coalescence of Black Holes

When two black holes coalesce the mass of the resulting black hole is greater than the mass of either but less than the sum. If two black holes of mass M coalesce to form one of mass 2Ma, the amount of energy released will be 2M(1-a). According to the laws of Black Hole Thermodynamics [31] $1/2 \leq a \leq 1$ and for typical energy extraction mechanisms $a \simeq 0.8$.

After n stages of coalescence (starting with black holes of mass M_o) the black hole mass is $2^n M_o a^n$ and the cumulative energy released is $2^n M_o(1-a^n)$. The cumulative specific energy $E=(1-a^n)/a^n \sim a^{-n}$.

Given that $M \equiv 2^n M_o a^n \sim t^r$ we have $n \sim \ln t$; substituting for n yields:

$$E \sim a^{-r\ln t/\ln 2a} \sim t^{-r/(1+\log_a 2)} \tag{29}$$

This varies from zero for a=1 (no conversion), through $t^{r/2}$ for $a \simeq 0.8$, to infinity as $a \rightarrow 1/2$ (black hole mass not increasing). The total mass used grows faster than the black hole mass itself as:

$$M_T = 2^n M_o \sim t^r/a^n \sim t^{r/(1+\log_2 a)} \tag{30}$$

This still demands only a logarithmically growing cumulative specific energy, by comparison with a power-law release; there is thus ample energy for black hole collection at all times.

Now if the trapped energy fraction should decrease with mass as $M^{-\mu} \sim t^{-\mu\alpha}$ the cumulative specific energy obtained will be reduced to:

$$E=((1-a)+a(1-a)(2a)^{-\mu}+a^2(1-a)(2a)^{-2\mu} + \ldots)/a^n \tag{31}$$

$$E=(1-a)/a^n.((a(2a)^{-\mu})^n-1)/(a(2a)^{-\mu}-1) \tag{32}$$

It may be seen that we still have $E \sim a^{-n}$, the actual value being changed only by a factor of order unity.

5.2 Black Holes within Causal Horizon

Since the total mass-energy within the causal horizon scales as t^2 the total number and mass of black holes within the horizon will scale as:

$$N \sim t^{2-r/(1+\log_2 a)} \tag{33}$$

$$NM \sim t^{2+r/(1+\log_a 2)} \tag{34}$$

The total available power within the horizon is:

$$P_T \sim t^{2-1+r/(1+\log_a 2)-lr/(1+\log_2 a)} \tag{35}$$

$$\text{i.e. } P_T \sim t^{1+r(1-\mu \log_a 2)/(1+\log_a 2)} \tag{36}$$

The rate of increase of available power is maximised when $r=1/3$ (as its minimum allowed value) and when $\mu=0$ (although the power still increases even if $\mu=1$).

Since a classical multi-stage scheme can provide $\mu \simeq 0$ at $a \simeq 0.8$ and $r=1/3$ we may choose such a scenario yielding $N \sim t^{1.51}$, $NM \sim t^{1.84}$ and $P \sim t^{0.84}$. The sustainable amount of normal matter $\sim P_T \sim t^{0.84}$, so both population and per capita wealth may continue to grow indefinitely.

5.3 Information Storage and Processing

Continued growth without the memory or historical records of times past and an accumulation of scientific knowledge and works of art would be of dubious value, so we must ask whether sufficient data can always be stored and processed.

Within the Earth-like environments information can be handled at a rate $\sim P_T \sim t^{0.84}$. But data can also be stored in the form of zero-rest-mass particles or radiation in space, where the energy per bit can scale as $T \sim t^{-1}$. Since the radiative energy within the horizon $\sim t^2$ the storage capacity within the horizon $\sim t^3$; this compares favourably with what is needed to allow a constant storage bit rate per unit of power consumed, which scales only as $t^{1.84}$ (that is, where the amount of data stored per capita is proportional to the amount of energy consumed per capita).

The power available for computing scaling as $t^{0.84}$ while the energy consumed per operation $\sim t^{-1}$, the processing rate or computing power scales as $t^{1.84}$. That is, all knowledge ($t^{1.84}$) can be accessed in a fixed length of time ($\sim t^{1.84-1.84}$), say one lifetime, at all epochs.

5.4 Effect of Background Radiation

Hitherto we have considered the background radiation only as the limiting thermodynamic cold heat sink; since according to the Second Law of Thermodynamics it is apparently useless for doing work. The 'heat death of the universe' is supposed to occur when all energy sources reach the temperature of the background, when their entropy is maximised and no more work can be done. However, since the universe continues to expand, and the temperature to fall, entropy can increase without limit, the heat-death never occur, and in principle even the maximal-entropy background radiation be used again.

If black holes have mass $\sim t^r$, $r \geq 1$ they will become cooler than their surroundings and absorb the background radiation. In these circumstances the effective value of the mass fraction a may equal (or exceed) unity, allowing $P_T \sim t$ and the ratio of black hole mass to background radiation mass to be held constant. Such a scheme may be useful in rehabilitating regions where all matter decays before mankind can reach them; this would appear to solve the problem of Section 4.1.

6. CONCLUSIONS

In this paper we have argued that widely held beliefs concerning the necessity for long-term zero population growth and the finitude of natural resources are in error. We have reached the remarkable conclusion that mankind can grow in population, knowledge and power forever.

It must be emphasised that these scenarios are not to be taken as actual predictions. Many of the details presented here would have been inconceivable scarcely a decade ago and the growth of science and technology is sure to outdate them within centuries (let alone 10^{100} years!). Nevertheless, since new knowledge can but increase our capabilities, we shall be able to do at least as much as I have described. This paper is thus a form of "existence proof" of an unlimited, an ever-open, future.

Does the Second Law of Thermodynamics really imply that we live in a dying universe? Many cosmologists of this century have accepted this depressing interpretation: "The more the universe seems comprehensible, the more it also seems pointless" [32]. Is human civilisation really doomed? Many think so: "It seems to me, then, that by 2000AD...man's social structure will have utterly collapsed...Nor is there likely to be a chance of recovery thereafter" [33].

But now, rejecting both sad claims, we may return to the hope of illimitable progress that is held at the heart of Western civilisation in the Judeo-Christian tradition [34, 35], in which, despite the ephemeral nature of this world, the ultimate hegemony of entropy is explicitly rejected: "And I saw a new heaven and a new earth...'Behold, I make all things new'" [36]; and a doctrine of eternal growth proclaimed: "And of the increase of his government and of peace there shall be no end" [37].

If then, population can continue to grow, without ecological burdens or economic burdens (as argued in Ref. 7) and without fear of "Malthusian catastrophe" (as argued in this paper), we ought still to ask whether such growth is desirable – for, as we have already seen, value judgements are essential to a complete study of this problem. Personal bias in favour of small populations may perhaps be suspected where a "global village" of relatively low population is recommended as the humanly optimum solution [38], but it is apparent that such arguments are usually based less on supposed intrinsic merits than upon Malthusian doctrines.

Is population growth, then, a good thing? I submit that, insofar as parents obtain pleasure from their children and have a desire for large families, it is good that their desires should be fulfilled. For it is pleasant to be part of a growing society, enlivened by children and young people. For this we must have population growth. Furthermore, I submit that, insofar as a person's life has on balance a positive value (and most people believe their own lives to have such value), is it good that many lives should be lived. For the more people there are, the greater the value, and the greater the total good that they can engender. For these – and other – reasons I would claim that population growth is indeed intrinsically a good thing, a conclusion which is in accord both with the utilitarian criterion of the "greatest good of the greatest number" and the biblical injunction to "be fruitful and multiply" [39].

We conclude therefore that it is both possible and desirable for mankind to grow in numbers, knowledge and power indefinitely.

REFERENCES

1. T. R. Malthus, An Essay on the Principle of Population Growth, London: J. Johnson (1803).
2. T. R. Malthus, Principles of Population, Homewood, Ill.: Irwin (1817/1963).

3. T. R. Malthus, J. Huxley and F. Osborn, On Population: Three Essays, New York: New Amer. Lib., Mentor Books (1830/1960).
4. P. R. Ehrlich, The Population Bomb, New York: Ballantine (1968).
5. D. H. Meadows, D. L. Meadows, J. Randers and W. W. Behrens, The Limits to Growth, New York: Potomac Ass. (1972).
6. W. Paddock and P. Paddock, Famine-1975!, Boston: Little, Brown (1967).
7. J. L. Simon, The Ultimate Resource, Princeton: Princeton University Press (1981).
8. "Only One Earth," World conference, Stockholm (1969).
9. A. Berry, The Next Ten Thousand Years, London: Hodder & Stoughton (1974).
10. G. H. Stine, The Third Industrial Revolution, New York: Ace, Grosset & Dunlap (1975).
11. T. A. Heppenheimer, Colonies in Space, New York: Warner (1977).
12. I. Asimov, A Choice of Catastrophes (ch15), London: Hutchinson (1980).
13. J. E. Pournelle, A Step Further Out, London, W. H. Allen (1980).
14. G. K. O'Neill, The High Frontier, New York: Morrow (1977).
15. C. Sagan, Cosmos (ch12), London: Book Club Assoc. (1980).
16. S. von Hoerner, "Population explosion and interstellar expansion," *JBIS*, **28**, 691-712 (1975).
17. L. J. Cox, Reply to Ref 21 in *Quart. J. Roy. Astr. Soc.*, **17**, 201-208 (1976).
18. A. G. Smith, "Constraints limiting the rate of human expansion into the Galaxy," *JBIS*, **34**, 363-366 (1981) – see also Correspondence, *JBIS*, **35**, 142-144 (1982).
19. F. J. Dyson, "Time without end: Physics and Biology in an open universe," *Rev. Mod. Phys.*, **51**, 447-460 (1979).
20. P. Birch, "Is faster-than-light travel causally possible? *JBIS*, **37**, 117-123 (1984).
21. M. H. Hart, "An explanation for the absence of extraterrestrials on earth," *Quart. J. Roy. Astr. Soc.*, **16**, 128-135 (1975).
22. F. J. Tipler, "Extraterrestrial intelligent beings do not exist," *Quart. J. Roy. Astr. Soc.*, **21**, 267-281 (1980).
23. C. E. Singer, "Galactic extraterrestrial intelligence -I," *JBIS*, **35**, 99-115 (1982).
24. J. C. Pati, "Grand unification and proton stability," Univ. of Maryland preprint No. 79-171 (1979).
25. C. W. Misner, K. S. Thorne and J. A. Wheeler, Gravitation, San Fransisco: W. H. Freeman (1973).
26. D. N. Schramm and E. Steigman, *Astrophys. J.*, **243**, 1-7 (1981).
27. S. Frautschi, "Entropy in an expanding universe," *Science*, **217**, 593-599 (1982).
28. See Ref. 13 for overview of black hole theory.
29. J. R. Gott III, *Nature*, **295**, 305-307 (1982).
30. See Ref. 19, and Ref. 29 and references therein.
31. Ref. 25, pp. 887-891.
32. S. Weinberg, The First Three Minutes, New York: Basic (1977).
33. I. Asimov, Quoted in Ref. 13.
34. J. M. Roberts, The Pelican History of the World, London: Hutchinson, Pelican (1980).
35. R. S. Swinburne, The Existence of God, Oxford: Clarendon Press (1979).
36. Revelations 21 vv 1&5.
37. Isaiah 9 v 7.
38. I. Asimov, Towards Tomorrow, London: Hodder & Stoughton (1977).
39. Genesis 1 v 28.

* * * * * * *

Journal of the British Interplanetary Society, Vol. 38, pp. 106-112, 1985.

OBSERVABLE CHARACTERISTICS OF EXTRATERRESTRIAL TECHNOLOGICAL CIVILISATIONS

ROBERT A. FREITAS, JR.
Xenology Research Institute, 8256 Scottsdale Drive, Sacramento, California 95828, USA.

Advanced extraterrestrial civilisations which make extensive use of the fusion fuel resources of their local star and planetary system have numerous potentially observable characteristics. A circumstellar nuclear fuel molecular effusion cloud, the principal observable, rapidly dissociates and neutralises to the atomic ground state, permitting the detection of hydrogen and tritium hyperfine transition radio lines at 1420 MHz and 1516 MHz, respectively. The negligible natural abundance of neutral atomic ground-state tritium suggests that its hyperfine line, the "tritium waterspout" centred in the radio SETI "waterhole" band, is ideal for interstellar communication and future SETI searches. Other possible observables of advanced civilisations include redshifted neutrino point sources, an artificial radio spectrum, anomalous blackbody radiation, fission waste absorption lines, Doppler and stellar spectral anomalies, and extraordinary magnetic fields.

1. INTRODUCTION

Conditions favourable to the development of life, intelligence, and civilisation may be widespread in the Galaxy. Current programmes to detect these civilisations, usually involving searches for powerful radio beacons, assume that alien societies are purposely calling attention to themselves [1-3]. A better approach is to search for the natural and anticipated byproducts of technological civilisation. This avoids the tenuous assumption that extraterrestrial intelligences are actively seeking contact or communication. Still, observing any but the most technologically rapacious civilisations is difficult with present equipment [4].

One of the best ways to detect evidence of intelligent activity around another star is to search for the material effluents of a spacefaring industrial civilisation. The mainstay of technical civilisation is energy, and nuclear fusion energy is the only plausible source for long-lived societies. The bulk of planetary mass in a solar system is likely to be fusionable hydrogen and helium, and the sun is a natural fusion reactor, so both may plausibly be employed.

However, solar energy alone may be regarded as insufficient because it restricts the maximum rate of power consumption. Civilisations may wish to release greater energies than the 10^{26}-10^{27} watts developed by their sun. Further, a G0 star typically emits 10^{44} joules during its main sequence lifetime, whereas 1 $M_{\odot}$ (solar mass) of fusion fuel carefully burned in a controlled reactor releases 2×10^{45} joules – a considerable motivation for astrophagy [5].

Advanced civilisations may turn to artificial fusion as a supplementary source of energy. They will begin by cannibalising fusionables from their planets to be burned in space-based reactors. Later, as their appetite for energy grows, they may begin draining light element fusionables from their star. G0 and G1 stars differ by 0.04 $M_{\odot}$, and an artificial 1% mass deficit would be undetectable with current instrumentation. Even a 10% deficit might go unnoticed because of our incomplete understanding of stellar nucleosynthesis.

To recover the full energy theoretically available *via* fusion, hydrogen atoms must be burned all the way to iron – Fe has the maximum binding energy per nucleon, and thus represents the natural endpoint of all fusion reactions. It is likely that heavy element products of fusion burning will be used for various constructive purposes – artificial structures, atmospheres, etc. – in addition to being burned for additional energy. But the closer the endproducts approach Fe the less fusion energy they can generate per atom burned, a law of diminishing marginal return which gives a very steep decrease in fusion efficiency and rising fusion ignition temperatures with increasing atomic mass.

The most likely mode of fusion energy production is hydrogen burning to ^4He at temperatures $<4 \times 10^6$ K, much like the PPI, PPII, and PIII chains in stellar nucleosynthesis [6], which releases 80% of the available nuclear binding energy in the fuel. Intermediate fusion products include D (^2H), T (^3H), ^3He, ^7Li, ^7Be, ^8Be, and ^8B. The temperature must be raised to 100×10^6 K to burn ^4He to ^{12}C to extract another 7% of the binding energy, and another 11% can be extracted only by resorting to temperatures in excess of 10^9 K. The remaining 2% of the binding energy escapes as neutrinos. Low temperature fuels will be burned in preference to higher temperature fuels, with the latter perhaps stored in tankage until required.

The D-^3He reaction has been discussed as a potential propulsion reaction for interstellar rockets [7], and Powell [8] argues that a large-scale fusion-based civilisation will generate major surpluses of ^3He. The D-T reaction is the most widely studied because it is one of the easiest to ignite, yields the second-highest energy of any fusion reaction after D-^3He, and is expected to be the fuel used in the first commercial fusion reactors on Earth [9-11]. T decays to ^3He with a half-life of 12.5 yr and β^--emits the second-softest radiation after ^{187}Re ($\sim 10^3$ watts/kg) of any radioactive element, thus may be regarded as a biologically benign radioisotope. All three isotopes are plausible fusion fuel candidates, in addition to H and ^4He.

2. FUSION ENERGY OBSERVABLES

Emission characteristics of large-scale fusion energy facilities in circumstellar orbit include neutrons, accidental leakage of high-energy plasma fuel/product mixtures, energetic neutrinos, contaminated reactor wall components, gamma ray photons, and fusion fuel diffusion and accidental spillage from storage bunkers. Reaction neutrons not absorbed by breeder blankets and containment walls decay with a half-life of 750 sec into high-energy protons and electrons which merge into the solar wind. Escaped plasma particles cannot be slowed appreciably by normal processes and are too energetic to de-ionise, dispersing rapidly into the interstellar medium along heliomagnetic field lines and

becoming indistinguishable from the primary cosmic ray background. The neutrino (ν) emission is observable in principle as a point source with a 1-10 eV gravitational redshift relative to solar emanations, but is unmeasurable using present-day detector technology [12-13] and must await the development of high-resolution neutrino spectroscopy. Contaminated components rich in artificial radionuclides are easily localised and recycled, and hence are not readily observable.

Gamma rays are produced in the reactions H(n, γ)D, H(D, γ)^{3}He, ^{3}He(^{4}He, γ)^{7}Be, ^{7}Li(p, γ)2^{4}He, and ^{7}Be(p, γ)^{8}Be, and by annihilation of positrons from p(p, e$^+$, ν)D reactions, with energies less than 1 MeV, but these should remain confined within the reactor vessel. As few as 10^{35} photons/sec at 10^{17} Hz released isotropically from near a star 10 pc distant should be detectable by the orbiting Einstein X-Ray Observatory, but such a flux rate ($\sim 10^{-4}$ rad/sec, human lethality $\sim 10^3$ rads) would probably render the circumstellar shell biologically uninhabitable.

Fusion fuel effluence is plausibly observable over interstellar distances. Fuel will be stored as diatomic (H_2, D_2, T_2) or monatomic (^{3}He, ^{4}He) gas at $T_o \leq 300$ K. For hydrogen gas emitted from an artificial circumstellar shell of radius R (1 AU), the mean thermal velocity $v_o = (2kT_o/2m_p)^{1/2} \leq 1.57$ km/sec $\ll (2GM/R)^{1/2} = 42.2$ km/sec = solar escape velocity, where $2m_p$ = hydrogen molecular mass, k is Boltzmann's constant and G is the gravitation constant. Leakage will occur from the surface of the circumstellar shell at some rate ΔM kg/sec, and molecules are subsequently swept from the solar system by solar wind particle collisions over the age of the civilisation τ. The most abundant effluent is molecular hydrogen. We assume a thick cloud model such that $\Delta M/m_p \gg J_w$, the solar wind proton flux, and the entire solar wind is absorbed by the cloud. If n is solar wind proton number density near the circumstellar shell and v_p is solar wind velocity at the shell, then $J_w = 4\pi n v_p R^2$ and the rate of ejection of H_2 is limited to J_w. Also, in a perfectly elastic collisional sequence two protons in molecular form are ejected but one striking proton is halted, for a net collisional ejection rate of $1/2\ (4\pi n v_p R^2)$, so the number of hydrogen molecules present in the artificial cloud $N_{H2} \sim \tau[(\Delta M/2m_p)-(4\pi n v_p R^2)/2]$.

Molecular hydrogen is dissociated with an efficiency β = (H_2 residence time)/(H_2 dissociation lifetime) = $t_r/t_d \leq 1$. For photodestruction of H_2 near the Sun, the best value is $t_d = 5 \times 10^{10}$ sec [14-16]. In the thick cloud model t_r = collision time (t_c) + ejection time (t_e) = $(\Delta M\tau/2m_p)/(4\pi n v_p R^2) + (R_b-R)/(v_p/2)$, where R_b is the distance at which the effusion cloud density falls to the interstellar background. $R_b \sim R\ (n_o/n_b)^{1/2}$, where n_o is emission number density near the shell ($n_o = \Delta M/4\pi R^2(2m_p v_o)$) and n_b = interstellar background number density ($\sim$ 0.1 H cm^{-3}), so $R_b = 0.0026\ \Delta M^{1/2}$ AU $\sim$ radius of heliopause. For R = 1 AU, n = 5 cm^{-3}, $v_p \sim 400$ km/sec, and $R_b \sim 100$ AU: β = 1.0 for $N_{H_2} \gtrsim 10^{46}$, 0.001 - 1.0 otherwise. Ionisation time for H in the Solar System is 10^{16} - 10^{17} sec [15-16], as compared to 5×10^{10} sec for neutralisation of H$^+$ [17]. Hence fusion fuel leakage may produce a cloud of fully neutralised atoms surrounding the target star if $N_H \gtrsim 10^{46}$, with number of cloud atoms $N_H = 2\ N_{H2} \sim \Delta M\tau/m_p$. Other neutral fuel atoms may also be present in varying lesser amounts.

What is ΔM? Fusion fuel emissions are due largely to diffusion. Leakage rates are negligible if a small number of very large fuel tanks are employed exclusively with radius r $\sim 10^9$ metres, near the theoretical maximum structure size in a 1 AU heliocentric orbit for normal building materials [18]. However, small-scale users will require more convenient storage, of necessity a very large number of small tanks. If the tanks are spherical and of thickness t, the entire fleet holds a mass of gas M_g, and D_o is the classical diffusion coefficient, $\Delta M = 3D_o M_g/rt$. For hydrogen gas stored in α-zirconium and tritium stored in stainless steel at 300 K, $D_o \sim 10^{-15}$ metres^2-sec^{-1} [19-20]. Thus for example, $M_g = 10^{-4}$ M_J (Jovian mass) = 2×10^{23} kg, r = 10 m and t = 1 cm gives $\Delta M = 10^{10}$ kg/sec leakage. For $\tau = 10^3$ - 10^9 yr, $N_H = 10^{47}$ - 10^{53} atoms, more if losses due to fuel processing and transfer operations are taken into account. So diffusion arguments cannot rule out the existence of dense artificial clouds near an extraterrestrial civilisation. In the most fundamental limit, if L_f is total fusion luminosity available to the civilisation, e_H = fusion efficiency of hydrogen = 0.92% c^2 joules/kg, and c = speed of light, then $\Delta M \leq L_f/e_H$. For $L_f \sim L_\odot$ (Solar luminosity), $\Delta M \leq 10^{12}$ kg/sec hydrogen leakage.

2.1 Natural Background

The natural background levels of neutral atomic H, D, T, ^{3}He, and ^{4}He in the neighbourhood of a late-type main sequence star should approximate the local interstellar medium. This is because even though all fusion isotopes are emitted as solar wind ions and in solar flares [21-25], their velocities are too high for braking or neutralisation to occur so there is no enhancement of local background. D, T, and ^{3}He are unimportant in advanced stellar evolution [26], and the decay of tritium further ensures its natural absence in the neutral atomic state.

Current measurements of natural neutral hydrogen abundances in the interstellar medium range from 0.01-0.2 H cm^{-3} [27-29], with a mean value usually taken as 0.1 H cm^{-3} [30-31]. Relative to hydrogen, other candidate fusion fuel isotopes have the following natural abundances: D/H = 2×10^{-6} - 3.5×10^{-4} [27, 32-36]; T/H $< 10^{-11}$ [25]; ^{3}He/H = $1\text{-}4 \times 10^5$ [32-33, 37]; and ^{4}He/H = 0.069 - 0.1 [32-33]. The mean excess of fusion fuel hydrogen atoms is $N_H/(4/3\ \pi R_b^3) \sim 7 \times 10^{-14} \Delta M\tau$ (H m^{-3}), plausibly up to $\sim 10^{13}$ H m^{-3}.

2.2 Optical Anomalies

Optical emission lines from an artificial light-element effusion cloud should not exist because of the low cloud temperature and its relatively great distance from possible sources of excitation. Observable absorption lines from the hypothetical artificial cloud must have column densities exceeding those of natural isotopes in the stellar atmosphere, which is unlikely. It is more difficult to resolve the Lyman and Balmer lines of tritium from those of deuterium than the deuterium lines from those of hydrogen, so although the natural background of stellar neutral atomic tritium is negligible a column density equivalent to that of naturally-occurring stellar deuterium would probably be required for tritium detection.

The D/H ratio has been determined by measuring interstellar deuterium absorption in the UV, from orbiting observatories, in early-type stars and a few late-type stars [27, 29, 35-36, 38]. Except in the case of Alpha Centauri, measured H concentration and D/H in the line of sight appear consistent with other observations and independent estimates for the interstellar medium. D has yet to be detected in any stellar atmosphere [39-41]. ^{3}He has been discovered spectroscopically in only a few early-type peculiar stars [42-45], but not in any later-type star except the Sun [46].

A final consideration is that to recognise a detected line as a local anomaly, off-star comparison spectra are required – an impossible requirement for optical absorption lines except in the rare case of a close visual binary.

2.3 Radio Anomalies

In radio frequencies, excited neutral atoms can be observed

via recombination lines in energetic environments such as HII regions [47]. For instance, Palmer [48] measured the H 109α recombination line at 5008.923 MHz and the ^{4}He 109α recombination line at 5010.964 MHz to determine the relative abundance of helium in various nebulae. From the earlier discussion, we expect that most leakage gas will be present in the neutral atomic state and that recombination lines should be relatively weak.

2.3.1 *Hyperfine Transition Lines*

The spontaneous magnetic dipole hyperfine transition is the only plausible observational characteristic of an artificial, neutral atomic gas cloud of hydrogen or helium isotopes in the ground state. However, in ground-state neutral helium, atomic electrons occupy all available spin states and hence the spontaneous spin transition is prohibited by the Pauli exclusion principle. The ^{3}HeI line at 6739.7013 MHz [49-50] and the corresponding ^{4}HeI line arise from a hyperfine transition in the 2s level, but excitation from 1s^2, $^1S_0$) to the metastable triplet state (1s 2s, $^3S_1$) requires 21.25 eV, 87% of the first ionisation energy, which is not available near late main sequence stars. Among ground-state hydrogen isotopes, the deuterium hyperfine line at 327.384 352 5222(17) MHz [51] has a brightness temperature below that of the galactic synchrotron background, and hence could only be observed [34, 52-54] in absorption against very bright radio sources with state-of-the-art equipment. This rules out the radio detection of artificial deuterium enhancements near main sequence stars except in the rare instance of a normal star occulting a very active radio source. Thus the neutral hydrogen ground-state hyperfine transition line at 1420.405 751 768(3) MHz [55] and the neutral tritium ground-state hyperfine line at 1516.701 9064(16) MHz [56] are the two most promising observational candidates.

2.3.2 *The Tritium Waterspout*

It has most commonly been argued [1-3] that a technological civilisation wishing to attract attention to itself to initiate contact would employ a powerful radio beacon. Operation on a single narrowband frequency against a quiet background would produce an obviously artificial signal and make most efficient use of available transmitter power.

It is interesting that the tritium line lies almost in dead centre of the traditional SETI "waterhole" region between the H and OH-spectral lines [1]. Thus, in addition to its value in a search for an artificial effusion cloud of fusion tritium, the tritium hyperfine line is virtually unique in that its detection alone is unambiguously artificial – no natural process could account for its presence. There is no possibility of confusion with H 163α and H 162α recombination lines, which lie at 1504.646 MHz and 1532.520 MHz, respectively, nor with the two ^{4}He lines 163α and 162α at 1505.259 MHz and 1533.144 MHz.

Thus the tritium line is the ideal choice as an interstellar communication frequency from the standpoint of acquisition. It is a unique signpost to intelligence, leaping up out of the waterhole to form the "tritium waterspout." The 1516 MHz tritium hyperfine line lies well outside major radio broadcasting bands allocated to aviation communications, aeronautical and maritime satellites at 1542.5-1558.5 MHz, and space operations telemetry at 1525-1535 MHz [57]. A variety of small fixed and mobile allocations exist between 1435-1525 MHz for transmissions between fixed stations and land/coastal radar tracking systems, so care must be taken to eliminate these potentially troublesome, though obvious, sources of RFI.

Searches for purposeful narrowband CETI beacon signals might also be conducted near the hydrogen fine-structure transitions (e.g., 1058 MHz, 3250 MHz, 9910 MHz [49]), the hyperfine lines for triplet-state ^{3}HeI, ground-state ^{3}HeII (8665.649 867(10) MHz [58], metastable $^2S_{1/2}$ state ^{3}HeII (1083.354 9807(88) MHz [59]), and other hyperfine lines for ^{3}He [60], ^{4}He, other elements, and various neutral and ionised molecules [61]. (Hyperfine transitions of excited neutral atomic hydrogen isotopes all lie <200 MHz and thus would be difficult to observe). However, many of these transitions may occur naturally [37] and none is distinguished as especially attractive for SETI work.

2.3.3 *Current Observational Status*

To date only a handful of full-sky hydrogen-line surveys have been performed at various ranges of galactic latitude, and there are only a few published attempts to detect 21-cm radiation emission from stars (most of them as part of SETI programmes). Of the more than two dozen SETI searches to date [62], none is likely to have detected an artificial hydrogen cloud. Kraus [63-64] and co-workers [65] are searching the entire sky rather than individual stars, and correct their frequency of observation to the Galactic Standard of Rest rather than the usual Local Standard of Rest. SETI observations by Wielebinskii and Seiradakis in 1977 and by Israel and Tarter in 1981 employed 4-20 MHz bandwidths, so a cloud with a 10 KHz linewidth probably could not be distinguished. Drake [66], Horowitz [67] and Tarter [68] used narrow bandwidths of 0.015-600 Hz/channel, which also would be unlikely to have detected a cloud. The U.C. Berkeley SERENDIP programme was an all-sky parasitic search which could not easily detect hydrogen-line enhancements at individual stars [69]. Verschuur [70] and Zuckerman with Palmer [71] searched numerous stars at the proper frequencies and reasonable bandwidths but, as with many of the above studies, failed to incorporate an off-star comparison measurement thus ruling out detection of artificial clouds. Published data on three additional stars surveyed by Verschurr [70] cannot rule out the possibility of a cloud up to several flux units of intensity. Thus existing SETI searches cannot yet exclude the existence of an artificial hydrogen cloud near even the closest stars. A search for 21-cm excess would also be sensitive to the existence, but not the content, of hypothetical radio messages possibly being transmitted to us now.

Individual stars have been observed in radio frequencies, including cm-band generally [72-75], near 21-cm (e.g., 1415 MHz [76-77]), and 21-cm hydrogen line observations. As even cm-band emissions of normal stars are expected to be too weak to detect, searches have concentrated on peculiar and highly energetic stars such as early-type stars, Of stars, Wolf-Rayet stars, various emission-line and shell stars, magnetic variables, flare stars, and novae [78-79]. A very few normal single stars have been observed at cm wavelengths, with negative results except in the case of X^1 Orionis, a GO V star 10.0 pc from the Sun [80]. Of the 21-cm hydrogen-line observations, the targets have been A, B, and O stars with known or anticipated interstellar optical absorption lines [81-85], sky positions near such stars [86], a few peculiar stars such as Rho Ophiuchi [87], and general sky survey positions unrelated to individual stars for galactic HI mapping. None of these would be sensitive to artificial hydrogen clouds near Sunlike stars.

There is only one recent report of a search of individual stars at the tritium hyperfine line [88]. Although it is an observationally convenient frequency for radio sky mapping, probably not much more information would be gained over existing 1415 MHz maps. The only survey spanning the tritium line, by Kardashev and Gindilis in 1972 covering

various frequencies between 1337-1863 MHz, used an all-sky dipole antenna [62] which would not be sensitive to point sources of tritium hyperfine radiation.

2.3.4 Future Hyperfine Line Observations

If R = radius of volume containing the leakage atoms, D_s is the distance to the star, σ = antenna beamwidth, and N is the number of atoms in the field of view, then for an unresolved source ($\sigma \gg R_b/D_s$) the brightness temperature T_B of the artificial cloud is given by $T_B = CN/A$, where the projected area $A = \pi R_b^2$ and $C = (3hc^3/32\pi k)(A_{10}/\omega^2)$, for ω = hyperfine frequency (Hz) and h = Planck's constant [89]. A_{10} is the computed Einstein A transition probability, which is (fol. Field [90]) 2.869×10^{-15} sec^{-1} for hydrogen and 3.493×10^{-15} sec^{-1} for tritium. No experimental value for tritium is yet available [91]. The flux of radio energy of hyperfine wavelength λ reaching the Earth is $F = (2k/\lambda^2)T_b\Omega = (2k/\lambda^2)(CN/D_s^2)$, where $\Omega = \pi(R_b/D_s)^2$. For the detection limit, taking D_s in parsecs and F in flux units, $N_H = 2.77 \times 10^{45} D_s$ atoms H and $N_T = 2.27 \times 10^{45} D_s$ atoms T.

A civilisation which has effluxed more than $\Delta M_{H}\tau \sim N_H m_p = (2.77 \times 10^{45})\, F_H D_s^2 m_p = 5 \times 10^{20}$ kg ($2 \times 10^{-7} M_J$) of hydrogen fusion fuel during its lifetime τ could be detected at $F \leq 1$ Jy sensitivity and $D_s \leq 10$ pc. Tritium decays with a half-life t_h ($\sim$ 12.5 yr) regardless of τ, so a civilisation which leaks tritium at a rate greater than $\Delta M_T \sim (2.27 \times 10^{45}) F_T D_s^2 m_p (t_h/\ell n(2))^{-1} = 7 \times 10^{11}$ kg/sec ($\sim 1\ L_\odot$ wastage, for $e_T = 0.64\%\ c^2$) could be detected at $F \leq 1$ Jy and $D_s \leq 10$ pc. Thus the tritium limit is less restrictive for $\tau > 22$ yr, but has the advantage that any detection is unambiguously artificial.

The observational frequency in each case must be corrected to the Local Standard of Rest by compensating for Earth's rotation ($\pm$ 2 KHz), Earth's orbital velocity around the Sun ($\pm$ 140 KHz), and the Sun's radial velocity toward the target star ($\pm$ 100 KHz). The bandwidth in searches for artificial clouds should span roughly the expected cloud thermal velocities, about $\pm$ 7.7 KHz for thermal line broadening at 300 K.

A tritium line search is also sensitive to SETI beacons or signals. Assuming a 15 KHz bandwidth 20 K detector with a one hour integration time, such a search could detect a 6 MW, 26-metre transmitter antenna 10 pc away pointed at Earth. Within 20 light-years of the Sun there are 86 stars, 80 of stellar class F-M, about 70 of which are visible from the northern hemisphere. There are many reasons for excluding O, B and A stars from the search [92], such as the probable lack of planets, the severe UV environment, and the brief residence time on the main sequence with the concommitant reduced time for the emergence and evolution of life. Fifty-three of the nearest stars have now been examined for narrowband tritium line emissions, using the 26-metre radiotelescope at Hat Creek Radio Observatory in California, to a sensitivity of 1-20 Jy [88]. No detections were made.

3. ADDITIONAL OBSERVABLES OF TECHNOLOGICAL CIVILISATIONS

Five other charactersitics of advanced technological civilisations may be visible across interstellar distances. Internal communications and power transmission equipment may generate radio leakage radiation upon which we may "eavesdrop." Large circumstellar structures may produce an anomalous blackbody radiation signature. The use of fission rather than fusion nuclear fuels might give rise to anomalous solar absorption lines. Large-scale movements of hot photospheric material may produce unusual spectral line broadening and clearly artificial ghost lines. Finally, very large-scale technical activities near a star may require or establish enormous magnetic fields which may be observable *via* Zeeman line splitting.

3.1 Artificial Radio Spectrum

Sullivan *et al* [93] performed an extensive survey of all sources of artificial radio energy leakage from Earth. An Arecibo-size antenna could detect terrestrial UHF television stations from two light-years away, and the US BMEWS military radars from 20 light-years away. A Cyclops array [1] could increase these ranges to 25 light-years and 250 light-years, respectively. Sullivan *et al* note that geopolitical boundaries and other information about human society can be deduced from Earth's leakage radiation, but an advanced circumstellar civilisation would present a vastly more complex picture. However, greater efficiency as well as greater energy are available to advanced societies so it cannot be assumed that extraterrestrial technological civilisations are necessarily "noisier" than Earth.

3.2 Anomalous Blackbody Radiation

Solar optical luminosity is decreased according to the fraction f of the circumstellar sphere blocked by optically dense orbiting material structures (i.e., a "Dyson shell"), reducing the stellar visual magnitude by -2.5 log(1-f) magnitudes. In nearby stars this produces an evidently distant but otherwise normal star with an infrared [94] and radio excess. The radio excess is difficult to detect. At 5 GHz, Arecibo could only detect fully-occulting (f = 1) artificial shells closer than 0.1 parsec. A proposed 10 km space-based radiotelescope array [95] could reach at least to 10 parsecs, and a 100 km system could reach 100 parsecs although this lies considerably beyond existing technology.

The infrared excess is easier to observe. A shell of orbiting artifacts creates a bimodal blackbody spectrum with two peaks of reciprocal amplitude, one near 500 nm (spectral class G V star) and the other near 10 microns (300 K shell of rotating bodies at 1 AU). Although this spectral signature is not unambiguously artificial, it is clearly unusual and invites further close scrutiny. The best current near-IR ground-based survey [96] at 0.8 micron could only have detected an optically dense artifact shell nearer than 0.01 pc, but the Infrared Astronomical Satellite (IRAS) permits detection [97] of fully-occulting (f = 1) Dyson shells out to 1000 pc and 1% occulting shells (f = 0.01) to 100 pc. Care must be taken to develop criteria for distinguishing artificial shells from stars such as Vega (recently discovered in IRAS data) and Be star MWC 349 [77], both of which display an infrared excess caused by natural circumstellar material.

3.3 Fission Product Absorption Lines

Whitmire and Wright [98] suggest that extraterrestrial civilisations might use the local star as a repository for radioactive fissile waste materials, and Gray *et al* [99] conducted a brief search for spectral line enhancements of the expected waste elements for three stars, using an optical telescope at Kitt Peak National Observatory in Arizona. However, there are several deficiencies in this approach. For instance, considerations of convective mixing and stellar lifetimes restrict the possible candidate stars to the approximate spectral range A5-F2, yet these stars are not thought to be suitable candidates either for the formation of planets or for the natural origin and evolution of life.

The major fissionable on Earth is thorium, which is about three times as abundant as uranium and probably represents more available energy in the minerals of the Earth's crust than from both uranium and fossil fuels. The abundance of thorium in the crust is about 12 ppm, about 4 ppm for uranium, 10^{-6} for radium, and 10^{-9} for polonium and several other rare naturally-occurring isotopes. The mass of Earth's crust down to 20 km assuming a mean density 2670 kg-m^{-3} is 3×10^{22} kg, of which 16 ppm are fissionable or 4×10^{17} kg. Collected and burned as fission fuel, this would release about 0.1% mass energy or only 4×10^{31} joules. Ultimately, all Solar System fissiles could conceivably be mined and burned. Fissile abundances of Th and U in the Solar System [32] are 3.2×10^{-10} and 1.5×10^{-10}, respectively, so total fissiles are 9.4×10^{20} kg and the total available energy is 8×10^{34} joules.

On the other hand, the total amount of fusionable hydrogen (the most abundant fusion fuel) is about 2×10^{20} kg on Earth, 2×10^{27} kg for all of the planets but not the Sun, and 2×10^{30} for the entire Solar System. Fusion fuel can release up to 0.92% of its mass energy, so these correspond to 2×10^{35} joules from terrestrial sources, 2×10^{42} joules from planetary sources, and 2×10^{45} joules for the entire Solar System.

So while an expanding civilisation might resort to fissionables as a last effort, clearly fusion fuels are more cost effective. They are easier to mine or extract and to transport. They are generally nonradioactive or, in the case of tritium, only weakly so, and hence may be stored more safely so far as biological beings and computers are concerned. Combustion of all fissionables in the Solar System, including those in the Sun, would release only as much energy as burning the fusion fuel on Earth alone. Fusion fuels are clearly the method of choice for artificial energy generation on an energy/kilogram basis.

Even if spaceborne fission reactors are employed, using stars as waste repositories is inadvisable for several reasons. First, if the atomic masses of the isotopes comprising the discarded matter lie much below or above 56 (Fe), nuclear binding energy is still available and is lost if not recovered. Second, the infall of matter towards a star represents a conversion of gravitational energy to kinetic energy, which is absorbed by the star and effectively lost to the orbital civilisation, along with the gravitational energy originally added to the matter to raise it from a planetary surface or atmosphere in the first place. Third, addition of foreign matter to stellar photospheres may disturb the natural ionic mix, alter flare and sunspot activity, and cause other undesirable side effects. Finally, there is little mixing between the photosphere and solar interior, so material deposited in stars remains there over long periods. If the star is later mined for its fusion energy physical resources, the discarded matter must again be raised against a strong gravity field.

3.4 Doppler and Stellar Spectral Anomalies

Large-scale technical activities may involve the removal of mass from the local star of radius $R_\odot$ to the circumstellar shell of radius R. The movement of hot photospheric plasma from $R_\odot$ to R will produce a weak optical (wavelength λ) Doppler component of order $\Delta\lambda = \lambda \Delta v/c$. $\Delta v = (2GM_\odot(R_\odot^{-1} R^{-1}))^{1/2} = 617$ km/sec, so at 500 nm, $\Delta\lambda \sim 1$ nm. This is a potentially larger effect than optical spectrum line broadening due to thermal velocities and photospheric turbulence (>0.01 nm), stellar rotation (>0.4 nm), or interstellar radial motion (>0.1 nm in the solar neighbourhood), and can easily be distinguished from double-line spectroscopic binaries.

The exact appearance of the artificial anomaly depends upon unknown stellar mass extraction trajectories. A single locus for removal and collection would give rise to single anomalous ghost lines shifted $\leq$ 1 nm. Several loci would make multiple ghost lines. Co-rotating loci would produce time-variable anomalies. Non-localised loci would result in large, probably asymmetrical, line broadening. These lines could be quite bright. If the natural energy available to the extraterrestrial civilisation $\sim L_\odot$, then the total plasma mass in transit from $R_\odot$ to R at any given moment is of order $M_p \sim 2L_\odot R/\Delta v^3 = 5 \times 10^{20}$ kg, about the mass of the solar photosphere. In addition to direct searches for ghost lines, observed line anomalies in stars classified as P-Cygni, Wolf-Rayet, T Tauri, and Ap magnetic and spectrum-variable should be re-examined for cases of possible spectral misclassification. Finally, any A0-A9 star showing both strong neutral H and neutral metal lines could be a misclassified late-type star surrounded by an artificial hydrogen cloud.

3.5 Anomalous Magnetic Fields

Technical activities in an artificial circumstellar shell of radius R could conceivably involve current loops of order R giving rise to a free space magnetic induction of order $B = \mu_o i/R$ and magnetic flux $F_B = 4\pi BR^2$ over the spherical habitat shell of energy $E_B = F_B i = (4\pi/\mu_o)R^3B^2$, where μ_o = permeability constant. The highest natural fields found in main sequence stars are 0.1-1 tesla, so a B = 10 tesla field would be clearly artificial and for R = 1 AU represents $E_B = 3 \times 10^{42}$ joules. To establish this field would require burning $\sim$ 1 M_J as fusion fuel, which seems excessive. Artificial fields $B < 10^3$ gauss, while observable *via* Zeeman line splitting (about 10^{-4} nm) in optical spectra, would not be unambiguously artificial when detected near late main sequence stars.

4. CONCLUSIONS

The most observable characteristic of an advanced extraterrestrial civilisation which makes extensive use of the fusion fuel resources of its local star and planets is an effusion cloud of molecular fuel elements. This cloud rapidly dissociates and neutralises to the atomic ground state. Optical anomalies would be difficult to observe, but the detection of both the hydrogen and tritium hyperfine transition radio lines is relatively straightforward. Existing searches at these lines are not sensitive to artificial fusion fuel clouds. In addition, the low natural abundance of neutral atomic ground-state tritium suggests that its hyperfine line, centred in the radio-SETI waterhole band, has minimum background noise and thus is ideal for interstellar communication and future SETI searches. With one exception [88], no SETI searches at the tritium line towards individual stars have been reported to date. Other observables of advanced civilisations, including redshifted neutrino point sources, an artificial radio spectrum, anomalous blackbody radiation, fission product absorption lines, Doppler and stellar spectral anomalies, and extraordinary magnetic fields, might also serve as the basis for future SETI research but are considerably more challenging observationally.

ACKNOWLEDGMENTS

The author thanks Francisco Valdes for contributions and comments on an earlier version of the manuscript. This research was supported by the Xenology Research Institute.

REFERENCES

1. Billingham, J. and Oliver B., *Project Cyclops: A Design Study of a System for Detecting Extraterrestrial Intelligent Life*, Revised Edition, NASA CR-114445 (1973).
2. Morrison, P., Billingham, J. and Wolfe, J., eds., *The Search for Extraterrestrial Intelligence, SETI*, NASA SP-419 (1977).
3. Billingham, J. and Pesek, R., eds., *Communication with Extraterrestrial Intelligence*, Pergamon Press, Oxford (1979).
4. Freitas, R. A. Jr., "Extraterrestrial Intelligence in the Solar System: Resolving the Fermi Paradox," *JBIS*, **36**, 496-500 (1983).
5. R. A. Freitas, Jr., "Terraforming Mars and Venus Using Machine Self-Replicating Systems (SRS)," *JBIS*, **36**, 139-142 (1983).
6. Truran, J. W., "Theories of Nucleosynthesis," in A. G. W. Cameron, ed., *Coosmochemistry*, D. Reidel, Dordrecht-Holland, pp. 23-49 (1973).
7. Martin, A. R., ed., "Project Daedalus – Final Report," *JBIS* Supplement (1978).
8. Powell, C., "Interstellar Flight and Intelligence in the Universe," *Spaceflight*, **14**, 442-447 (1972).
9. Glasstone, S. and Lovberg, R. H., *Controlled Thermonuclear Reactions*, Van Nostrand Reinhold, Scarborough, Canada (1960).
10. Petrie, T. W. R., "A Review of Possible Fusion Fuels," in G. H. Miley, ed., *Advanced Energy Conversion for Fusion Reactors*, University of Illinois Report No. C00-2218-18, pp. A1-A17 (1974).
11. "Starfire – A Commercial Tokamak Fusion Power Plant Study," Argonne National Laboratory, ANL/FPP-80-1, September 1980.
12. Saenz, A. W., Uberhall, H., Kelly, F. J., Padgett, D. W. and Seeman, N., "Telecommunication with Neutrino Beams," *Science*, **198**, 295-297 (1977).
13. Roberts, A., "DUMAND: The Ocean as a Neutrino Detector," in H. Faissner, H. Reithler, P. Zerwas, eds., *Proceedings of the International Neutrino Conference 1976*, Friedr. Vieweg & Sohn Verlagsgesellschaft MBH, Braunschweig, pp. 688-702 (1977).
14. Hollenbach, D. J., Werner, M. W. and Salpeter, E. E., "Molecular Hydrogen in HI Regions," *Ap. J.*, **163**, 165-180 (1971).
15. O'Donnell, E. J. and Watson, W. D., "Upper Limits to the Flux of Cosmic and X-Rays in Interstellar Clouds," *Ap. J.*, **191**, 89-92 (1974).
16. Jura, M., "Formation and Destruction Rates of Interstellar H_2," *Ap. J.*, **191**, 375-379 (1974).
17. Watson, W. D., "Formation and Destruction of Interstellar Molecules," in Roger Balian, Pierre Encrenaz, James Lequeux, eds., *Atomic and Molecular Physics and the Interstellar Matter*, American Elsevier Pub. Co., New York (1975).
18. Dyson, F. J., "The Search for Extraterrestrial Technology," in R. E. Marshak, ed., *Perspectives in Modern Physics*, John Wiley & Sons, New York, pp. 641-655 (1966).
19. Kearns, J. J., "Diffusion Coefficient of Hydrogen in Alpha Zirconium, Zircaloy-2 and Zircaloy-4," *J. Nucl. Materials*, **43**, 330-338 (1972).
20. Austin, J. H. and Elleman, T. S., "Tritium Diffusion in 304- and 316-Stainless Steels in the Temperature Range 25 to 222 °C," *J. Nucl. Materials*, **43**, 119-125 (1972).
21. Shlosman, I., Kozlovsky, B. Z. and Shaviv, G., "Dwarf-M Stars as a Source of He^3 in the Interstellar Medium," *Astron. Astrophys.*, **73**, 358-360 (1969).
22. Lal, D., Libby, W. F., Wetherill, G., Leventhal, J. and Alton, G. D., "Collecting a Sample of Solar Wind: An Experimental Study of Its Capture in Metal Films," *J. Appl. Phys.*, **40**, 3257-3267 (1969).
23. Ramaty, R. and Kozlovsky, B., "Deuterium, Tritium, and Helium-3 Production in Solar Flares," *Ap. J.*, **193**, 729-740 (1974).
24. Fireman, E. L., "Solar-Wind Tritium Limit and the Mixing Rate of the Solar Atmosphere," *Ap. J.*, **205**, 268-272 (1976).
25. Fireman, E. L., DeFelice, J. and D'Amico, J., "The Abundances of ^3H and ^{14}C in the Solar Wind," *Earth Planet Sci. Lett.*, **32**, 185-190.
26. Cujec, B. and Fowler, W. A., "Neglect of D, T, and ^3He in Advanced Stellar Evolution," *Ap. J.*, **236**, 658-660 (1980).
27. Dupree, A. K., Baliunas, S. L. and Shipman, H. L., "Deuterium and Hydrogen in the Local Interstellar Medium," *Ap. J.*, **218**, 361-369 (1977).
28. Vidal-Madjar, A., Laurent, C., Bruston, P. and Audouze, J., "Is the Solar System Entering a Nearby Interstellar Cloud?" *Ap. J.*, **223**, 589-600 (1978).
29. McClintock, W., Henry, R. C., Linsky, J. L. and Moos, H. W., "Ultraviolet Observations of Cool Stars. VII. Local Interstellar Hydrogen and Deuterium Lyman-Alpha," *Ap. J.*, **225**, 465-481 (1978).
30. Adams, T. F. and Frisch, P. C., "High Resolution Observations of the Lyman Alpha Sky Background," *Ap. J.*, **212**, 300-308 (1977).
31. Ajello, J. M., "An Interpretation of *Mariner 10* Helium (584 Å) and Hydrogen (1216 Å) Interplanetary Emission Observations," *Ap. J.*, **222**, '068-1079 (1978).
32. Cameron, A. G. W., "Abundances of the Elements in the Solar System," *Space Sci. Rev.*, **15**, 121-146 (1973).
33. Reeves, H., "On the Origin of the Light Elements," *Ann. Rev. Astron. Ap.*, **13**, 437-469 (1974).
34. Pasachoff, J. M. and Cesarsky, D. A., "Further Observations at the Interstellar Deuterium Frequency," *Ap. J.*, **193**, 65-67 (1974).
35. York, D. G. and Rogerson, J. B. Jr., "The Abundance of Deuterium Relative to Hydrogen in Interstellar Space," *Ap. J.*, **203**, 378-385 (1976).
36. Laurent, C., Vidal-Madjar, A. and York, D. G., "The Ratio of Deuterium to Hydrogen in Interstellar Space. IV. The Lines of Sight to Delta, Epsilon, and Iota Orionis," *Ap. J.*, **229**, 923-941 (1979).
37. Rood, R. T., Wilson, T. L. and Steigman, G., "The Probable Detection of Interstellar $^3He^+$ and its Significance," *Ap. J.*, **227**. L97-L101 (1979).
38. Rogerson, J. B. Jr. and York, D. G., "Interstellar Deuterium Abundance in the Direction of Beta Centauri," *Ap. J.*, **186**, L95-L98 (1973).
39. Peimbert, M. and Wallerstein, G., "A Search for Deuterium in Stellar Spectra II. Normal Stars of Types B, A, and F," *Ap. J.*, **142**, 1024-1027.
40. Beckers, J., "A Search for Deuterium on the Sun," *Ap. J.*, **195**, L43-L45 (1975).
41. Krat, V. A. and Pravdjuk, L. M., "On the Abundance of Deuterium in the Solar Atmosphere," *Solar Phys.*, **61**, 279-281 (1979).
42. Sargent, W. L. W. and Jugaku, J., *Ap. J.*, **134**, 777 (1961).
43. Sargent, A. I., Greenstein, J. L. and Sargent, W. L. W., "A Search for Neon in the Spectra of Peculiar A and B Stars," *Ap. J.*, **157**, 757-768 (1969).
44. Dworetsky, M. M., "Helium-3 in Iota Orionis B," *Ap. J.*, **184**, L75-L78 (1973).
45. Hilditch, R. W. and Hill, P. W., „Identification of He^3 in the Binary System 68u Herculis," *Mon. Not. R. Astr. Soc.*, **172**, 29P-34P (1975).
46. Hall, D. N. B., "Spectroscopic Detection of Solar ^3He," *Ap. J.*, **197**, 509-512 (1975).
47. Kardashev, N. S., "The Possibility of Detection of Allowed Lines of Atomic Hydrogen in the Radiofrequency Spectrum," *Soviet Astr. AJ.*, **3**, 813-820 (1960).
48. Palmer, P., Zuckerman, B., Penfield, H. and Lilley, A. E., "Determinations of Helium Abundance from Radiofrequency Recombination Lines," *Ap. J.*, **156**, 887-901 (1969).
49. Barrett, A. H., "Spectral Lines in Radio Astronomy," *Proc. IRE*, **46**, 250-259 (1958).
50. White, J. A., Chow, L. Y., Drake, C. and Hughes, V. W., "Hyperfine Structure of the Metastable Triplet State of Helium Three," *Phys. Rev. Lett.*, **3**, 428-429 (1959).
51. Wineland, D. J. and Ramsey, N. F., "Atomic Deuterium Maser," *Phys. Rev.*, **A5**, 821-837 (1972).
52. Weinreb, S., "A New Upper Limit to the Galactic Deuterium-to-Hydrogen Ratio," *Nature*, **195**, 367-368 (1962).
53. Cesarsky, D. A., Moffet, A. T. and Pasachoff, J. M., "327-MHz Observations of the Galactic Center: Possible Detection of a Deuterium Absorption Line," *Ap. J.*, **180**, L1-L6 (1973).
54. Sarma, N. V. G. and Mohanty, D. K., "Search for the Deuterium Absorption Line at 327 MHz in the Direction of the Galactic Center," *Mon. Not. R. Astr. Soc.*, **184**, 181-184 (1978).

55. Hellwig, H., Vessot, R. F. C., Levine, M. W., Zitewitz, P. W., Allen, D. W. and Glaze, D. J., "Measurement of the Unperturbed Hydrogen Hyperfine Transition Frequency," *IEEE Trans. Instrum. Meas.*, **IM-19,** 200-209 (1970).
56. Mathur, B. S., Crampton, S. B., Kleppner, D. and Ramsey, N. F., "Hyperfine Separation of Tritium," *Phys. Rev.*, **158,** 14-17 (1967).
57. *Reference Data for Radio Engineers,* Internatl. Tel. & Tel. Corp., New York (1975).
58. Schuessler, H. A., Fortson, E. N. and Dehmelt, H. G., "Hyperfine Structure of the Ground State of $^3He^+$ by the Ion-Storage Exchange-Collision Technique," *Phys. Rev.*, **187,** 5-38 (1969).
59. Prior, M. H. and Wang, E. C., "Hyperfine Structure of the 2s State of $^3He^+$," *Phys. Rev. A,* **16,** 6-18 (1977).
60. Lawler, J. E., Ferguson, A. I., Goldsmith, J. E. M., Jackson, D. J. and Schawlow, A. L., "Doppler-Free Intermodulated Optogalvanic Spectroscopy," *Phys. Rev. Lett.*, **42,** 1046-1049 (1979).
61. Blicharski, J. S., "On Radiofrequency Transitions and Nuclear and Electron Polarization for Hydrogen Molecular Ions H_2+," *Can. J. Phys.*, **46,** 823-827 (1968).
62. Tarter, J., "Searching for THEM: Interstellar Communications," *Astronomy,* **10,** 6-22 (1982).
63. Kraus, J., *Big Ear,* Cygnus-Quasar Books, Powell, Ohio, (1976).
64. Kraus, J., "We Wait and Wonder," *Cosmic Search,* **1,** 3, 31-34 (1979).
65. Dixon, R. S. and Cole, D. M., "A Modest All-Sky Search for Narrowband Radio Radiation Near the 21-cm Hydrogen Line," *Icarus,* **30,** 267-273 (1976).
66. Drake, F. D., "Project OZMA," *Phys. Today,* **14,** (4) 40-46 (1961).
67. Horowitz, P., "A Search for Ultra-Narrowband Signals of Extraterrestrial Origin," *Science,* **201,** 733-735 (1978).
68. Tarter, J., "An American View of SETI," *Spaceflight,* **21,** 57-58 (1979).
69. Bowyer, S., Zeitlin, G., Tarter, J., Lampton, M. and Welch, W. J., "The Berkeley Parasitic SETI Program." *Icarus,* **53,** 147-155 (1983).
70. Verschuur, G. L., "A Search for Narrow Band 21-cm Wavelength Signals from Ten Nearby Stars," *Icarus,* **19,** 329-340 (1973).
71. Zuckerman, B., "Searches for Electrmagnetic Signals from Extraterrestrial Beings," in Michael H. Hart, Ben Zuckerman, eds., *Extraterrestrials: Where Are They?* Pergamon Press, New York, pp. 8-18 (1982).
72. Oster, L., "Radio Emission from Stellar and Circumstellar Atmospheres." In B. Baschek, W. H. Kegel, G. Traving, eds., *Problems in Stellar Atmospheres and Envelopes,* Springer-Verlag, New York, pp. 301-323 (1975).
73. Woodsworth, A. W. and Hughes, V. A., "Observations of Radio Stars at 10.6 GHz," *Astron. Astrophys.*, **58,** 105-111 (1977).
74. Haisch, B. M., Linsky, J. L., Slee, O. B., Hearn, D. R. Walker, A. R., Rydgren, A. E. and Nicholson, G. D., "A Coordinated X-Ray, Optical, and Microwave Study of the Flare Star Proxima Centauri," *Ap. J.*, **225,** L35-L37 (1978).
75. Feldman, P. A. and Kwok, S., *J.R.A.S.*, **73,** 271 (1979).
76. Braes, L. L. E. and Miley, G. K., "Radio Detection of Cygnus X-3," *Nature,* **237,** 506 (1972).
77. Braes, L. L. E., Habing, H. J. and Schoenmaker, A. A., "MWC 349, a New Radio Star," *Nature,* **240,** 230 (1972).
78. Braes, L. L. E., "Radio Continuum Observations of Stellar Sources," in F. J. Kerr, S. C. Simonson, III, eds., *Galactic Radio Astronomy,* D. Reidel Publ. Co., Dordrecht-Holland, pp. 377-381 (1974).
79. Altenhoff, W. J., Braes, L. L. E., Olnon, F. M. and Wendker, H. J., "A Search for Radio Emission from Stars," *Astron. Astrophys.*, **46,** 11-17 (1976).
80. Gary, D. E. and Linsky, J. L., "First Detection of Nonflare Microwave Emission from the Coronae of Single Late-Type Dwarf Stars," *Ap. J.*, **250,** 284-292 (1981).
81. Lawrence, R. S., "Radio Observations of Interstellar Neutral Hydrogen Clouds," *Ap. J.*, **123,** 30-33 (1956).
82. Howard, W. E. III, Wentzel, D. G. and McGee, R. X., "On a Correlation Between the Radial Velocities of Optical and Radio Interstellar Lines," *Ap. J.*, **138,** 988-1001 (1963).
83. Van Woerden, H., *I.A.U. Symp. No. 31,* p.3 (1967).
84. Habing, H. J., "An Atlas of 21-cm Line Profiles in the Directions of Stars with Interstellar Absorption Lines," *Bull. Astr. Inst. Netherlands,* **20,** 120-128 (1968).
85. Goldstein, S. J. Jr. and MacDonald, D. D., "Observations of the 21-cm Hydrogen Line Toward High-Latitude Stars," *Ap. J.*, **157,** 1101-1118 (1969).
86. Takakubo, K., *Bull. Astr. Inst. Netherlands,* **19,** 125 (1967).
87. Meszaros, P., "Dust and Atomic Hydrogen near Rho Ophiuchi," *Astrophys. Space Sci.*, **2,** 510-519 (1968).
88. Valdes, F. and Freitas, R. A. Jr., "A Search for the Tritium Hyperfine Line from Nearby Stars," paper presented at the 13th IAA International Review Meeting on Communication with Extraterrestrial Intelligence (CETI), 35th Annual Congress of the IAF, Palais de Beaulieu Lausanne, 8-13 October 1984.
89. Pacholczyk, A. G., *Radio Astrophysics,* W. H. Freeman, San Francisco, (1970).
90. Field, G. B., "Excitation of the Hydrogen 21-cm Line," *Proc. IRE,* **46,** 240-250 (1958).
91. Fuhr, J. R., Personal communication, U.S. Dept. of Commerce, National Bureau of Standards, Data Center on Atomic Transition Probabilities, 18 November 1982.
92. Dole, S. H., *Habitable Planets for Man,* Blaisdell Pub. Co., New York (1964).
93. Sullivan, W. T. III, Brown, S. and Wetherill, C., "Eavesdropping: The Radio Signature of the Earth," *Science,* **199,** 377-388 (1978).
94. Dyson, F. J., "Search for Artificial Stellar Sources of Infrared Radiation," *Science,* **131,** 1667-1668 (1959).
95. Buyakas, V. I. *et al.*, "An Infinitely Expandable Space Radiotelescope," in J. Billingham, R. Pesek, eds., *Communication with Extraterrestrial Intelligence,* Pergamon Press, New York, pp. 175-201 (1979).
96. Craine, E. R., "Optical Infrared Sky Survey," *Astron. J.*, **83,** 1598-1606 (1978).
97. Reynolds, R. T., Tarter, J. C. and Walker, R. G., "A Proposed Search of the Solar Neighborhood for Substellar Objects," *Icarus,* **44,** 772-779 (1980).
98. Whitmire, D. P. and Wright, D. P., "Nuclear Waste Spectrum as Evidence of Technological Extraterrestrial Civilization," *Icarus,* **42,** 149-156 (1980).
99. Gray, R. H., Dixon, R. S., Ehman, J. P. and Talent, D. L., "21-cm Radio Emissions with Geometric Fine Structure," preprint, 1982.

* * * * *

Journal of the British Interplanetary Society, Vol. 38, pp.113-119, 1985.

ON THE POTENTIAL PERFORMANCE OF NON-NUCLEAR INTERSTELLAR ARKS

GREGORY L. MATLOFF
Pratt Institute, Educational Technology Group and Department of Computer Science, 200 Willoughby Avenue, Brooklyn, New York 11205, USA.

Previous publications which have presented various aspects of non-nuclear interstellar flight, are reviewed. These papers have demonstrated the utility of optimised hyperthin or perforated solar sails deployed behind occulters during close perihelion passes limited only by sail internal thermal constraints, multiple sail missions, and electric propulsion during the pre-perihelion trajectory leg. After accounting for the acceleration tolerance of the human occupants, trip times substantially less than 1000 years are possible for one-way missions to Alpha Centauri of payloads of 5 x 10^6 kg or larger. This paper extends this analysis and considers utilisation of the Light Sail Windmill as a "storage battery" and electric propulsion for the early post-perihelion trajectory leg of the mission. The Light Sail Windmill's energy storage capability will also be useful for on-board power during the long interstellar cruise phase of the mission. Appropriate combination of various propulsive techniques reveals that trip times of less than 800 years may ultimately be feasible.

1. INTRODUCTION

In a series of recent papers we have investigated various aspects of non-nuclear interstellar flight. The efficacy of the high-performance space-manufactured solar sail as an interstellar booster was evaluated in Ref. 1. Using parabolic solar orbits with perihelion of 0.01-0.03 Astronomical Units (AU) from the Sun's centre, sub-division of payloads among several sails, diamond cables, and partial deployment of the sails behind massive occulters before perihelion release, acceleration-limited human-occupied space habitats can be directed towards Alpha Centauri on missions requiring approximately 1000 years; more rugged robot probes are considerably faster. Application of Ehricke's nuclear-pulse peri-Saturn manoeuvre [2] during the pre-perihelion phase can reduce the flight times significantly.

The theoretical presentation of Ref. 1 was next incorporated into an optimisation [3]. Optimum starship configurations and trajectories were described for various payloads, perihelion distances and starting star luminosities. Transfer of momentum between sail-launched pellets and a departing starship was also investigated in Ref. 3, using the approach first suggested by Singer for consideration of mass-driver launched pellets [4].

Next, we considered non-nuclear alternatives to the peri-Saturn manoeuvre [5]. Viable alternatives to this manoeuvre require electric drive acceleration inward towards perihelion from a starting point as much as 300 AU from the Sun. Electric drives considered include rockets such as the ion drive and MPD thrusters and the solar electric ramjet [6]. Although ramjet performance is poor during the post-perihelion phase of the mission, it can be improved during the pre-perihelion acceleration phase by the enhancement of the density of the local interplanetary medium.

Although high performance solar sails are quite adequate for interstellar missions, they may not be optimum. The hyperthin partially transparent metallic sail and the perforated solar sail are improvements. These were considered theoretically in Ref. 7. Although these devices seem capable in theory of increasing projected performance of solar sail starships, a great deal of experimental work must sill be performed.

Finally, we returned in Ref. 8 to consideration of state-of-the-art solar sails as interstellar boosters with a discussion of robot interstellar precursor missions that may be possible with the World Space Foundation's current sail designs.

Computer-aided design was utilised to model sail stress and thermal characteristics. Because the occulter might be useful in stress and heat transfer, it was suggested that staged occulter drops might occur *after* sail full deployment. Later manned missions could benefit from this effect by using the occulter to shield from cosmic rays from the Sun.

In the following analysis, we first examine what might be possible by combining pre-perihelion electric acceleration with subdivided payloads and hyperthin sails. Then, the efficacy of Birch's Light Sail Windmill as a storage battery during the post-perihelion mission phase is investigated [9]. As the analysis demonstrates, the ultimate performance potential of non-nuclear propulsion for interstellar arks is coming into view.

2. ACHIEVEMENTS OF HIGH POST-PERIHELION VELOCITIES

A number of options have been investigated, in Refs. 1, 3, 5 and 7, that can be combined to yield high post-perihelion velocities for interstellar arks carrying payloads in the vicinity of 5 x 10^6 kg, with total masses including shielding as much as 10 times greater. These craft could be reconstructed during interstellar cruise into configurations that might resemble current designs for self-sufficient space habitats for hundreds or thousands of people [10].

These options include payload subdivision, a powered run towards perihelion, and use of perforated solar sails. In the examples discussed in this section, the following performance parameters are assumed.

An accelerated inbound preperihelion trajectory leg is assumed, as discussed in Ref. 5. Acceleration utilises a solar-electric ramjet in a local interplanetary medium with an enhanced density 1000 times the normal value. Performance parameters for such a craft are outlined in Table 1 of Ref. 5.

Since we are investigating ultimate performance in this case, we will continue solar-electric ramjet acceleration to 1AU instead of terminating it at 25AU, as was done in Ref. 5. If acceleration is maintained at the same rate as at 25AU, a hyperbolic excess of 0.0014c should be achieved at 1AU from the Sun. More conventional solar electric drives may offer similar performance particularly since it has recently been pointed out that they could use oxygen for fuel [11].

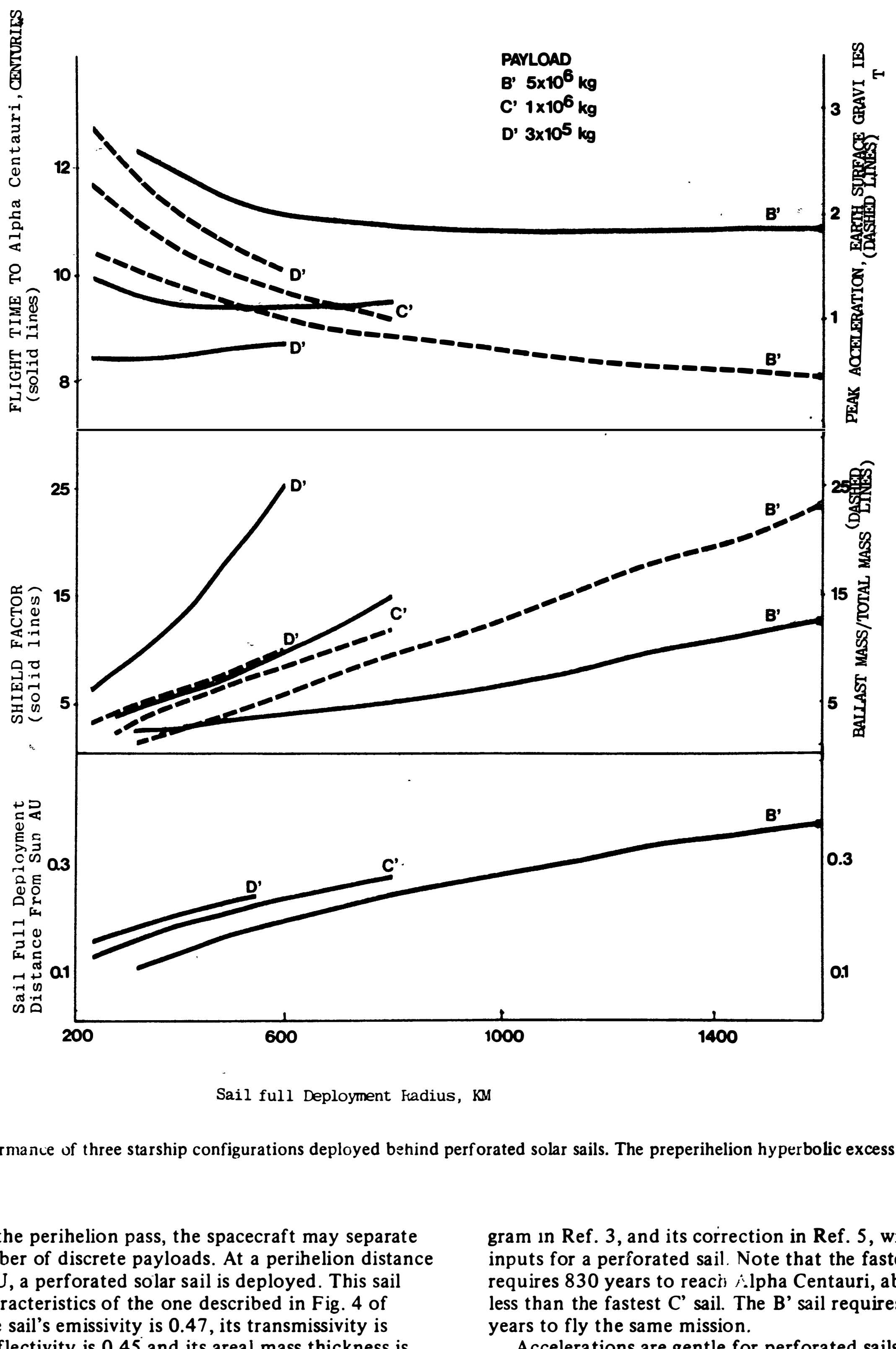


Fig. 1. Performance of three starship configurations deployed behind perforated solar sails. The preperihelion hyperbolic excess velocity is 0.0014c.

During the perihelion pass, the spacecraft may separate into a number of discrete payloads. At a perihelion distance of 0.038AU, a perforated solar sail is deployed. This sail has the characteristics of the one described in Fig. 4 of Ref. 7. The sail's emissivity is 0.47, its transmissivity is 0.28, its reflectivity is 0.45 and its areal mass thickness is 1.2×10^{-6} kg/m^2.

Figure 1 presents performance characteristic of three different payload subdivision strategies: B', C', and D'. Letters B' and C' correspond to cases B and C in Fig. 4 of Ref. 7. Case B' is for a payload of 5×10^6 kg per sail; case C' is for a payload of 1×10^6 kg per sail and case D' is for a payload of 3×10^5 kg. A 5×10^6 kg mission requirement requires 1 B' sail, 5 C' sails, or 17 D' sails.

These results are for optimum sail configurations and were generated using a modification of the computer program in Ref. 3, and its correction in Ref. 5, with appropriate inputs for a perforated sail. Note that the fastest D' sail requires 830 years to reach Alpha Centauri, about a century less than the fastest C' sail. The B' sail requires about 1080 years to fly the same mission.

Accelerations are gentle for perforated sails. Even the fastest D' sails accelerate at no more than twice Earth surface gravity at perihelion release.

Note the shield and ballast factors for the perforated sail missions. As noted in Ref. 7, shield factors and ballast masses are lower for perforated than for hyperthin sails.

As discussed in Ref. 8, it may pay to retain much of the ballast until the sail is fully deployed. The sail full deployment distances in Fig. 1, which vary in an approximately linear fashion with sail radius, as for those points where the sail is fully deployed and all ballast is dropped.

The fastest mission in Fig. 1 is the 300 km sail radius D' mission. Each of the 17 sails required will have a total (sail + cable + payload) mass of 2.4×10^6 kg. A ballast mass of 10^7 kg is required per sail, which indicates a total mission mass of approximately 2.1×10^8 kg at perihelion. If a ratio of pre-perihelion occulter/total mass of 10 is required and the occulter mass can double as ballast mass, a mass of 3×10^8 kg at the conclusion of the powered pre-perihelion leg is required.

It will be difficult to greatly reduce the 830 year flight time of the system D' spacecraft. To do so will require additional consideration of power sources for the post-perihelion trajectory. One such power source is the Light Sail Windmill.

3. THE LIGHT-SAIL WINDMILL AND INTERSTELLAR FLIGHT

Birch has described the use of the Light Sail Windmill in terrestrial or solar orbit as a method of obtaining energy from the Sun [9]. Incoming solar energy would strike the blades of the windmill and cause the windmill to rotate by solar radiation pressure. Some of the kinetic energy of rotation could be transmitted to Earth by microwaves or other techniques.

In this application, we consider a windmill which is "spun-up" during the time when the spacecraft is close to perihelion. Later, during the post-perihelion phase of the mission, the windmill's kinetic energy could be used to provide energy for an electric propulsion system or for on-board power.

The kinetic energy of any rotating object can be expressed [12]:

$$K.E. = \tfrac{1}{2} I w^2, \qquad (1)$$

where I is the moment of inertial and w is the angular velocity. From Fig. 5 of Birch's paper [9], the Light-Sail Windmill will resemble a hollow cylinder with a partially-filled cross section. The moment of inertia of such a cylinder could be approximated by [12]:

$$I \approx \tfrac{1}{2} m (R_i^2 + R_o^2), \qquad (2)$$

where m is the hollow cylinder's mass, and R_i and R_o are respectively the inner and outer radii.

The mass of the cylinder can be written:

$$m = \pi (R_o^2 - R_i^2)\, t f \rho, \qquad (3)$$

where t is the area mass thickness, ρ is the density of the Light Sail material and f is the fraction of the cylinder's cross section that is filled with windmill "blades." Substitution of Eq. (3) into Eq. (2) yields:

$$I \approx \frac{\pi}{2} (R_o^4 - R_i^4)\, t f \rho, \qquad (4)$$

Recalling that angular velocity w can be related to linear velocity v using $w = v/R_o$, Eq. (4) can be substituted into Eq. (1) to obtain:

$$KE \approx \frac{\pi}{4} (R_o^4 - R_i^4)\, t f \rho v^2 / R_o^2. \qquad (5)$$

If we next assume that the outer radius R_o will be 10 times greater than the inner radius R_i, the kinetic energy can be approximated by:

$$KE \approx \frac{\pi}{4} t f \rho v^2 R_o^2. \qquad (6)$$

The specific energy of the windmill in Joules of Energy stored per kilogram of mass can be approximated by dividing Eq. (6) by Eq. (3) and assuming $R_o \gtrsim 10\, R_i$:

$$S.E. \approx v^2/4 \text{ Joules/kg.} \qquad (7)$$

We see, therefore, that the velocity of the rotating blades is the major factor determining the specific energy stored in the system. The maximum allowable blade velocity can be approximated as follows.

The tensile stress of the Light-Sail material, σ_m, must exceed the centripetal radial stress on the windmill. From the definition of the centripetal force and Eq. (3):

$$\sigma_m \geqslant \frac{mv^2}{2\pi R_o^2 t} \approx f\rho v^2/2. \qquad (8)$$

substituting this result into Eq. (7), we obtain

$$S E \lesssim \frac{\sigma_m}{2f\rho} \text{ Joules/kg,} \qquad (9)$$

where σ_m is in units of Newtons/m^2.

We can reasonably expect future engineering materials to have mechanical properties between those of diamond and copper. From Ref. 1, $\rho = 3.52 \times 10^3$ kg/m^3 and $\sigma_m = 5.3 \times 10^{10}$ Newton/m^2 for diamond; $\rho = 8.52 \times 10^3$ kg/m^3 and $\sigma_m = 3.71 \times 10^{10}$ Newton/m^2 for copper. From Eq. (9).

$$\begin{aligned} S E \text{ diamond} &\lesssim \frac{8 \times 10^6}{f} \text{ Joules/kg} \\ S E \text{ copper} &\lesssim \frac{2 \times 10^6}{f} \text{ Joules/kg} \end{aligned} \qquad (10)$$

If we require a windmill specific energy of 2×10^{10} Joules/kg, $f = 4 \times 10^{-4}$ for a windmill with the mechanical properties of diamond and $f = 10^{-4}$ for a windmill with the mechanical properties of copper. We see therefore that for storage of a substantial amount of energy, the fraction of the hollow cylinder cross section filled will be very small.

As an example, consider an energy storage requirement of 3×10^{16} Joules in a four-bladed windmill with a mass of 10^6 kg. The specific energy is 3×10^{10} Joules/kg. Now, from Eq. (7), $v \approx 350$ km/sec $\approx 0.001c$. This compares to Birch's value of 230 km/sec for windmill blade velocity [9].

If this windmill has the tensile strength of copper, we can utilise Eq. (10) to estimate the maximum possible value for cross-sectional area fill fraction f as 7×10^{-5}. Assuming a 1000 km windmill radius and the four-bladed configuration shown in Fig. 2, then each blade will have a width of approximately 60 m.

The blade's areal mass thickness in kg/m^2, σ_s, can be estimated: $4\, \sigma_s \times 60 \times 10^6 = 10^6$, or $\sigma_s \approx 4 \times 10^{-3}$ kg/m^2, which is well above the minimum value for solid hyperthin sail materials, as discussed in Refs. 1 and 3. Birch, for comparison, considers a blade areal mass thickness of 6×10^{-3} kg/m^2 [9].

The initial assumption regarding Moment of Inertia in Eqs. (2) and (4) is an approximation and other approximations have been made in the calculation presented above. We can check these results using the Moment of Inertia for four independent slender rods, using Ref. 12. The moment of inertia for a slender rod can be written as I_{sr}:

$$I_{sr} = 1/3\, m_{sr} L_{sr}^2, \qquad (11)$$

where m_{sr} and L_{sr} are respectively the mass and length of each rod. For $L_{sr} = 10^6$ m and $m_{sr} = 2.5 \times 10^5$ kg, $I_{sr} = 8 \times 10^{16}$ kg-m^2.

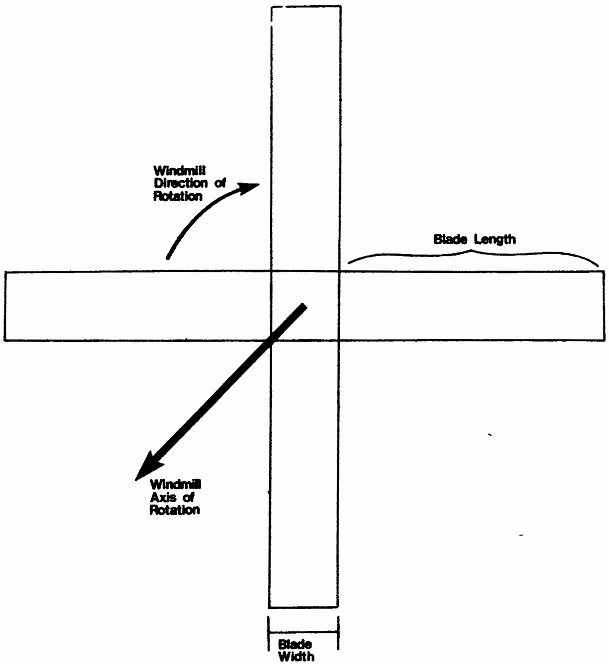


Fig. 2. Configuration of the Light Sail Windmill.

The windmill is rotating at 350 km/sec and its circumference is 2000 π km. The angular velocity w is therefore 0.35 radians/sec. From Eq. (1), the kinetic energy for all four blades is 2×10^{16} Joules. Thus, our estimate of SE = 3×10^{10} Joules/kg for this configuration is perhaps 33% too high, based upon another approximation to the light sail windmill's moment of inertia.

In a recent report, Forward has examined the energy storage capabilities of a number of potential space power sources [13]. The best possible chemical energy storage approaches have specific energies about three orders of magnitude lower than the light sail windmill.

Some attention should be paid to the "spin-up" process for the light-sail windmill. For a windmill mass of 10^6 kg, a radius of 10^3 km, and a spin velocity of 350 km/sec, the centripetal force on the blades is approximately 10^6 Newtons. The radial acceleration of the blades is about 10^4 Earth surface gravities. If the blades are spun-up at a uniform rate to their final velocity of 350 km/sec during a 10^6 sec spin-up period, the blade liner acceleration during this period will be 0.35 m/sec^2.

Assume that light-sail windmill blade spin-up takes place during the early phases of the post-perihelion trajectory leg, while the starship is between 1 and 50 AU from the Sun. If the ship's velocity at 1 AU is 0.005c the ship requires approximately 5×10^6 sec to reach 50 AU.

A 300 km sail radius receives about 3×10^{11} watt of solar energy at 50 AU from the Sun, if it is normally situated to the Sun [14]. If only 2% of this energy is available for light-sail windmill spin-up, and spin-up occurs at a uniform rate between 1 and 50 AU, 6×10^9 watt of power is supplied to the windmill. During the 5×10^6 sec spin-up interval, 3×10^{16} Joules of energy will be stored within the windmill.

4. ACCELERATION DURING THE POST-PERIHELION TRAJECTORY LEG

Having a light-weight solar-energy storage battery improves the acceleration possibilities for the post-perihelion leg of the trajectory. It will first be shown that much more efficient performance is possible if this energy is applied to solar-electric rocket propulsion than to solar-electric ramjet propulsion. These propulsion systems have been previously examined in Ref. 5.

4.1 Solar-Electric Ramjets

We first consider utilisation of the Light-Sail Windmill with the Solar-Electric Interplanetary Ramjet during the post-perihelion trajectory leg. Equation (8) of Ref. 5 allows us to calculate the acceleration of this propulsion option, $\dot{V}_s$:

$$\dot{V}_s = \frac{\dot{M}_f}{M_s} \left(-V_r + \sqrt{V_r^2 + 2\dot{E}/\dot{M}_f}\right) \tag{12}$$

In Eq. (12), $\dot{M}_f$ is the rate at which reaction mass from the interplanetary medium is utilised, M_s is the total spacecraft mass, V_r is the relative velocity of the spacecraft and the local interplanetary medium, and $\dot{E}$ is the power delivered to the fuel acceleration system.

In the post-perihelion phase of the mission, a low-power high relative-velocity approximation for Eq. (12) will be useful. For an electric-propulsion system specific mass of 1 kg/kW [5], $\dot{E} \lesssim 10^9$ watt. To determine the lowest reasonable value for $\dot{M}_f$, we use the following equation [5]:

$$\dot{M}_f = \rho_i M_p V_r A_{sc}, \tag{13}$$

where ρ_i is the interplanetary medium density ($\rho_i \sim 2 \times 10^6$ protons/m^3 in an unmodified interplanetary medium), M_p is the proton mass (1.64×10^{-27} kg), and A_{sc} is the ramjet scoop area.

For a low-energy approximation to Eq. (12), we require

$$V_r^2 \geqslant 2\,\dot{E}/\dot{M}_f$$

or

$$V_r \geqslant \left(\frac{2\dot{E}}{\rho_i M_p A_{sc}}\right)^{1/3} \tag{14}$$

If the ramjet scoop's effective field radius is 1000 km [15], $A_{sc} = 3.14 \times 10^{12}$ m^2. Therefore, after substituting appropriate values for $\dot{E}$, ρ_i and M_p, we find that

$$V_r \gtrsim 5.8 \times 10^5 \text{ m/sec} \approx 0.002c.$$

Therefore, unless we utilise a modified interplanetary medium with the fuel pellets moving only "slightly" slower (in interstellar terms) than the starship, $V_r^2 > 2\,\dot{E}/\dot{M}_f$ will apply in the post-perihelion trajectory leg. Equation (12) can now be rewritten using the binomial approximation:

$$\dot{V}_s \approx \frac{\dot{E}}{M_s V_r}. \tag{15}$$

Note that for this approximation, spacecraft acceleration is independent of ρ_i and A_{sc}. If $\dot{E} = 10^9$ watt, $M_s = 10^7$ kg, and $V_r \approx 0.004c$ (1.2×10^6 m/sec), $\dot{V}_s < 10^{-4}$ m/sec $\approx 10^{-5}$ Earth surface gravities.

If a 1000 km radius solar sail and a 10% efficient solar-electric energy conversion system are utilised in the early post-perihelion trajectory leg, direct solar energy could provide 10^9 watt for the first 650 Astronomical Units (AU) of the outbound trajectory. At a spacecraft velocity relative to the Sun of 0.005 c (1.5×10^6 m/sec), this distance is traversed in about 6×10^7 sec.

A Light-Sail Windmill containing 3×10^{16} Joules could provide an acceleration power of 10^9 watt for only an additional 3×10^7 sec, even at 100% energy conversion efficiency. The Solar-Electric Ramjet is therefore useful for only the first few years of the post-perihelion trajectory. At an acceleration of 10^{-5} Earth surface gravities, it is capable of increasing outbound velocity by no more than a few per cent, which is in agreement with the results presented in Ref. 5.

4. 2 Solar-Electric Rockets

The solar-electric rocket is a much more efficient method of utilising both direct and stored solar energy for propulsive purposes during the post-perihelion leg of the interstellar trajectory. We begin our consideration of the solar-electric rocket in this application from the equation for power delivered to the electric-rocket fuel:

$$\dot{E} = ½ \dot{M}_f V_e^2, \qquad (16)$$

where $\dot{M}_f$ is the fuel accelerated per second and V_e is the exhaust velocity. Referring to Ref. 5, we see that electric-rocket designs based upon currently feasible technology should be capable of specific impulses as high as 20,000 sec, which corresponds to a maximum achievable exhaust velocity of 2×10^5 m/sec (0.0007c).

Substituting $\dot{E} = 10^9$ watt and $V_e = 2 \times 10^5$ m/sec into Eq. (16), we find that $\dot{M}_f \approx 0.05$ kg/sec. This corresponds to a fuel emission rate of 1.5×10^6 kg/year.

The rocket equation [12] can be written:

$$\frac{M_f + M_s}{M_s} = \exp(\Delta V_s / V_e) \qquad (17)$$

where M_f is the total fuel mass, M_s is the total starship mass excluding the fuel, and ΔV_s is the electric drive total velocity increment. For $M_s = 6 \times 10^6$ kg and $M_f = M_s$, the electric drive must operate for approximately four years. Assuming that $V_e = 2 \times 10^5$ m/sec, $\Delta V_s \approx 1.5 \times 10^5$ m/sec ≈ 0.00035c.

At the start of the post-perihelion acceleration leg, the starship is moving at 0.005c. Seven years later, after the electric drive fuel is exhausted, the ship's velocity has increased by 8% to 0.0054c. During the period of (linear) electric drive acceleration, the starship will have moved 0.021 light years or about 1400 AU from the Sun.

Direct solar-energy received by the 1000 km solar sail and converted to electric drive propulsive energy at 10% efficiency is sufficient for only the first half of the acceleration run. After the Sun-starship distance has exceeded about 700 AU, it will be necessary to supplement the direct energy with energy stored in the Light Sail Windmill.

During the third and fourth years of the post-perihelion acceleration run, the starship-Sun distance will increase to about 1400 AU. The average power received from the Sun will fall by 50%. To maintain full acceleration, it will be necessary to supply on average about 5×10^8 watts to the accelerator for 6×10^7 sec, from the Light Sail Windmill.

Because this will deplete the 3×10^{16} Joules of energy stored in the Light Sail Windmill, the electric drive fuel emission rate must be reduced after the starship-Sun separation has reached 1400 AU. At 1400 AU, the electric-rocket fuel emission rate and starship acceleration will be 25% of their values at 700 AU.

We have somewhat arbitrarily cut off electric-drive operation at 1400 AU. If more electric drive fuel were carried, acceleration could continue beyond this point. The fuel emission rate would, of course, be reduced.

One advantage of terminating electric-rocket operation after a fairly short post-perihelion acceleration run is that the comparatively small Sun-starship separation allows use of the 1000-km radius solar sail to recharge the Light-Sail Windmill for on-board power during the interstellar cruise phase of the voyage. This phase will be considered in more detail in the following section of this paper.

It is interesting to note that at 0.0054c, the terminal starship velocity assumed in this analysis, less than 800 years are required to reach Alpha Centauri, excluding pre-perihelion and post-perihelion acceleration phases. Even with higher specific impulses, energy conversion efficiencies, and fuel masses, it will be difficult to reduce voyage duration much below 750 years.

The electric-rocket fuel could be used for course correction instead of acceleration. Trajectory aim errors as high as 5 degrees could be corrected using this post-perihelion propulsion option.

5. ENERGY FOR THE INTERSTELLAR CRUISE

The Light-Sail Windmill could serve as an energy storage device during the long cruise phase of the interstellar voyage. Other energy sources such as nuclear or starship kinetic energy [16, 17] could be supplemented or replaced.

Before evaluating the effectiveness of the Light-Sail Windmill as a cruise-phase storage battery, some review of the energy requirements per person on the starship are in order. In Ref. 16, we utilised O'Neill's estimate of 10^4 watt/person [18].

One of the major sinks for energy will be agriculture for food and life support. If agriculture were very efficient in terms of energy utilisation, it would require a very small percentage of the population's energy allotment because a typical person requires about 3000 calories of food energy per day [19].

Gitelson *et al* have discussed an experiment in semi-closed life support systems that can serve as an energy-utilisation model [20]. During the six-month experiment, 100% of the oxygen, 95% of the water, and about 20% of the food requirements for a crew of three were supplied by two higher plant "phytotrons."

Each of these chambers had an area of 20×4 m^2 and was irradiated at 180 watt/m^2. The agricultural energy required was approximately 2400 watt/person. We can expect technological improvements, genetic engineering and experience with closed and semi-closed life support systems in the space environment to reduce this energy requirement long before interstellar arks become practical. Even if this were not the case, a linear entrapolation of the requirement for 20% food to 100% food results in a human life-support energy requirement of less than 10^4 watt.

Pecoraro and Morris have presented early designs for a 100% regenerable life support system to be utilised on the lunar surface [21]. During the lunar night, they estimate a power requirement for lighting of 8-30 kW/person.

In 1977, the Hensons published a description of an orbital space farm with a photosynthetic area of 32 m^2/person [22]. They expect an agricultural power requirement of 24 kW/person.

Johnson and Holbrow have edited the most exhaustive examination to date of design details for large human communities in space [23]. They estimate the solar irradiance required for agriculture to be about 6.6 kW/person, using a combination of techniques. According to Ref. 23, the total power required by the human population will be about 10^4 kW/person.

Non-agricultural energy requirements can also be estimated using figures presented by O'Neill [18]. In 1975, the total United States electrical energy generation was 5×10^{11} watt. Dividing this by a population of 2.25×10^8 people, we can

expect the electrical energy requirement to be 2000 watt/person. This value too can be expected to decrease in the future.

If we assume an average interstellar ark population of 100 persons and an 800 year interstellar voyage, 10^6 watt of on-board power is required and the total on-board energy requirement is 2.4×10^{16} Joules. At 10% efficiency, the power received from the 1000 kW radius solar sail falls below 10^6 watt when the Sun-starship separation exceeds about 20,000 AU, or about 0.3 light years. On an 800 year voyage to Alpha Centauri, the light sail windmill or some other on-board energy source must be used for 760 years.

At the conclusion of the four-years post-perihelion acceleration phase, when the spacecraft is 1400 AU from the Sun, the 1000-km solar sail can be used to "recharge" the Light Sail Windmill. If the energy conversion efficiency is 10%, the power input to the Windmill is approximately 2×10^8 watt. This is 200 times the power required to support the interstellar ark's population.

Two years later, the Sun-starship separation has increased to 2100 AU. The power input to the windmill has fallen to about 10^8 watt, which is about 100 times the population's power requirement. Continuing to evaluate the spin-up procedure for the Light-Sail Windmill, we see that the energy required for an 800 year voyage is stored in this device 20 years after the conclusion of post-perihelion acceleration. The Sun-starship separation at the conclusion of the windmill spin-up procedure is 8500 AU.

Interstellar erosion of the Light-Sail Windmill can be minimised during the interstellar cruise phase by orienting the windmill spin axis perpendicular to the starship line of flight. After windmill spin-up, a dust bumper of similar dimensions to the windmill blades but much less areal mass thickness could be deployed forward of the windmill.

Dust erosion on the bumper can be evaluated as follows. As Aannestad and Purcell have noted, the interstellar dust grains are typically 5×10^{-8}-10^{-7} metres in size. The ratio of hydrogen gas/dust mass densities is typically 100-300 in the interstellar medium [24]. Assuming that dust grains specific gravity ≈ 1, the mass of a typical interstellar dust grain is 4×10^{-18} kg.

From Spitzer and Jenkins [25], the density of hydrogen atoms in the intercloud medium near the Solar System is in the neighbourhood of 10^{-5} hydrogen atom/m^3. The maximum expected dust density will therefore be about 1.7×10^{-24} kg/m^3. Dust particle separations in the local intercloud medium are of the order of 100 metres.

For one dust impact per square metre, the starship must traverse a distance of 2.5×10^6 metre. Because the cross-sectional area of a dust particle is typically 10^{-13} m^2, the starship must traverse 2.5×10^{19} metres before the bumper will be totally pitted by impacts of interstellar dust grains. This is more than 400 times the current separation of the Sun and Alpha Centauri. Martin has considered the physical effects of erosion by interstellar dust grains in more detail [26].

5. CONCLUSIONS

In this publication we have continued our analysis of non-nuclear interstellar arks. We have found that application of multiple sail deployment strategies and perforated solar sails will allow post-perihelion velocities in excess of 0.005c.

Application of the Light-Sail Windmill as a post-perihelion storage battery and the solar-electric rocket for post-perihelion acceleration will reduce transit times to Alpha Centauri to 800 years or less. As Oberg has noted [11], the utilisation of electric rockets will be greatly simplified by the use of Oxygen as reaction fuel instead of Argon, Xenon, or Mercury. The solar-electric rocket is much more effective than the solar-electric ramjet in post-perihelion acceleration.

The Light-Sail Windmill could be recharged after the conclusion of post-perihelion acceleration and utilised as a source of on-board power during the long interstellar cruise phase. A 10^6 kilogram windmill could supply all on-board power required to support 100 people for 800 years.

No attention has been paid here to the technology required to effect Windmill spin-up or spin-down. Some of the required technological development may be derived from more conventional applications to terrestrial wind machines [27]. Also, further technological development may reveal methods more effective than the Light-Sail Windmill for the storage of solar energy.

A number of additional methods of reducing the trip time remains to be considered. One could, for example, utilise the occulter as a heat-sink during the perihelion pass. Because the occulter has similar dimensions to the partially deployed solar sail, the solar irradiance on the sail could be reduced by a factor of two. This would reduce the sail temperature at perihelion by about 20% and would allow the perihelion distance to be reduced by about 30%. From Fig. 4 of Ref. 3, the voyage duration could be reduced by a few decades in this fashion.

During the pre-perihelion acceleration run, giant planet swingbys could also be utilised to increase kinetic energy. The effectiveness of such manoeuvres will be analysed in a future paper.

Combination of these and other techniques, while effective, will not reduce the travel time between the Sun and Alpha Centauri much below the values discussed in this paper. Barring development of a momentum-transfer technique such as the one described by Singer [4], or the beaming of copious amounts of energy to the receeding starship from the Earth [28], the fastest solar-powered interstellar arks will require approximately 750 years to reach Alpha Centauri.

REFERENCES

1. G. L. Matloff and E. Mallove, "Solar Sail Starships: The Clipper Ships of the Galaxy," *JBIS*, 34, 371-380 (1981).
2. K. A. Ehricke, "Saturn-Jupiter Rebound: A Method of High Speed Spacecraft Ejection from the Solar System," *JBIS*, 25, 561-571 (1972).
3. G. L. Matloff and E. Mallove, "The Interstellar Solar Sail-Optimization and Further Analysis," *JBIS*, 36, 201-209 (1983).
4. C. E. Singer, "Interstellar Propulsion Using a Pellet Stream for Momentum Transfer," *JBIS*, 33, 107-115 (1980).
5. G. L. Matloff, "Beyond the Thousand-Year Ark; Further Study of Non-Nuclear Interstellar Flight," *JBIS*, 36, 483-489 (1983).
6. A. J. Fennelly, G. L. Matloff, E. H. Walker and G. Frye, "Some Solar System Applications of an Interstellar Ion Scoop," *JBIS*, 29, 489-493 (1976).
7. G. L. Matloff, "Interstellar Solar Sailing: Consideration of Real and Projected Sail Materials," *JBIS*, 37, 135-141 (1984).
8. G. L. Matloff, "The State of the Art Solar Sail and the Interstellar Precursor Mission," *JBIS*, 37, 491-494 (1984).
9. P. Birch, "Orbital Ring Systems and Jacob's Ladders – III," *JBIS*, 36, 231-238 (1983).
10. G. K. O'Neill, "The Colonization of Space," *Physics Today*, 27 (9), 32-40 (1974).
11. J. E. Oberg, *Mission to Mars*, Meridian, New York (1982).
12. F. W. Sears, M. W. Zemansky and H. D. Young, *University Physics Part I*, 5th Edition, Addison-Wesley, Reading, Mass. (1977).
13. R. L. Forward, "Alternate Propulsion Energy Sources," *AFRPL TR-83-039*, Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California (1983).
14. G. O. Abell, *Exploration of the Universe*, 3rd Edition, Holt, Rinehart, and Winston, New York (1975).
15. G. L. Matloff and A. J. Fennelly, "Interstellar Applications

and limitations of Several Electrostatic/Electromagnetic Ion Collection Techniques," *JBIS*, **30**, 213-222 (1977).
16. G. L. Matloff, "Utilisation of O'Neill's Model 1 Lagrange Point Colony as an Interstellar Ark," *JBIS*, **29**, 775-785 (1976).
17. G. L. Matloff and A. J. Fennelly, "A Superconducting Ion Scoop and its Application to Interstellar Flight," *JBIS*, **27**, 663-673 (1974).
18. G. K. O'Neill, *The High Frontier*, Morrow, New York (1977).
19. I. R. Richards and P. J. Parker, "Estimates of Crop Areas for Large Space Colonies," *JBIS*, **29**, 769-774 (1976).
20. I. T. Gitelson, I. A. Terskov, B. G. Kovrov, F. Ya Sidko, G. M. Lisovsky, Yu. N. Okladnikov, V. N. Belyanin, I. N. Trubachov and M. S. Rerberg, "Life Support System with Autonomous Control Employing Plant Photosynthesis," *Acta Astronautica*, **3**, 633-650 (1976).
21. J. N. Pecoraro and F. K. Morris, "Progress in Regenerative Life Support Systems for a Lunar Surface Base," *Acta Astronautica*, **1**, 561-574 (1974).
22. H. K. Henson and C. M. Henson, "Closed Ecosystems for High Agricultural Yield," in *Space Manufacturing Facilities/ Space Colonies*, ed. J. Grey, American Institute of Aeronautics and Astronautics, New York (1977), pp. 105-114.
23. R. O. Johnson and C. Holbrow eds., "Space Settlements: A Design Study," NASA SP-413, p. 102, (1977).
24. P. A. Aannested and E. M. Purcell, "Interstellar Grains," *Annual Review of Astronomy and Astrophysics*, **II**, 309-362 (1973).
25. L. Spitzer, Jr. and E. B. Jenkins, "Ultraviolet Studies of the Interstellar Gas," *Annual Review of Astronomy and Astrophysics*, **13**, 133-164 (1975).
26. A. R. Martin, "Project Daedalus: Bombardment by Interstellar Material and its Effects on the Vehicle," *JBIS*, Supplement, S116-S121 (1978).
27. M. I. Hoffert, G. L. Matloff and B. A. Rugg, "The Lebost Wind Turbine: Laboratory Tests and Data Analysis," *Journal of Energy*, **2**, 173-181 (1978).
28. D. P. Whitmire and A. A. Jackson IV, "Laser Powered Interstellar Ramjet," *JBIS*, **30**, 223-226 (1977).

* * * * * * *

Journal of the British Interplanetary Society, Vol. 38, pp. 120-128, 1985.

PLASMA EXPANSION IN THE DAEDALUS FIRST STAGE ENGINE

JOHN O. ELLIOTT and WILLIAM K. TERRY
School of Nuclear Engineering, Purdue University, West Lafayette, Indiana 47907, USA.

This paper describes a detailed study of the expansion of the micro-explosion plasma into the magnetically protected reaction chamber of the Daedalus conceptual fusion rocket engine. The plasma was found to expand almost spherically up to turnaround. The distance of closest approach and the magnetic pressure on the chamber wall were found as functions of polar angle. An analysis of plasma stability to inertially-driven fluting was performed. The results of these calculations support the feasibility of the Daedalus concept.

1. INTRODUCTION

The conceptual design of the Daedalus fusion pulse rocket engine is described in Refs. 1 and 2. The principle of the Daedalus engine is basically straightforward. An inertial confinement D-^{3}He fusion pellet is detonated in a magnetically protected reaction chamber, as shown in Fig. 1. The electrically conducting reaction products expand in the chamber, compressing the magnetic field. This field in turn slows and finally reverses the expanding plasma, which is then expelled from the chamber at very high velocity. Repeating this process many times per second allows the impulse received by the reaction chamber to be merged into a fairly smooth thrust.

Although quite comprehensive, the Daedalus design study relies to a considerable degree on approximate scaling laws. Within that context, the design shows such great potential for pulsed fusion engines that some additional, more detailed analysis seems justified even though the inertial confinement fusion technology on which the concept is based is itself far from practical applicability.

One area which warrants detailed investigation is that of plasma expansion. The plasma, as it expands, will be susceptible to instabilities which could conceivably render the propulsion concept infeasible. Also, the complicated structure of the magnetic field will result in uneven approach distances of the plasma to the wall, possibly allowing localised wall contact, and in an uneven magnetic pressure distribution on the wall, which should be accounted for in any attempt to refine the design of the chamber wall support structure.

In the following sections an analysis is described which accurately models the expanding plasma ball as it interacts with the chamber magnetic field. The plasma is followed to its turnaround point and studied to determine its degree of hydrodynamic stability. In addition these results give a good picture of the expanding plasma and its closest approach to the reaction chamber wall, while providing accurate values of pressures distributed on the wall. It is hoped that this work will lead to a better understanding of the processes taking place in the engine, thus bringing this concept at least moderately closer to reality.

2. THE INITIAL FIELD

The first step in the analysis of the Daedalus propulsion system is to solve for the magnetic field as it exists in the reaction chamber prior to pellet detonation. The initial field is needed to obtain a boundary condition for the magnetic stream function which appears in the plasma expansion calculation of Section 3.

For this work it was necessary to develop a computer code that would provide values for the field at any point in the reaction chamber. The magnetic field vector, $\vec{B}$, may be obtained for each field coil from the relation

$$\vec{B} = \nabla \times \vec{A} , \qquad (1)$$

where $\vec{A}$ is the magnetic vector potential of the field coil, which is represented as a simple current loop. Reference 3 gives an expression for this vector potential in spherical coordinates (SI units) as

$$A_\phi(r, \theta) = \frac{Ia\mu_0}{\pi(a^2 + r^2 + 2ar\sin\theta)^{1/2}} \left[\frac{(2-k^2)K(k) - 2E(k)}{k^2} \right] \qquad (2)$$

where the argument of the elliptic integrals E and K is given by

$$k^2 = \frac{4ar\sin\theta}{a^2 + r^2 + 2ar\sin\theta} , \qquad (3)$$

in which I expresses the current in the loop, a is the loop radius, and r and θ are as shown in Fig. 2. Note that A_ϕ is the only component, since the current is entirely in the ϕ direction.

Now applying Eq.(1) and the relation $\vec{B} = \mu_0\vec{H}$, and changing to cylindrical coordinates for simplicity, the components of the magnetic induction vector $\vec{H}$ are found to be

$$H_\rho = \frac{I(a/\rho)^{1/2} zk}{8\pi\rho a} \left[-2K + \frac{E(2-k^2)}{(1-k^2)} \right] \qquad (4)$$

and

$$H_z = \frac{I(a/\rho)^{1/2}}{2\pi\rho} \left\{ \frac{(2-k^2)K - 2E}{2k} + \frac{1}{k^2} \left[\frac{k}{2} - \frac{k^3}{4}(1+\rho/a) \right] \left[-2K + \frac{E(2-k^2)}{(1-k^2)} \right] \right\} , \qquad (5)$$

where ρ and z are coordinates of a point of interest, P, also shown in Fig. 2.

The use of these equations now allows the magnetic induction vector to be found at any point. In the rocket's reaction chamber superposition is used to give the total field resulting from the four coils. The field lines are plotted by following the field vector for a large number of small steps.

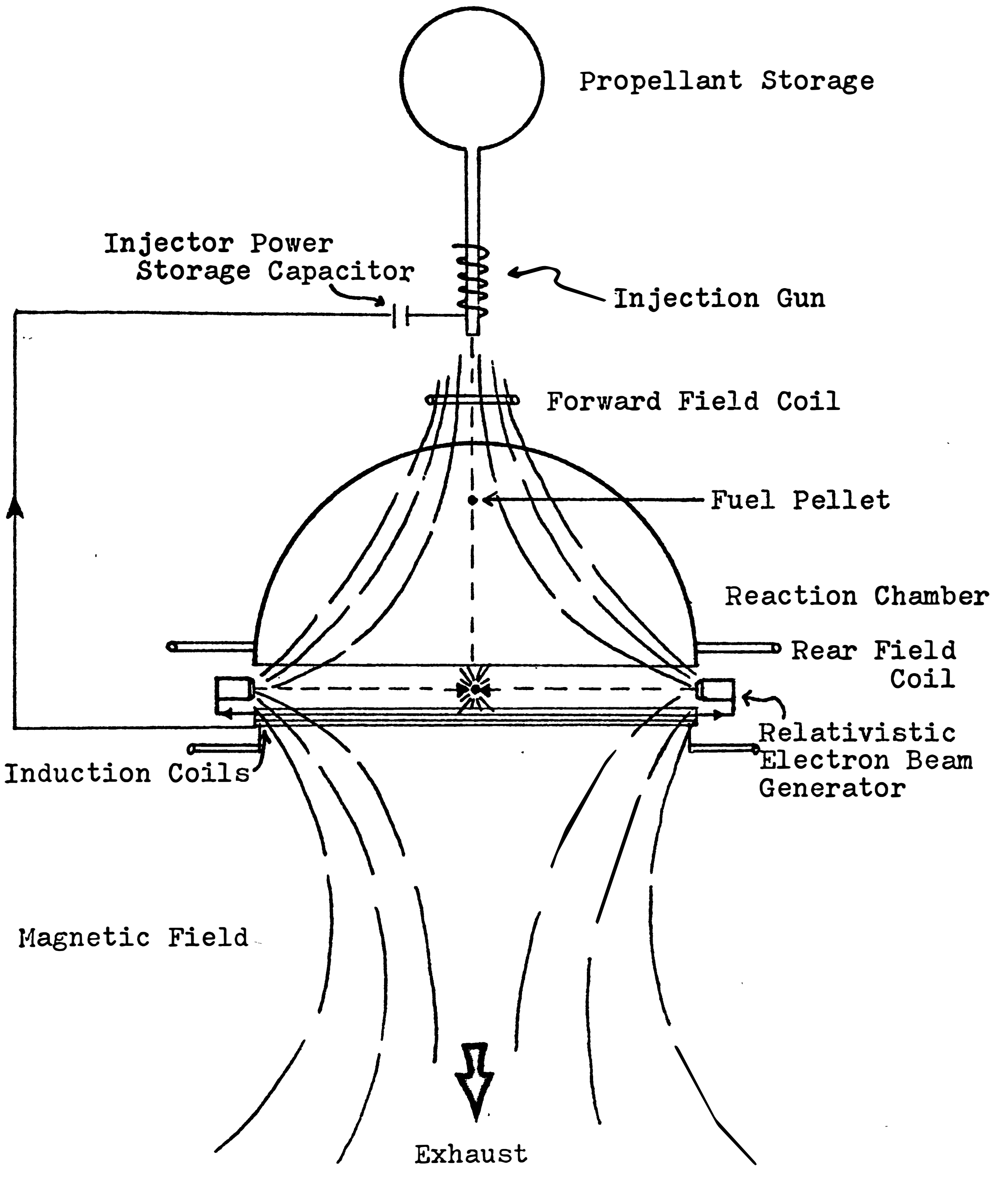


Fig. 1. The Daedalus Fusion Pulse Engine (after Ref. 1).

Figure 3 shows the results of this code, which agree very well with the pictures given in the Daedalus report. The currents in the four coils, and their locations, are given in Table 1.

3. EXPANSION MODELLING

Calculations of the motion of the plasma are based on a model described by Poukey [4] in which equations of motion were developed and applied to describe the expansion of a plasma into a uniform, infinite, solenoidal field. The model has been modified for the present specific case of a cusp-shaped field bounded by a flux conserving shell.

For the equations of motion consider the plasma as a fully ionised, perfectly conducting shell, initially spherical. This plasma shell is expanding with uniform initial speed v_o into a region filled by a cusp-shaped magnetic field, bounded by a hemispherical flux conserving shell of radius 50 m. The plasma is at all times assumed to have no internal field and shell motion is affected solely by the magnetic pressure at the surface,

$$p_m = B^2/2\mu_o \qquad (6)$$

This analysis considers the region bounded by $\theta = 0$, corresponding to the spindle cusp injection corridor, and

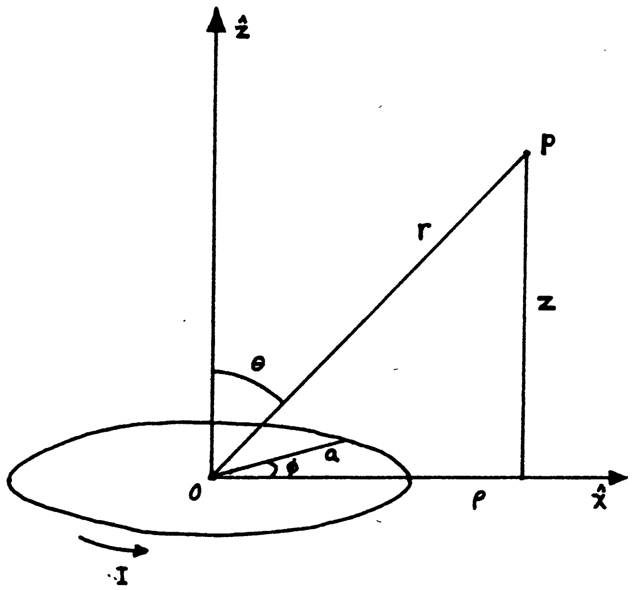


Fig. 2. Coordinate system.

TABLE 1. Field Coil Parameters.

Parameter	Coil 1	Coil 2	Coil 3	Coil 4
Current (MA)	9.88	1.05	6.16	-6.83
Radius (m)	12.32	39.60	55.00	55.00
Axial Station (m)	0.00	17.60	44.00	55.00

θ = 1.452 radians, the angle of electron beam injection into the ring cusp. The pellet explosion point is taken to be the centre of curvature of the flux conserving shell. Because of symmetry about the longitudinal axis, the plasma expansion will be purely in the r- and θ-directions.

The plasma shell is divided into azimuthal rings which retain their identity as the shell expands. At time t = 0, the polar angle of a ring is denoted by θ_o, and the incremental polar angle subtended by the ring at the origin is denoted by $d\theta_o$. At later times, the ring subtends an incremental angle $d\theta$ at angle θ, as shown in Fig. 4. The independent variables for the equations of motion are the time t and the Lagrangian angle θ_o.

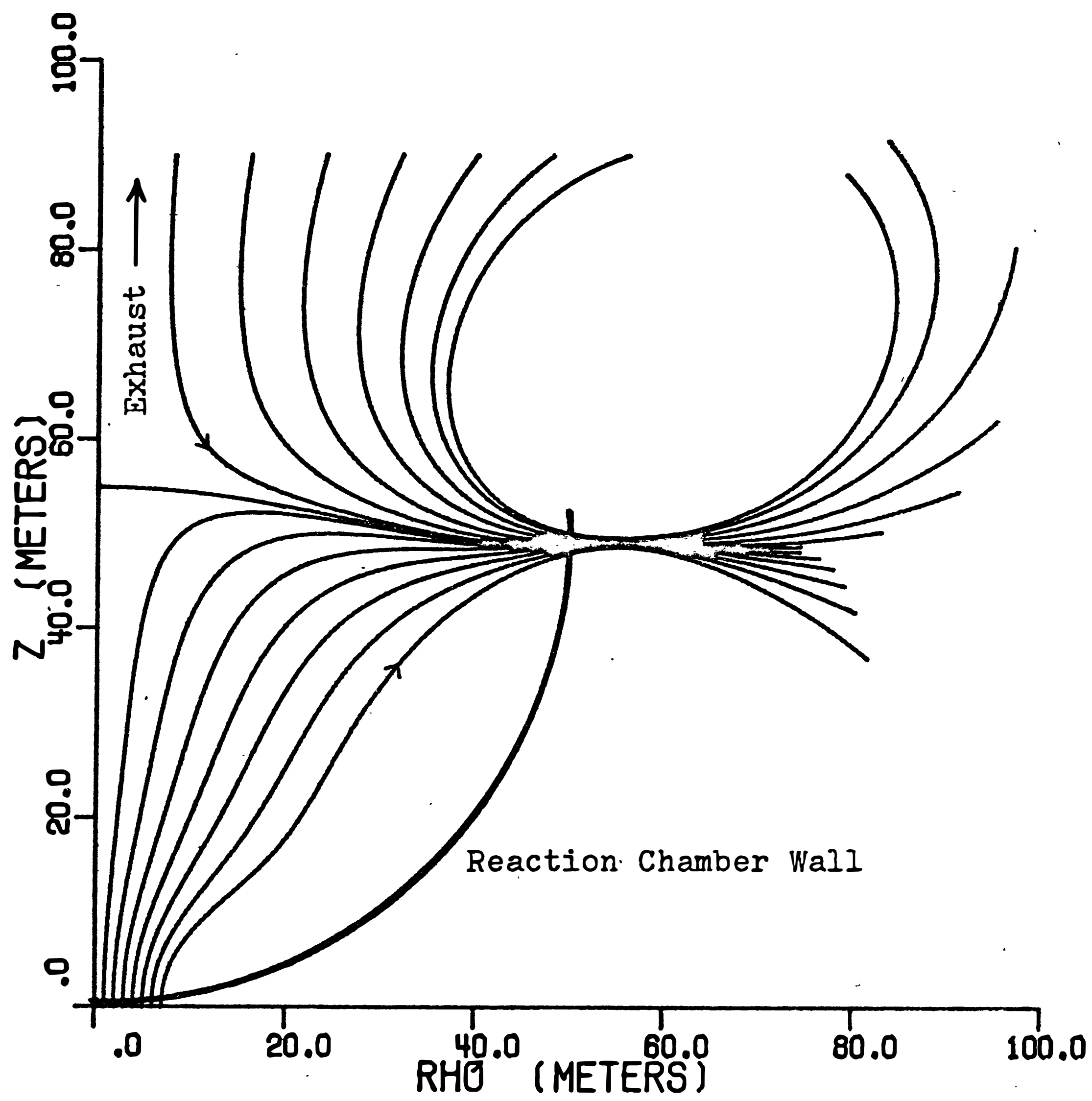


Fig. 3. Initial Magnetic Field Configuration.

The mass of a given ring is

$$dM = \frac{M}{2} \sin\theta \, d\theta = \frac{M}{2} \sin\theta_o \, d\theta_o \ , \tag{7}$$

where M is the total plasma mass.

The position of an element at time t is expressed as (r, θ) where r and θ are functions of element initial angle as well as time: $r = r(\theta_o, t), \theta = \theta(\theta_o, t)$. Elemental velocity is simply $v_r \hat{r} + v_\theta \hat{\theta}$, where

$$v_r = (\partial r/\partial t)_{\theta_o} \tag{8}$$

and

$$v_\theta = r(\partial \theta/\partial t)_{\theta_o} \ . \tag{9}$$

Since p_m represents the sole retarding force, the hydrodynamic equations of motion for an element may be simply derived from basic principles of particle motion. Using the nomenclature described above, and applying Eq. (7), one finds

$$\left(\frac{\partial v_r}{\partial t}\right)_{\theta_o} - \frac{v_\theta^2}{r} = \frac{4\pi p_m r^2}{M} \frac{\sin\theta}{\sin\theta_o} \left(\frac{\partial \theta}{\partial \theta_o}\right)_t \tag{10}$$

and

$$\left(\frac{\partial v_\theta}{\partial t}\right)_{\theta_o} + \frac{v_r v_\theta}{r} = \frac{4\pi p_m r}{M} \frac{\sin\theta}{\sin\theta_o} \left(\frac{\partial r}{\partial \theta_o}\right)_t \ . \tag{11}$$

In order to solve these equations at each time step it remains to calculate $p_m(\theta, t)$ for each time, t. This may be accomplished by solving the equations

$$\nabla \times \vec{B} = 0 \tag{12}$$

and

$$\nabla \cdot \vec{B} = 0 \tag{13}$$

outside the plasma shell, and subsequently finding p_m at the plasma surface from Eq. (6). Solution for the components of the magnetic field at the surface may be facilitated by use of the 'stream' function $\psi(r_c, \theta, t)$ defined by

$$B_r = \frac{-1}{r_c^2 \sin\theta} \left(\frac{\partial \psi}{\partial \theta}\right)_{r_c, t} \tag{14}$$

and

$$B_\theta = \frac{1}{r_c \sin\theta} \left(\frac{\partial \psi}{\partial r_c}\right)_{\theta, t} \ , \tag{15}$$

where r_c denotes the radial coordinate at any point external to the plasma shell.

The stream function for this problem satisfies the equation

$$\frac{\partial^2 \psi}{\partial r_c^2} + \frac{\sin\theta}{r_c^2} \frac{\partial}{\partial \theta} \left(\frac{1}{\sin\theta} \frac{\partial \psi}{\partial \theta}\right) = 0 \ , \tag{16}$$

which is obtained by application of Eqs. (14) and (15) to Eqs. (12) and (13). Given proper boundary conditions this elliptic differential equation may be solved for the stream function.

The stream function $\psi(r_c, \theta, t)$ is equal to the magnetic flux per radian of azimuthal angle through the portion of a

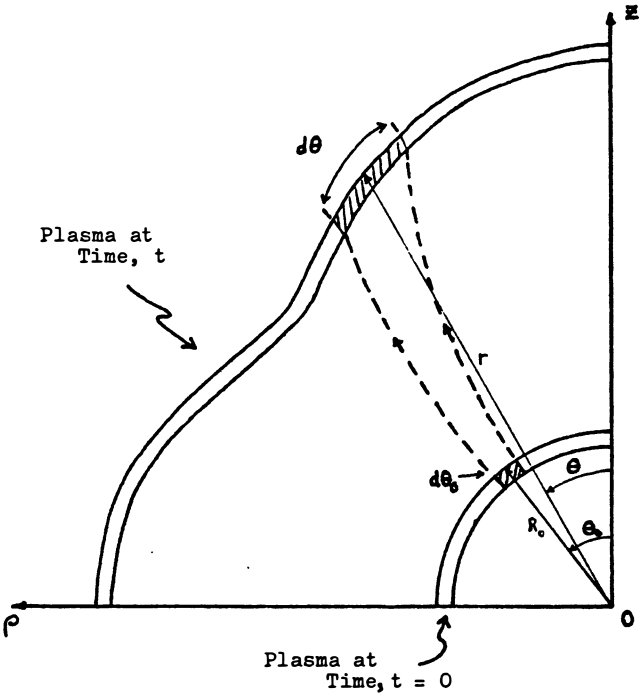


Fig. 4. Illustration of Nomenclature for Eulerian and Lagrangian Shell Element Coordinates.

spherical shell of radius r_c which subtends an angle θ at the origin. Thus, it is apparent that field lines are lines of constant ψ. Since the B-field must be tangent to all points on the plasma surface, it is clear that ψ is equal to a constant at this surface, assigned to be zero. In addition ψ will be zero at the cusps. Thus the boundary conditions for three of the four boundary arcs of the region in which Eq. (16) is to be solved are

$$\psi = 0 \left\{ \begin{array}{l} r_c = r(\theta, t) \\ \\ \theta = 0, 1.452 \end{array} \right. \ . \tag{17}$$

The final boundary condition may be found by noting that the magnetic field lines passing through the conducting reaction chamber wall will be tied into the wall for the time of expansion. Thus the magnetic field programme of Section 2 may be employed to give initial values of the field at this wall, which may then be integrated to give the time-invariant values of ψ along this boundary as a function of θ.

$$\psi = F(\theta) \quad , r_c = 50 \text{ m} \ . \tag{18}$$

Using Eqs. (17) and (18), the elliptic equation for ψ may now be solved for all points in the region bounded by the plasma and the reaction chamber wall, from 0 to 1.452 radians. Once values of $\partial\psi/\partial\theta$ and $\partial\psi/\partial r$ are determined at the plasma surface ($r_c = r$), Eqs. (14) and (15) may be evaluated for B_r and B_θ. These then determine the magnetic pressure at each point on the plasma surface, which allows the equations of motion (Eqs. (10) and (11)) to be solved. The radial and angular components of velocity may then be used to advance the elements of the shell to their new positions, whereupon the process is repeated for as many timesteps as necessary to give a detailed description of plasma expansion.

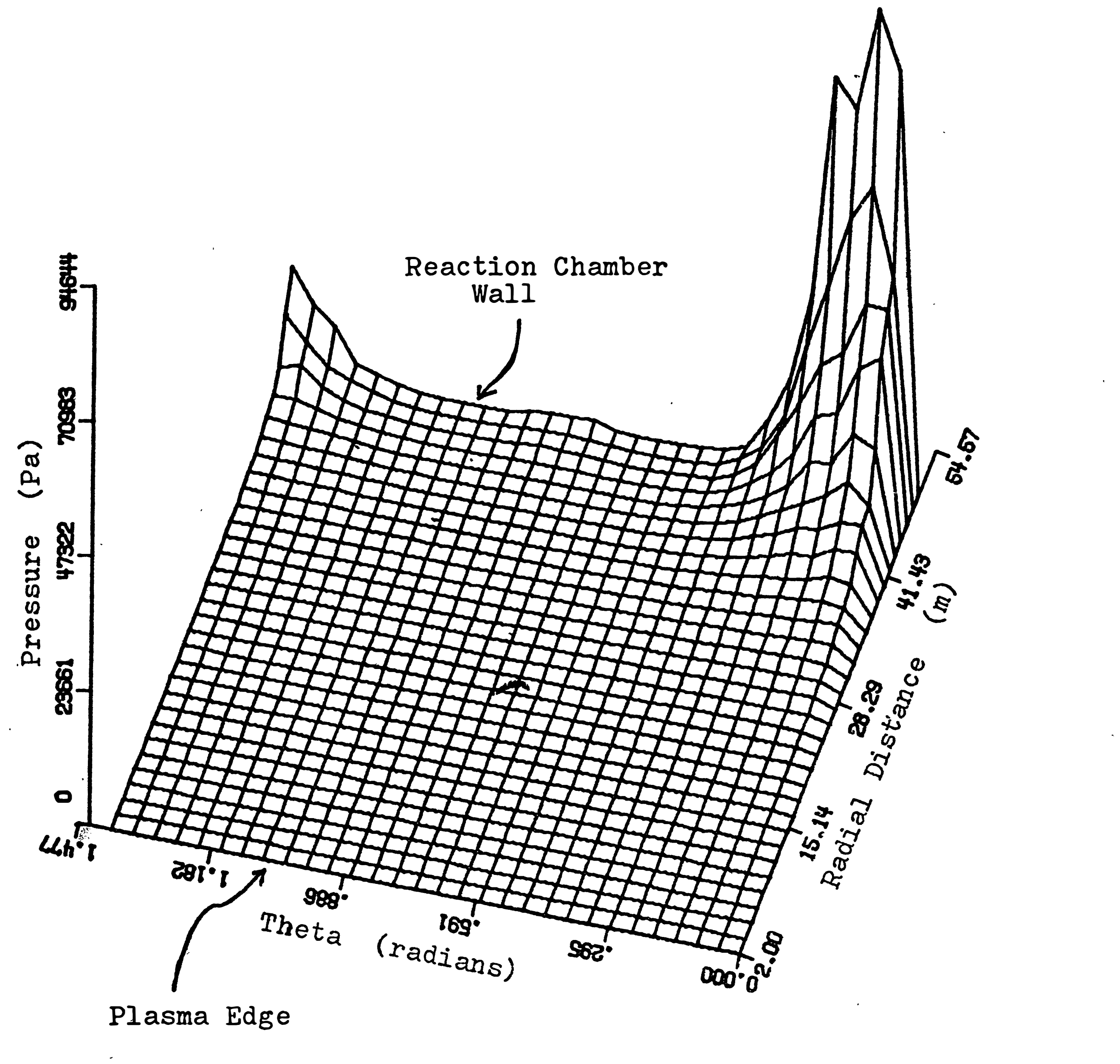


Fig. 5. Initial magnetic pressure.

Equation (16), with its boundary conditions, was solved by the International Mathematical and Statistical Library (IMSL) code, TWODEPEP [5]. The input for TWODEPEP, and listings of all the codes created for this work, may be found in Ref. 6.

At very late times in the plasma expansion, the fractional variation of the distance between the plasma and the wall became too great for TWODEPEP to use the plasma surface as a boundary (even though the absolute variation in plasma radius was quite small). Thus, a very simple flux conservation code was written to follow the plasma expansion for about the last half meter.

4. RESULTS OF EXPANSION CALCULATIONS

The program for plasma motion was initiated with a spherical plasma shell 2 m in radius, divided into 95 equally spaced plasma ring elements, expanding with a radial velocity of 1.1×10^7 m/s. The analysis was begun at 2 m, rather than the pellet radius of 0.0197 m, in order to assure accuracy of the finite element code TWODEPEP used to calculate ψ. When an arc of the order of the pellet circumference was used to establish the boundary condition at $r_c = r$, the triangulation methods used by TWODEPEP to obtain a finite element grid became inaccurate. The choice of a 2 m initial radius did not impart any error to the plasma motion calculation, since the plasma is practically unaffected by the very weak magnetic field near the origin.

Figure 5 shows the initial magnetic pressure distribution in the region between the plasma shell and the wall. Although the nominal magnetic pressure in the cusp apertures is relatively high, particles moving directly along the field lines are not reflected by the field. Thus, the effective magnetic

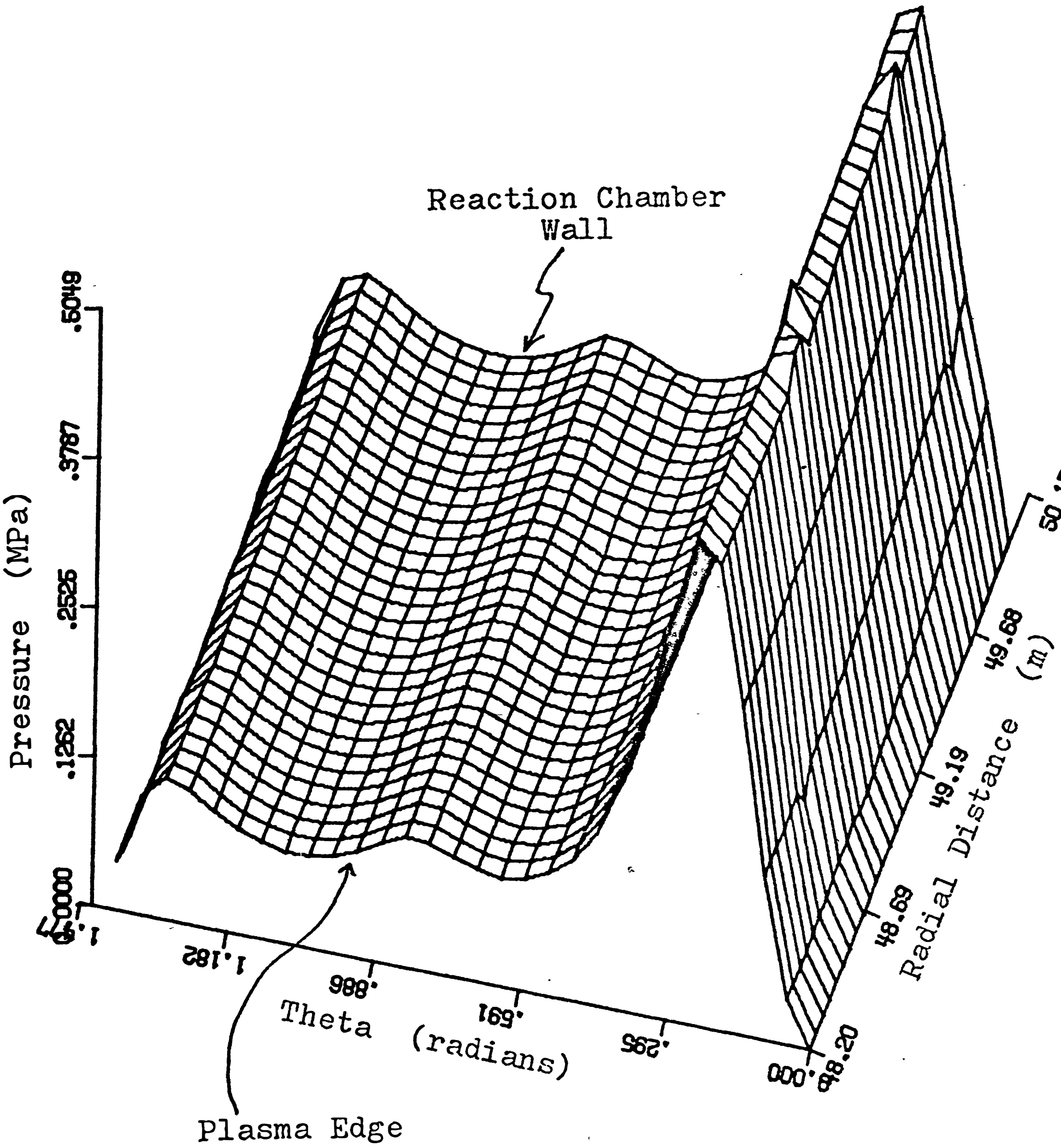


Fig. 6. Magnetic pressures at 48.2 m expansion.

pressures at the cusp separatrices (θ = 0 and θ = 1.452 radians) are zero, as indicated in Fig. 5, and the ring elements moving along the separatrices were allowed to expand unimpeded. Because, as the field is compressed, it retains a very substantial radial component in the vicinity of the separatrices, the ring elements near the separatrices have a substantial part of their velocity along the field. Thus, the distances of closest approach predicted for the first few elements around the cusp separatrices are not very accurate. However, this inaccuracy is not serious since some shielding will certainly have to be provided in these areas to catch particles leaking through the cusps.

The plasma was seen to expand almost spherically up to the turnaround point, with velocities dropping significantly only in the last few tenths of a metre from the wall. This finding agrees with expectations, since the initial magnetic pressures in most of the chamber were quite low, as shown in Fig. 5.

Figure 6 shows the magnetic pressure when r $\approx$ 48 m; the plasma has not yet appreciably slowed down, but the flux has been compressed enough that there is little variation between the plasma and the wall for a given θ. Note that the axes of Fig. 6 have been renormalised, as the plasma occupies a much narrower region and the magnetic pressures are much higher. Also note, for this stage in the field compression, that the peaks in the magnetic pressure have shifted somewhat away from the cusp throats. This is because the field is compressed more where it is more nearly parallel to the wall.

The first element to reverse its motion was the element adjacent to the ring cusp separatrix, at θ = 1.437 radians. This element reversed its direction at a point 0.51 cm from the reaction chamber wall, the closest approach of any element. In the next timestep, one nsec later, the first element past the θ = 0 element, at θ = 0.0154 radians in the spindle cusp mirror, reversed also, reaching a closest approach

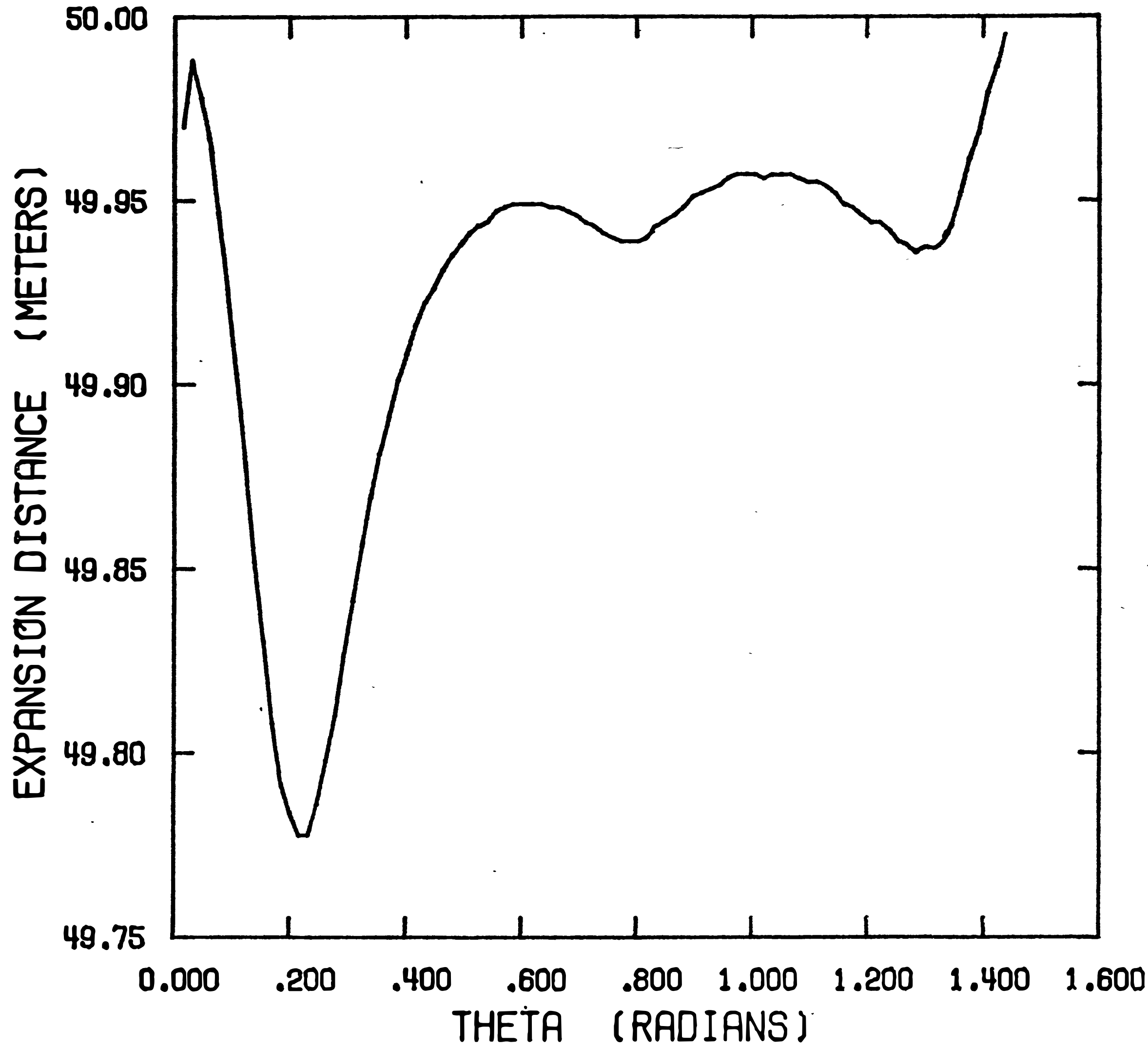


Fig. 7. Plasma element position at closest approach (since plasma elements do not all turn around simultaneously, this curve does not represent plasma proximity to the wall at any one instant in time).

of 3.01 cm. Subsequent timesteps saw reverses spreading inward from these two ends until the last element, at θ = 0.2317 radians, reversed at 22.2 cm from the wall. This came about 28 nsec after the first element reflection.

A plot of maximum r vs. θ for the elements at their individual turnaround points is presented in Fig. 7. It is noteworthy that the turnaround points form a curve very like a reflection of the shape of the magnetic pressure distribution shown in Fig. 6. The elements in areas of higher pressure will, of course, tend to slow more gradually and reverse at a point farther from the wall than those in areas of low pressure. In the low pressure areas, the element is not slowed appreciably until the magnetic field lines can be tightly bunched against the shell, leading to very high final pressures needed to slow and reverse the still rapidly moving plasma. This effect is especially evident in the cusp apertures, where relatively little compression takes place in the mostly radial field until very late in the plasma expansion. Figure 8 shows the turnaround magnetic pressure at each point.

The approach distances in the region between the cusps are in the vicinity of 5 cm. This value agrees well with a prediction based on a simple formula given in the Daedalus report, which is 4.25 cm.

Because of the more abrupt final deceleration required for elements moving in regions of lower initial magnetic pressure, the actual peak magnetic pressure is highest in regions where initial magnetic pressure is lowest. Thus, the curve representing magnetic pressure at turnaround has the same general shape as the curve of plasma approach to the wall at turnaround.

5. LARMOR RADIUS CRITERION

To ensure that the plasma does not contact the wall, it is necessary that the distance of closest approach to the wall be greater than the Larmor radii of the plasma particles. The Larmor radius is given by

$$r_L = mv_{\perp}/ZeB \quad , \qquad (19)$$

where m = particle mass, Z = charge number, e = elementary charge, and $v_{\perp}$= velocity transverse to the magnetic field $\vec{B}$. Of the products of the D-^{3}He reaction, the alpha-particle will

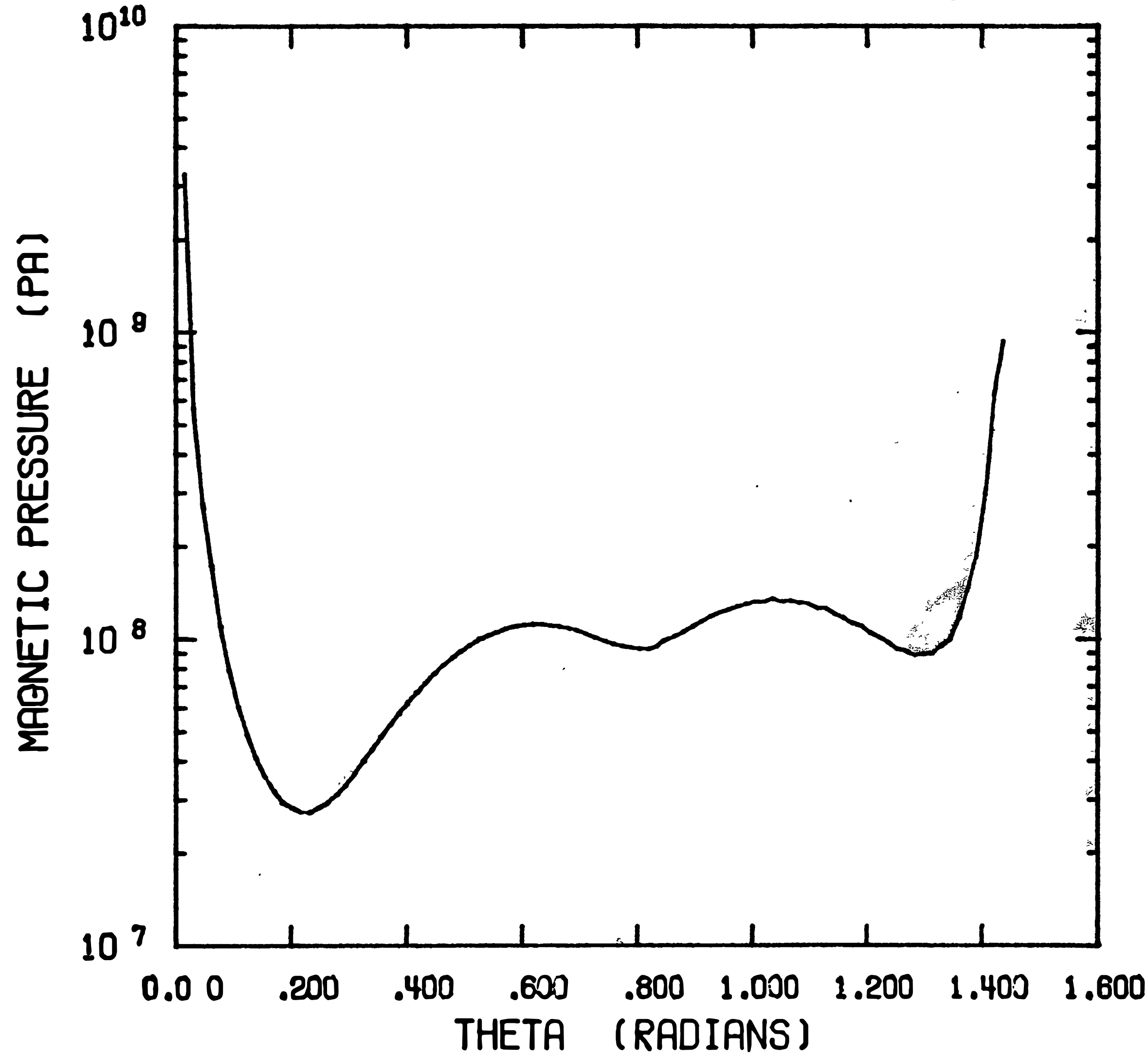


Fig. 8. Magnetic pressures at turnaround (since plasma elements do not all turn around simultaneously, this curve does not represent magnetic pressure at any one instant in time).

have a larger Larmor radius than the proton, assuming $v_\perp = 1.1 \times 10^7$ m/s for each. For a compressed magnetic field of 15T (corresponding to $p_m \approx 10^8$ Pa), the values $Z = 2$ and $m = 6.63 \times 10^{-27}$ kg appropriate for an alpha-particle give $r_L = 1.5$ cm, which is well below the distance of closest approach everywhere except the cusp separatrices, where some particle impingement is unavoidable. (In the region near $\theta = .2$, where $p_m \approx 2 \times 10^7$ Pa, $r_L \approx 3.5$ cm, but the distance of closest approach is much greater).

6. STABILITY

While it is evident that an expanding plasma of this type will be prone to development of flute instabilities driven both inertially (deceleration of the plasma by the vacuum magnetic field drives the Rayleigh-Taylor instability) and by bad curvature of the plasma surface, it was shown in Ref. 7 that this type of plasma will be stabilised early in its expansion by finite Larmor radius stabilisation. The different electron and ion Larmor radii will build up a charge separation out of phase with particle drift separation. Since this drift separation drives the flute instability, the result in a plasma of this type tends to be stable oscillation, at least for the early part of the expansion.

For an examination of gravitationally driven flute instability growth at later times in the expansion, the theory developed in Ref. 4 is used.

Flute growth for this plasma configuration is expressed as

$$A = A_0 \exp(t/\tau) \qquad (20)$$

where τ, the instability growth time, is found to be

$$\tau = (2/3)\,(n\alpha)^{-1/2}\,\text{sec}, \quad n\alpha \gg 1, \qquad (21)$$

or

$$\tau = (32/81)^{2/3}\,(n\alpha)^{-2/3}\,\text{sec}, \quad n\alpha \ll 1, \qquad (22)$$

in which n is the number of flutes. This is analogous to the hydrodynamic Rayleigh-Taylor instability with the gravitational acceleration represented by

$$\alpha = \frac{2\pi B^2 R_0^3}{\mu_0 M v_0^2} = \frac{\pi B^2 R_0^3}{\mu_0 E_0} \qquad (23)$$

where B is the magnetic induction and R_O is the initial radius of the plasma expanding outward with inital velocity v_O, total mass M, and kinetic energy E_O.

For this analysis a worst case scenario is adopted by letting α be calculated from the maximum value of B at the maximum expansion, around 50T. The pellet radius R_O is taken as 1.97 cm, and $E_O = 3.2 \times 10^{11}$ Joules. Then $\alpha = 1.5 \times 10^{-7}$. If the instability is to threaten the plasma expansion, the characteristic time τ must be no longer than the expansion time, around 5 μsec. Setting $\tau = 5$ μsec in Eq. (22) gives $n\alpha = 3.5 \times 10^7$, which contradicts the applicability of the equation. Setting $\tau = 5$ μsec and $\alpha = 1.5 \times 10^{-7}$ in Eq. (21) gives $n \approx 10^{17}$, which gives a wavelength of $2\pi \times 50\ \mathrm{m}/10^{17} \approx 10^{-15}\ \mathrm{m} <<< r_L$, so the only fast-growing modes will be stabilised by finite radius effects.

The case of curvature driven instabilities is not, unfortunately, nearly so straightforward. For a quiescent plasma confined by a vacuum magnetic field, interchange instability occurs if the boundary surface is concave towards the plasma ('bad curvature'). While it is obvious that the plasma at turnaround exhibits a uniformly bad curvature, the rate of flute growth resulting from this condition may well turn out to be as insignificant as the inertially driven case. An analysis was attempted to estimate growth rates for this condition, but the calculations rapidly expanded beyond the scope of this study. Thus, while it may be stated that a static plasma of the shape exhibited by the Daedalus plasma at turnaround would be unstable to this mode of flute growth,it is left to a more detailed study to determine whether a quiescent model has any validity, and to investigate the timescales involved.

7. PRESSURES ON CHAMBER WALL

It is possible to use the magnetic pressure data to estimate the maximum pressures felt by the chamber wall with each pulse.

The graph of Fig. 8 presents the maximum magnetic pressures on the plasma at turnaround. Because the plasma is so close to the wall at turnaround, the magnetic pressure does not vary between the plasma and the wall, so Fig. 8 also represents the peak magnetic pressures on the wall. The net magnetic force per unit area on the wall is equal to the difference between the external and internal magnetic pressures. However, since the magnetic field is 'frozen' into the wall during the expansion, the internal magnetic pressure is equal to the initial magnetic pressure on the wall, as obtained in Section 2. Subtracting this internal pressure from the peak magnetic pressure at turnaround gives a graph indistinguishable from that of Fig. 8, the internal pressures being far outweighed by the external pressures resulting from plasma expansion. These values would prove useful in refining the structural design of the reaction chamber and its supports.

8. SUMMARY

A procedure has been developed to follow the expansion of an inertial confinement fusion pellet in an axisymmetric cusp-shaped magnetic field, based on an earlier model for a straight magnetic field. The codes required to implement this method are presented in Ref. 6, except for the commercially available TWODEPEP code.

Application of the method to the Daedalus first stage engine shows that the magnetic field turns the plasma around at a safe distance from the wall, except directly in the cusp apertures, where some protective sacrificial structure will be required.

Investigation of expanding plasma stability indicates a plasma essentially unaffected by the inertially driven flute instability. While it was determined that the configuration at turnaround will promote instability driven by bad curvature, a detailed stability analysis will be required to determine the growth rates of these modes.

Additionally, a detailed mapping of the pressures felt by the reaction chamber wall during expansion was obtained. These values should be of use in any design refinements undertaken in the future.

REFERENCES

1. A. R. Martin and A. Bond, 'Project Daedalus: The Propulsion System, Part I: Theoretical Considerations and Calculations,' *JBIS* Supplement, pp. S44-S62 (1978).
2. A. Bond and A. R. Martin, 'Project Daedalus: The Propulsion System, Part II: Engineering Design Considerations and Calculations,' *JBIS* Supplement, pp. S-63-S82 (1978).
3. John D. Jackson, *Classical Electrodynamics*, John Wiley & Sons, Inc. (1975), pp. 177-178.
4. J. W. Poukey, 'Expansion of a Plasma Shell into a Vacuum Magnetic Field,' *Physics of Fluids*, **12**, 1452-1458 (1969).
5. International Mathematical and Statistical Library, *TWODEPEP User's Manual*, IMSL, Inc. (1982).
6. John Othniel Elliott, 'An Analysis of Plasma Expansion Characteristics in the Daedalus Project Fusion Pulse Engine,' MS Thesis, School of Nuclear Engineering, Purdue University, West Lafayette, Indianna, USA (1984).
7. Joseph J. Devaney, 'First Wall Magnetic Protection in an Inertially Confined Thermonuclear Reactor,' LASL Informal Report LA-8286-MS (1980).

* * * * *

Journal of the British Interplanetary Society, Vol. 38, pp. 129-132, 1985.

TREND ANALYSIS FOR INTERSTELLAR RAMJET TECHNOLOGIES

R. J. STALKER
Department of Mechanical Engineering, University of Queensland, St. Lucia, Queensland, 4067, Australia.

A simple trend extrapolation model is applied to produce forecasts of the research effort required to develop selected technologies to a level such that they can be applied to an interstellar ramjet. The model assumes that technical capability will grow exponentially in response to a research effort which is measured by the product of the time and the number of workers involved. The forecasts indicate that the effort required to develop the technologies is well within the resources of a civilisation such as ours.

1. INTRODUCTION

It is less than three decades since Bussard [1] introduced the concept of the Interstellar Ramjet and, in doing so, established the notion of interstellar flight as a scientifically feasible venture – at least within our present frame of knowledge. It has since been followed by other concepts, such as antimatter rockets, or laser beam sailing, which also pass the test of scientific feasibility.

However, a feature of all these concepts is that they demand improvements by many orders of magnitude in our ability to produce specific physical effects. Thus extremely high flux density magnetic fields and large values of fusion reaction containment parameters are required for a Bussard ramjet, extremely long anti-matter containment times are demanded for an anti-matter rocket, and very high power lasers are needed for laser propulsion. The gap between requirements and achievement in these technologies is such that interstellar flight is still many orders of magnitude removed from technical feasibility.

In fact, this gap is so great that it might reasonably be asked whether or not the effort required to bring about technical feasibility is likely to make such an excessive demand on the intellectual and physical resources of our civilisation that interstellar flight is rendered effectively unachievable. To answer this question, some means of making an order of magnitude estimate of this effort is required.

Fortunately, during the last three decades considerable attention has been given to techniques of predicting future technological capability, leading to recognition of Technology Forecasting as a distinct and developing discipline [2-5]. Whilst accepting that the future is unpredictable, this discipline seeks to eliminate unnecessary uncertainty by making use of existing knowledge in formulating an estimate of future technical capability.

One of the most widely used forms of technology forecasting is Trend Extrapolation. It involves attempts to extrapolate existing trends, either through the development of suitable models, or simply by assuming that the past rate of improvement in a chosen parameter will continue in the future. It can also be used to estimate the effort required to achieve a given value of a parameter by assuming that the effort expended in the past to yield a given rate of improvement will continue to yield the same rate in the future.

Trend extrapolation techniques are here applied to forecasting the development of technology for interstellar flight. Initially, a simple trend extrapolation forecast is presented, and is used to point to the need for a suitable forecasting model. A model is then outlined, and is applied to forecasting the development of some of the technologies appropriate to the interstellar ramjet. The interstellar ramjet is chosen not only because of its historical conceptual importance, but also because the technology involved has been under development for long enough to allow reasonable estimates to be made of the effort required in the past to yield a given rate of technical improvement.

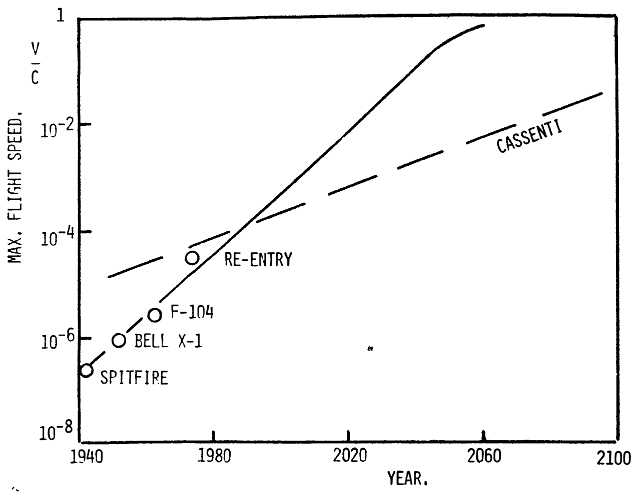


Fig. 1. Simple trend extrapolation.

2. SIMPLE TREND EXTRAPOLATION

The simplest form of trend extrapolation is based on the assumption that growth in the value of a particular parameter will continue as in the past. One can apply this technique to plot a trend curve for the maximum velocity achieved by flight vehicles, as shown in Fig. 1. When this velocity is plotted on a logarithmic scale against time on a linear scale, the historical data is fitted reasonably well by a straight line. When this line is extrapolated to yield a forecast, it is seen that speeds approach the velocity of light at about the middle of the 21st century. Such vehicle speeds are a prime requirement for interstellar travel and so, based on this technique, the forecast indicates a possibility of interstellar travel in about 70 years.

However, the result obtained by this method depends upon the data base selected. For example, if one follows Cassenti [6], and plots the maximum speed achieved by any form of piloted vehicle from the year 1800 forward, the average slope of the line is reduced, and the possibility of interstellar travel recedes by some 200 years. Such uncer-

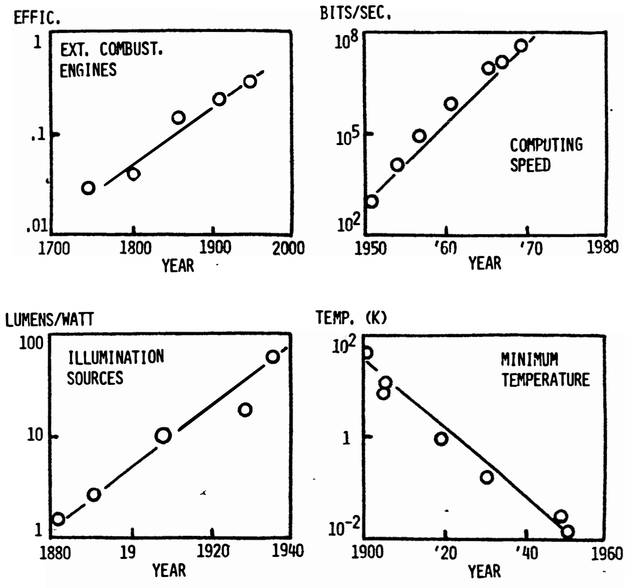


Fig. 2. Exponential improvement in technical performance parameters.

tainty is an unfortunate aspect of trend extrapolation, and is a reminder of an important aspect of this type of forecasting. The validity of a forecast depends upon the relevance of the data base selected.

But even with a relevant data base, a further problem arises in that the resource implications of the extrapolation are not considered. This limitation has led forecasters to develop models which will allow such effects to be taken into account.

3. TREND ANALYSIS MODEL

One such model has been developed in a number of forms, but its essentials have been outlined by Floyd [7]. The form of the model discussed below involves some adaptation of Floyd's analysis.

First of all, it has been widely noted that technical performance parameters tend to increase exponentially with time. As shown in Fig. 1, this is evidently true for the maximum speed of flight vehicles. Other examples are shown in Fig. 2, where it is seen that factors as diverse as computing capacity [8], external combustion engine efficiency [9], the efficiency of illumination sources [10] and the lowest temperature achieved in laboratories [11] all tend to show a roughly exponential variation with time.

One can speculate on reasons for this. For example, it might be taken to imply that the synergistic effects of developments in other branches of science and technology combine to continually speed up the rate of development of a specific area, and that this tends to produce the exponential increase observed. An alternative reason might be that research workers generally tend to set their objectives in terms of percentage gain in a technical parameter. Too large a percentage gain in a given time may be seen as unrealistically ambitious, and too low a gain as trivial. Thus the tendency is to seek a roughly uniform percentage gain, and this ensures that exponential growth results.

Whatever its cause may be, the tendency to exponential growth in technical parameters will be accepted here as a basis for trend extrapolation, and so the logarithim of a chosen technical parameter will be used as a measure of the growth in that parameter. This will be referred to as a technical Figure of Merit, f.

Of course, the figure of merit cannot be expected to continue to grow indefinitely when there is an obvious physical limit to its growth. The external combustion engine is an example of this, where the efficiency clearly has an ultimate limit of unity. Thus the rate of growth may be expected to reduce as the figure of merit approaches its ultimate value. The simplest way of representing this effect is to assume that the rate of growth varies as (F-f), where F is the ultimate figure of merit.

Another factor which will influence the rate of growth is the number of workers seeking to improve the figure of merit. It is clear that 100 workers in a field can be expected to make progress more rapidly than ten workers. It is much less clear that they will progress at ten times the rate but nevertheless, to retain simplicity, this assumption will be made. Thus the rate of growth is taken to be proportional to N, the number of workers in the field. It is probably closer to the truth in passing from five to 50 workers, rather than from 50 to 500.

Thus we may write

$$\frac{df}{dt} = KN(F-f) \,, \tag{1}$$

where K is a constant, and t is the time. When this is integrated, and an initial value of $f = f_0$ at $t = t_0$ is used, it is found that

$$\ln\left(\frac{F-f}{F-f_0}\right) = -KN(t-t_0) \,. \tag{2}$$

When f is much smaller than F, indicating that the figure of merit is well removed from its ultimate value, then this equation takes on a linear form, i.e.

$$f-f_0 = FKN(t-t_0) \,. \tag{3}$$

Thus, if historical data points can be used to establish the value of FK then this equation can be used to predict the improvement in f resulting from $N(t-t_0)$ man years of effort.

Of course, some means is required of estimating the total international scientific effort associated with attempts to improve f. The approach taken here is to use the number of delegates at major international conferences in a field closely related to the technical parameter under consideration. This is likely to yield figures which are within a factor of two or three of the total number of effective principal workers in the field, and this is adequate for present purposes.

4. INTERSTELLAR RAMJET TECHNOLOGY

The interstellar ramjet is considered, essentially in the form proposed by Bussard. It is conservatively assumed that it will be necessary to employ the p-p fusion reaction as the power source, and that the benefits of carbon catalysis [12] in promoting this reaction should be ignored. As outlined by Fishback [13] and by Martin [14], magnetic intake field strengths of the order of 10^7 Tesla are required, combined with very high strength materials in order that the structure which confines the field sources be strong enough to counterbalance the forces exerted on the sources by the fields they create. Thus three critical technologies are the confinement of a p-p reaction, high magnetic fields, and high strength materials. An attempt will be made to forecast the growth of a figure of merit for each of these in turn.

4.1 The Fusion Reaction

To maintain a power producing fusion reaction, it is neces-

TABLE 1. Development of Fusion Containment Technology.

Year	Conference	Estimated Number of Delegates	f
1958	2nd Int. Conf. on Peaceful Uses of Atomic Energy	200	15
1965	Plasma Physics and Controlled Fusion Research (2nd Int. Conf.)	200	17
1974	Plasma Physics and Controlled Fusion Research (5th Int. Conf.)	400	18
1979	European Controlled Fusion and Plasma Physics Conference	300	19
1982	Plasma Physics and Controlled Fusion Research (9th Int. Conf.)	600	19.5

TABLE 2. Development of Field Strength Capability.

Year	Conference	Estimated No. of Delegates	f
1962			.7
1968	2nd Int. Conf. on Cryogenic Engineering	40	1.15
1978	7th Int. conf. on Cryogenic Engineering	50	1.3
1980	Oji International Seminar, Japan "Physics in High Magnetic Fields"	80	1.3

sary to contain plasma in a fusion reactor at a sufficient density for a sufficient period of time. The product $n\tau$ of the particle number density, n, and containment time, τ, (the "Lawson Number") therefore has been widely used as a parameter of technical merit for fusion experiments in the past. It has normally been expressed in powers of 10, and so $f = \log_{10} n\tau$ will be used as a figure of merit. For the p-p reaction, the required valoe of $n\tau$ is 10^{40} $m^{-3}s.$, and the aim here is to estimate the amount of research effort required to achieve this figure.

There is no apparent physical limit to $N\tau$, and so the growth equation will be used in the form of Eq. (3). The historical data used is shown in Table 1. Taking N in Eq. (3) as the mean number of delegates over the 24 years covered in the Table, the extrapolations shown for p-p fusion in Fig. 3 are obtained, by combining the data for 1958 with each of the other four years respectively. They indicate that approximately 40,000 man years of effort will be needed to achieve the required value of f=40. Their consistency is reassuring, as it tends to confirm the validity of the exponential growth model for this field.

It might be noted that this extrapolation implies that, if the present level of research effort in this field is sutained, then somewhat less than 150 years will be needed to achieve the required figure of merit.

4.2 The Magnetic Field

Seeking field strengths of the order of $B = 10^7$ Tesla, $f = \log_{10} B$ is taken as a figure of merit. Assuming that a steady field will be required, and noting that this is the best achieved at present by superconducting magnets, it is appropriate to use historical data for superconducting magnets as the basis for forecasting growth in field strength capability. This data is displayed in Table 2. It is pertinent to note that only a fraction of the participants at the International Conferences on Cryogenic Engineering were concerned with high magnetic fields and therefore it was necessary to estimate this fraction by assuming that it was equal to the fraction of the papers presented which was related to this subject.

Using 1962 as the starting point, this data yields the extrapolations for the magnetic field shown in Fig. 3. They indicate that the effort required to achieve a field strength of 10^7 Tesla is somewhere between 4000 and 9000 man years. Once again, if the present international research effort is maintained, appropriate figures of merit may be achieved

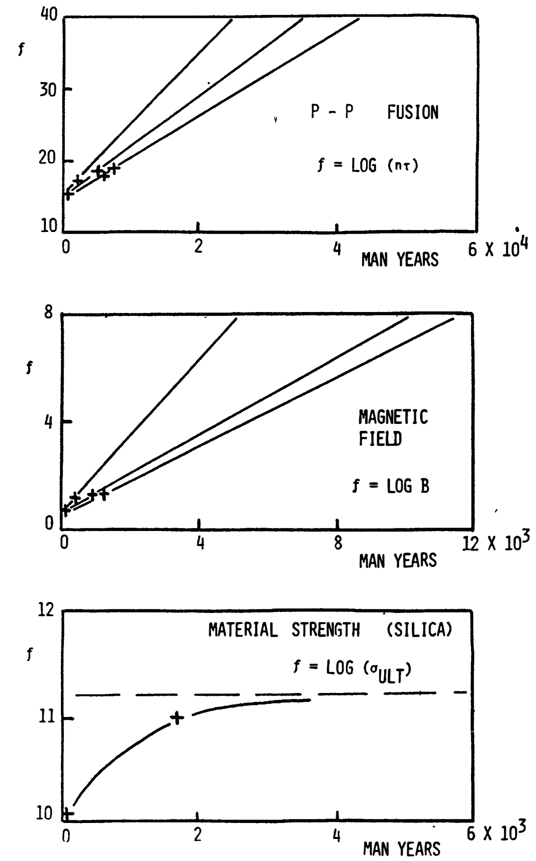


Fig. 3. Trend forecasts.

in about 150 years.

4.3 Structural Materials

Fishback's analysis [12] indicates that the speed up to which an interstellar ramjet can sustain an acceleration of 1 g is limited by the strength to density ratio of available materials. Whilst present strengths are likely to be adequate for journeys of up to 20 to 30 light years (see also Ref. 15 for discussion of this point), nevertheless it is interesting to attempt a trend extrapolation for strengths which allow this limit to be exceeded. The highest strengths obtained for given materials have been with small, pure, samples (whiskers) in the laboratory and it is possible to develop a trend curve for the strength of material in that form.

TABLE 3. Strength of Silica

Year	Conference	Estimated No. of Delegates	f
1920			10
1960	Society for Experimental Stress Analysis – Biannual Conference	40	11

Table 3 shows historical data for silica. Here f = $\log_{10}$ (ultimate strength in dynes cm^{-2}).

As shown by the curve in Fig. 3, the ultimate value of f, is F = 11.2, indicating that strengths close to the theoretical ultimate are already being achieved in the laboratory. However, the strength of materials in practical use is well below this limit. Whilst this fact is presumably spurring research efforts to produce practical materials with strengths closer to theoretical values, it nevertheless illustrates than an extrapolation based on figures of merit achieved in the laboratory does not necessarily indicate the availability of such a figure for practical use.

5. CONCLUSIONS

Using the trend analysis technique outlined here, forecasts of future technical capability can be made without excessive labour. It can be applied to any of the technolgies which are seen as candidates for the realisation of interstellar travel, provided that a history of technical development can be established. Here it is applied to the interstellar ramjet.

The forecasts indicate that an effort of the order of 10^5 man years would be required to achieve containment of a p-p fusion reaction, and of the order of 10^4 man years to achieve appropriate magnetic field strengths. It must be noted that these figures are based on estimates of the historical level of effort which consider only the number of workers who might be classified as "principal scientists" i.e. the main contributors to intellectual advances in a field. Depending upon the field selected, many other workers may be involved. For example, when nuclear fusion budgets in past years are related to the number of delegates at conferences, it is found that the order of one million US dollars was spent per year per delegate in this area. Thus caution should be exercised in converting these figures into budgets in monetary terms.

Also, the example of structural materials serves as a warning that a forecast of technical feasibility is not the same as a forecast of technical availability.

Combining consideration of these factors with the assumptions made in formulating the trend analysis model, together with the approximate nature of the data used, it is clear that the forecasts should be seen as order of magnitude estimates only. Nevertheless, they are sufficient to indicate that development of basic technologies necessary for an interstellar ramjet are well within the capability of a civilisation such as ours. Whilst the effort required is large, it is, relative to the resources of our civilisation, no greater than that which we devote to the development of military technology or, to take what is perhaps a more apt comparison, that which European medieval societies devoted to the building of cathedrals.

ACKNOWLEDGEMENTS

The author takes pleasure in acknowledging the assistance of C. Deacon, J. Lean, B. Moosad, S. Thurgate and G. White who, as undergraduates in Physics at the Australian National University, participated in an early study of this topic.

REFERENCES

1. Bussard, R. W., "Galactic matter and interstellar flight," *Astronautica Acta*, **6**, 179-194 (1960).
2. Bright, J. R. Ed., "Technological Forecasting for Industry and Government," Prentice Hall, Inc., New Jersey, 1968.
3. Jantsch, E., "Technological Forecasting in Perspective," O.E.C.D. Paris, 1967.
4. Martino, J. P., "Technological Forecasting for Decision Making," American Elsevier Publishing Co., New York, 1971.
5. Cetron, M. J. and Ralph, C. A., "Industrial Applications of Technological Forecasting," John Wiley & Sons, New York, 1971.
6. Cassenti, B. N., "A comparison of interstellar propulsion methods," *JBIS*, **35**, 116-124 (1982).
7. Bright, J. R., *op cit*, p. 95.
8. Bright, J. R., *op cit*, p. 79.
9. Martino, J. P., *op cit*, p. 721.
10. Cetron, M. J. and Ralph, C. A., *op cit*, p. 58.
11. Martino, J. P., *op cit*, p. 151.
12. Whitmore, D. P., "Relativistic spacecraft and the catalytic nuclear ramjet," *Acta Astronautica*, **2**, 497-509 (1975).
13. Fishback, J. P., "Relativistic interstellar spaceflight," *Astronautica Acta*, **15**, 25-35 (1969).
14. Martin, A. R., "Magnetic intake limitations on interstellar ramjets," *Astronautica Acta*, **18**, 1-9 (1973).
15. Martin, A. R., "Structural limitations on interstellar spaceflight," *Astronautica Acta*, **16**, 353-357 (1971).

* * * * *

Journal of the British Interplanetary Society, Vol. 38, pp. 133-136, 1985.

NON-NUCLEAR INTERSTELLAR FLIGHT: APPLICATION OF PLANETARY GRAVITATIONAL ASSISTS

GREGORY L. MATLOFF
Educational Technology Group/Pratt Computer Resource, Pratt Institute, 200 Willoughby Avenue, Brooklyn, New York 11205, USA.

EUGENE MALLOVE
Astronomy New England, Inc., 215 Highland Street, Holliston, Mass. 01746, USA.

Previous publications have considered pre- and post-perihelion acceleration for non-nuclear interstellar spacecraft. This paper presents the theory of giant-planet gravity assists and examines the utility of this propulsion option for near-term interstellar precursor probes and future interstellar arks. Application of gravity assists by Uranus, Saturn, and Jupiter will significantly reduce electric fuel requirements during the powered pre-perihelion leg of an interstellar mission. Post-perihelion gravity assists will be less useful for interstellar arks launched within the foreseeable future but could provide a significant fraction of the hyperbolic excess velocity for interstellar precursor probes.

1. INTRODUCTION

In a recent series of papers, we have investigated various aspects of non-nuclear interstellar flight [1-6]. Using a variety of techniques (including hyperthin or perforated solar sails partially deployed behind occulters and released at perihelion approaches close to the solar photosphere, payload subdivision among multiple sails, planetary rebounds or electric acceleration during the pre-perihelion acceleration leg of the flight, and the light-sail windmill as a power source during the post-perihelion phase) robot probes and interstellar arks can be accelerated on trips to Alpha Centauri respectively requiring a few centuries and less than 800 years. Even current sail materials are capable of accelerating probes to hyperbolic excess velocities several times higher than those of Pioneer 10/11 and Voyager 1/2 [5].

One of the techniques discussed in Refs. 1 and 2 is the planetary gravitational rebounds that have been researched by Ehricke [6]. The most effective of these, the Jupiter-Saturn rebound, requires a gravity assist at Jupiter towards Saturn and a 15-25 km/sec manoeuvre at 0.05-0.15 g Earth acceleration at peri-Saturn. Because, as Ehricke points out [7], the only foreseeable propulsion system for the peri-sat manoeuvre is the nuclear pulse rocket, we investigated several non-nuclear alternatives to this manoeuvre in Ref. 3. Pre-perihelion sunbound acceleration utilising the solar-electric rocket or solar-electric ramjet [8], seem most effective.

The outerplanet/extrasolar probes Pioneer 10/11 and Voyager 1/2 have all utilised giant planet gravity assists to expell tham from the Solar System [9, 10]. Although it does not seem feasible to combine the Jupiter-Saturn rebound with solar-electric propulsion during the pre-perihelion leg, this paper examines the utility of combining giant-planet gravity assists with solar clectric propulsion. As will be demonstrated, such an approach (which would require careful timing of an interstellar mission to a particular destination) would result in a significant reduction in electric-propulsion fuel requirements.

2. GRAVITY ASSIST THEORY

The theory of planetary gravity assists is developed using two-body interactions in a central force field and has been published in many places. We base our analysis upon Chapter 6 of *Fowles Analytical Mechanics* [11].

For a Hohmann minimum-energy transfer ellipse between two coplanar solar orbits, the eccentricity (e) is a function of aphelion distance (r_1) and perhelion distance (r_o):

$$e = (\frac{r_1}{r_o} - 1) / (1 + \frac{r_1}{r_o}) . \quad (1)$$

If Earth-orbit departure is assumed, the initial post-boost velocity relative to the Sun, v_o, can be derived from the eccentricity of the transfer ellipse and the Earth's circular velocity around the Sun, $v_{earth\ cir}$.

$$e = \frac{v_{\odot}^2}{v^2_{earth\ cir}} - 1 . \quad (2)$$

This can be generalised for arrival at the destination planet by replacing $v_{earth\ cir}$ by $v_{planet\ cir}$.

The eccentricity of the approach hyperbola to the target planet e_p, can be related to the velocity at the closest approach to the planet v_p (initial relative velocity of the spacecraft and planet plus escape velocity from the planet at closest approach distance) and the circular velocity for an orbit at the distance of closest approach, v_{cp}:

$$e_p = (\frac{v_p}{v_{cp}})^2 - 1 \quad (3)$$

After the spacecraft has departed from the gravitational force field of the gravity assist planet, the spacecraft's velocity relative to the planet $V\infty$ can be expressed as:

$$V_\infty = V_{cp} (e_p - 1)^{1/2}. \quad (4)$$

The velocity increment due to the planetary gravity assist, $\Delta V\infty$, can be calculated from $V\infty$ and the pre-gravity-swingby spacecraft velocity relative to the planet, V_{ro}:

$$\Delta V_\infty = V_\infty - V_{ro} . \quad (5)$$

Corliss has expressed an equation for the trajectory bend angle ψ caused by a planetary swingby [12]:

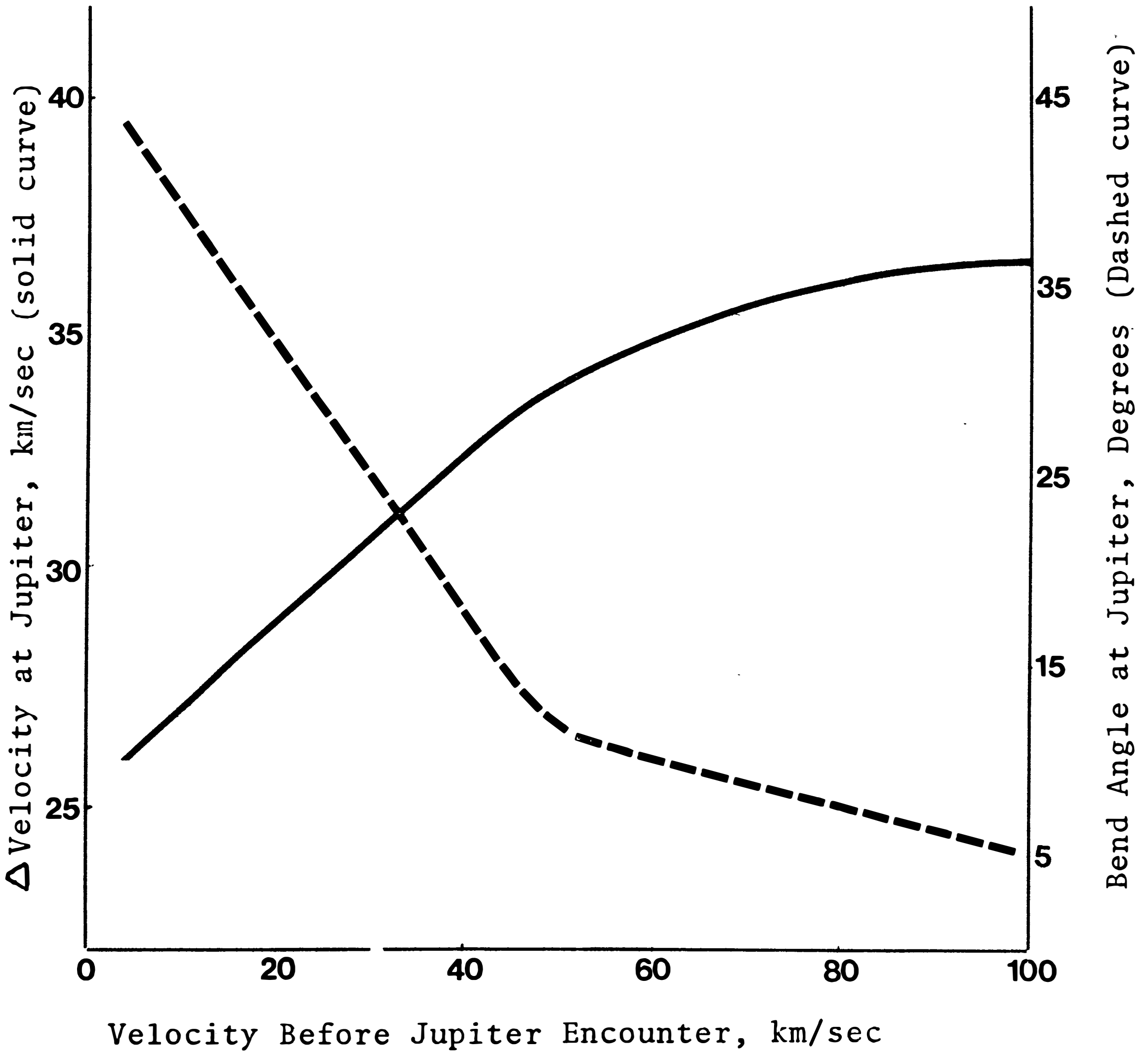


Fig. 1. Effects of a 2-Jupiter Radii perijove Jupiter flyby upon spacecraft trajectory.

$$\mathrm{Ctn}\ (\psi/2) = \frac{R_p V_p^2}{G M_p}, \qquad (6)$$

where R_p is the distance of closest approach to the planet's centre, G is the gravitational constant, and M_p is the planet's mass. As Fowles discusses [11], this equation is derived from scattering theory in a central force field.

After writing a simple computer program containing the theory presented above, we performed a number of test experiments to check against previously published work. Mesov and Phillipov have investigated the Venus gravity assist as a propulsion option within the inner Solar System [13]. For a peri-synthian distance of 11,000 km, Mersov and Phillipov report a ΔV_∞ of about 5 km/sec; we obtain 4.8 km/sec.

Because Jupiter's rings extend 1.72-1.81 planetary radii from the planet's centre [14], it seems unlikely that a spacecraft could safely pass much closer than 2 planetary radii from this planet's centre. For a Hohmann orbital transfer from the Earth and $R_p = 2$ Jupiter radii, we calculate $\Delta V_\infty = 27$ km/sec. Ehricke calculates that the maximum ΔV_∞ we can expect from this manoeuvre is 26.6 km/sec [7].

Of course, for minimum energy launch from the Earth, these estimates for ΔV_∞ will differ from the true hyperbolic excess velocity because of the large bending angle produced by the Jupiter swingby. For a detailed examination of Earth-Jovian Hohmann trajectory and the Jupiter gravity assist, see Ref. 15.

In the following analysis, we will consider the effectiveness of planetary gravity assists during a low-thrust powered pre-perihelion run in from the outer Solar System. Information regarding planetary masses, orbits and escape velocities has been obtained, in general, from Ref. 16.

3. APPLICATION OF GRAVITY ASSISTS ON THE PRE-PERIHELION TRAJECTORY LEG

Before we discuss details of the pre-perihelion acceleration run, some discussion of launch window intervals is in order. These will be a function of the number of planets involved. All intervals will assume a straight-line planetary alignment and a powered flight inwards towards the outermost gravity assist planet, after a Hohmann transfer to the outer Solar System.

If we simply desired a grand alignment of the planets allowing a spacecraft to use Jupiter gravity assist to visit Saturn, Uranus and Neptune, in a trajectory similar to that of Voyager 2, then we could launch every 179 years [9]. Of course, the giant planets would not be aligned within the same constellation at each succeeding launch window.

Launching outward from Earth orbit, the Jupiter gravity

assist can be utilized to direct a probe towards a particular target at intervals of 13 months. The Jupiter-Saturn rebound can be utilised at intervals of 19.9 years [7].

Jupiter has a sidereal period of 11.9 years. The sidereal period of Saturn is 29.5 years. Therefore, at intervals of about 180 years, these planets will line up in an essentially straight line in the same direction. Because of the different inclinations of Jupiter's and Saturn's orbits to the ecliptic (1.3° and 2.49° respectively), the line up will almost never be a perfect overlap as viewed from the Earth [17].

If we are willing to perform mid-course trajectory adjustment during the pre-perihelion gravity assist phase, we might consider utilising Uranus as the first gravity assist planets. Uranus has an orbital period of 84 years and an inclination to the ecliptic of 0.8° [17, 18]. Therefore, at succeeding Jupiter-Saturn straight-line alignments in a selected direction, Uranus will have shifted its position by about 50°.

No matter how many planets are involved in gravity assists, the target stars will rarely be in or near the plane of the ecliptic. Thus, the probe or starship will, in most cases, flyby the planet(s) and Sun above or below the ecliptic planes. Alpha Centauri for example, has a declination of -60° [18]. A spacecraft targeted towards this planet would pass Jupiter 60° north of this planet's equator, discounting the 3° tilt of Jupiter's equatorial plane to its orbital plane [16].

A launch from Earth into a Hohmann transfer ellipse to Neptune would require a minimum launch velocity of 17 km/sec. Thirty-one years would be required for the spacecraft to reach the vicinity of Neptune [18]. Much of the required energy could be supplied by electric propulsion or the solar sail.

After passing aphelion, the spacecraft would move sunward towards its first planetary encounter. As shown in Fig. 1, the amount of kinetic energy that the spacecraft can obtain from a planetary gravity assist is a direct function of its pre-encounter velocity. Thus, sunward electric propulsion should begin at or near the aphelion of the Hohmann transfer ellipse.

Figure 1 also presents the trajectory bend angle, calculated from Eq. (6), for Jovian flyby as a function of pre-encounter spacecraft velocity (relative to Jupiter). Note that Jupiter-encounter is less significant in altering trajectory direction for higher pre-encounter spacecraft velocities. The highest pre-encounter spacecraft velocity relative to Jupiter considered in these calculations is 1,500 km/sec. Results from this velocity (which are not included in Fig. 1) reveal a velocity change of 42.7 km/sec and a bend angle of about 3 arc minutes.

The following discussion considers several alternative approaches to the utilisation of gravity assists from Uranus, Saturn and Jupiter during the pre-perihelion acceleration leg of an interstellar mission. In all cases, the spacecraft starts its inward acceleration at the orbit of Neptune. Utilising ion drive or a solar electric ramjet [3, 8] the spacecraft's inward hyperbolic excess at Uranus is 20 km/sec.

When electric-drive acceleration is considered for this entire pre-perihelion run, the velocity increments between Uranus and Saturn, Saturn and Jupiter, and Jupiter and the Sun respectively are 30, 15 and 13 km/sec. These velocity increments are estimated from the electric drive parameters discussed in Ref. 3.

Planetary flyby distances are calculated as follows. Because Uranus' rings extend between 1.6 and 1.95 planetary radii, the peri-Uranus distance will be 2 planetary radii [14]. A peri-Saturn distance of 2.82 planetary radii will be assumed because Pioneer 11 survived its passage through the ring plane at this distance [14]. As discussed above, the peri-Jove distance will be 2 planetary radii.

Table 1 presents hyperbolic excesses for powered (p) and unpowered (u) flights past Jupiter only (case 1), Saturn and Jupiter (case 2) and Uranus, Saturn, and Jupiter (case 3). Barring provision for extensive trajectory alteration during the powered acceleration run, planetary alignment allowing case 3 will be very rare. Case 2 missions could be flown at intervals of 180 years and case 1 missions at intervals of 12 years. Velocities in Table 1 should be compared to the 0.006c (180 km/sec) hyperbolic excess velocities considered in Refs. 1-3.

TABLE 1. Effects of Multi-Planet Gravity Assists Upon Hyperbolic Excess at Perihelion, for Powered (p) and Unpowered (u) Pre-Perihelion Trajectories.

Case	Planets Encountered	Hyperbolic excess at Perihelion Total	Due to Planet(s)
1 U	Jupiter	50.9 km/sec	30.9 km/sec
1 P		115.6	35.6
2 U	Saturn, Jupiter	70.8	50.8
2 P		135.8	55.8
3 U	Uranus, Saturn, Jupiter	85.8	65.8
3 P		149.6	69.6

As Table 1 indicates, planetary gravity assists can provide 31-47% of the perihelion hyperbolic excess velocity, for powered trajectories. Even with planetary gravity assists, fully powered pre-perihelion trajectories are necessary to approach the hyperbolic excess velocities discussed in Refs. 1-3. The powered 3-planet trajectories, which are comparatively rare, are only about 15 km/sec faster than the corresponding 2-planet trajectories.

We see, therefore, that multi-planet gravity assists, particularly those of Saturn and Jupiter are useful for pre-perihelion acceleration. We will next consider their utilisation during the post-perihelion leg of an interstellar mission.

4. APPLICATION OF GRAVITY ASSISTS ON THE POST-PERIHELION TRAJECTORY LEG

In the consideration of gravity assists during the post-perihelion trajectory leg, we will examine two different types of interstellar expeditions. These, the intersellar precursor probe and the interstellar ark, represent the opposite extremes of mission categories that a space-faring technology might apply gravity assists to.

The interstellar precursor probe has been considered in Refs. 5, 10 and 15. A state-of-the-art solar sail would be deployed as close to the Sun as possible and would be pushed out of the Solar System by solar radiation pressure. A small payload would be towed behind the sail and would include instruments for the measurement of plasma densities, magnetic fields, etc. in the interstellar medium. A typical interstellar precursor probe might require more than 10,000 years to travel the 4.3 light years between the Sun and Alpha Centauri; the hyperbolic excess velocity at Solar System ejection would be in the neighbourhood of 100 km/sc.

Interstellar arks would be released closer to the Sun and deployed behind much more advanced solar sails [1-4, 6]. These would require 800-1400 years to reach Alpha Centauri. The hyperbolic excess velocity of a sail-launched interstellar ark might be as high as 1500 km/sec at Solar System ejection.

We first consider the interstellar precursor probes. A precursor probe accelerated to 100 km/sec within the inner Solar System can pick up an additional 35 km/sec from

Jupiter. Jupiter can alter the trajectory of this probe by 5°.

The slowest precursor probe considered in Ref. 10, which is expelled from the inner Solar System at 40 km/sec, could pick up an additional 32 km/sec from Jupiter. The bend angle produced by Jupiter upon this probe's trajectory is 25°. Therefore the slower probe could accelerate out from the inner Solar System in or near the ecliptic. A close pass by one of Jupiter's poles could almost double the probe's hyperbolic excess velocity and allow exploration of almost 30° of the extra-ecliptic near-interstellar medium.

If we can wait 180 years between missions or are not interested in a particular probe direction, the interstellar precursor probe can be directed by Saturn. Almost 20 km/sec can be added to the probe's hyperbolic excess velocity, relative to the Sun, by Saturn gravity assist. Finally, an additional 12 km/sec or so can be added to the probe's hyperbolic excess velocity by Uranus gravity assist, if the mission is carefully planned around planet position and the aim point is less significant than the final hyperbolic excess velocity.

For an interstellar ark passing Jupiter at 1500 km/sec, Jupiter gravity assist would increase the spacecraft velocity by less than 3%. The bend angle to the spacecraft's trajectory produced by Jupiter gravity assist would be approximately 3 arc minutes. Therefore, unless targets for interstellar colonisation exist on the ecliptic, post-perihelion giant-planet gravity assists for interstellar arks will not be a favoured propulsion option.

5. CONCLUSION

It has been demonstrated that giant-planet gravity assists will supplement other propulsion methods during a number of missions and mission stages. During the powered pre-perihelion acceleration phase [3], for example, Saturn and Jupiter gravity assists can produce 55.8 km/sec out of a total 135.8 km/sec hyperbolic excess at perihelion.

Assuming an electric rocket exhaust velocity of 2×10^5 m/sec as in Ref. 3, the electric fuel requirement is reduced by about 50%. If the solar electric ramjet is utilised instead of the electric rocket, giant-planet gravity assists may allow utilisation of an unmodified interplanetary medium ion density.

We should not expect that the gravity assist velocity increments can be combined algebraically with the electric drive velocity increment. This is because, if gravity assists are utilised, the solar-powered spacecraft will have less pre-perihelion acceleration time.

In the near term, we can expect that post-perihelion giant-planet gravity assists will be capable of supplying a significant fraction of the final hyperbolic excess velocity to the interstellar precursor probe. Depending upon probe pre-gravity assist velocity and aim point, 50% or more of the final hyperbolic excess velocity could be supplied by post-perihelion giant-planet gravity assists.

For interstellar arks launched within the foreseeable future, post-perihelion giant-planet gravity assist will not be useful because of the paucity of near-ecliptic targets for interstellar colonisation missions. However, as Cesarone *et al* [10] have indicated, solar-type stars may pass within a light year of the Sun at intervals of hundreds of thousands of years. If such a close approach is fortuitously combined with an ecliptic-plane crossing, a technologically and sociologically sophisticated Solar System civilisation could utilise the post-perihelion giant-planet gravity assists in the acceleration of interstellar arks.

REFERENCES

1. G. L. Matloff and E. Mallove, "Solar Sail Starships: The Clipper Ships of the Galaxy," *JBIS*, **34**, 371-380 (1981).
2. G. L. Matloff and E. Mallove, "The Interstellar Solar Sail-Optimization and Further Analysis," *JBIS*, **36**, 201-209 (1983).
3. G. L. Matloff, "Beyond the Thousand-Year Ark: Further Study of Non-Nuclear Interstellar Flights," *JBIS*, **36**, 483-489 (1983).
4. G. L. Matloff, "Interstellar Solar Sailing: Consideration of Real and Projected Sail Materials," *JBIS*, **37**, 135-141 (1984).
5. G. L. Matloff, "The State of the Art Solar Sail and the Interstellar Precursor Mission," *JBIS*, (to be published).
6. G. L. Matloff, "On the Potential Performance of Non-Nuclear Interstellar Arks," *JBIS*, (to be published).
7. K. A. Ehricke, "Saturn-Jupiter Rebound: A Method of High Speed Spacecraft Ejection from the Solar System," *JBIS*, **25**, 561-571 (1972).
8. A. J. Fennelly, G. L. Matloff, E. H. Walker, and G. Frye, "Some Solar System Applications for an Interstellar Ion Scoop," *JBIS*, **29**, 489-493 (1976).
9. M. Washburn, *Distant Encounters*, Harcourt-Brace-Jovanovich, New York (1983).
10. R. J. Cesarone, A. B. Sergeyevsky and S. J. Kerridge, "Prospects for the Voyager Extra-Planetary and Interstellar Mission," *JBIS*, **36**, 99-116 (1984).
11. G. R. Fowles, *Analytical Mechanics*, Holt, Rinehart, and Winston, New York (1962).
12. W. R. Corliss, *Space Probes and Planetary Exploration*, Van Nostrand, New York (1965).
13. G. A. Mersov and V. A. Phillippov, "Use of Venus Gravitational Field for Solar Probe Trajectory Control," *J. Spacecraft and Rockets*, **7**, 1182-1186 (1970).
14. J. A. Burns, "Planetary Rings," in *The New Solar System, 2nd edition*, eds. J. K. Beatty, B. O'Leary and A. Chaikin, Cambridge, New York, Chapter 13 (1982).
15. L. D. Jaffe, C. Ivie, J. C. Lewis, R. Lipes, H. N. Norton, J. W. Stearns, L. D. Stimpson and P. Weissman, "An Interstellar Precursor Mission," *JBIS*, **33**, 3-26 (1980).
16. J. C. Brandt and S. P. Maran, *New Horizons in Astronomy*, W. H. Freeman, San Fransisco (1972).
17. W. K. Hartmann, *Astronomy, The Cosmic Journey*, Wadsworth, Belmont, California (1978).
18. J. M. Pasachoff, *Contemporary Astronomy*, W. B. Saunders, Philadelphia, Pensylvannia (1977).
19. R. W. Buchheim, *Space Handbook*, Random House, New York (1959).

* * * * *

Journal of the British Interplanetary Society, Vol. 38. pp. 137-138, 1985.

THE ZOO WE LIVE IN

V. B. GERARD
59 Blue Mountains Road, Silverstream, Upper Hutt, Wellington, New Zealand.

The optimistic ideas of Sagan [1] and many others regarding the possibility, indeed some optimists call it a near certainty, of there being many technology-bearing planets in the Universe is presently being tempered by the extremely pessimistic views of people like Tipler [2] and Bond [3] who avow that the chances of such a civilisation arising are near to zero. It cannot be zero because we are here! Humanity must, on these latter views, be a very rare and maybe unique phenomenon.

The well-known Drake equation attempts to evaluate the mathematical probability of life and civilisation occurring in, say, our Galaxy by evaluating the products of the various probabilities involved. There are several of these, like the chance of intelligent life arising on a planet which has given birth to single cell organisms. But these individual probabilities are mostly so poorly known that the final result is to all intents and purposes meaningless, though Bond [3] attempts a very detailed refinement of the biological factors involved. His conclusions are very pessimistic indeed. However, the key point is that one can't do statistics with just one example – the Earth. The fact that life apparently originated here, and not arrived from somewhere else, is cited by the optimists as clear proof that it can easily originate and evolve if conditions are suitable. But, even so, what are the chances of a technological civilisation coming into being? We will not detect any other, at least not for a very long time until our space-probes chance upon such a planet in a future large scale galactic exploration, should this ever occur. I am here assuming that there is no life remaining to be discovered in our own Solar System in hypothesised locations like Jupiter's atmosphere or on Titan.

We must also ask the well-known Fermi question, "Where is everybody?"

If life is so plentiful, and the Sun is a relatively young star compared with the time elapsed since the Big-Bang, then there has been plenty of time for older technological civilisations to develop interstellar flight and explore the Galaxy. So why has Earth apparently not been visited by at least one of these, and why aren't we aware of "them"? In much the same way as we are well aware of other intelligent species on Earth, like the dolphins, there is no logical reason why this awareness couldn't extend to a space-faring species superior to us.

There appear to be two extreme conclusions to be drawn. Either we have been visited many times because life is very common, but right now no one is particularly interested in us because we are just one ant-hill amongst many, or life is very very rare and we have never been visited and are never likely to be. However, in scientific arguments when two very contrasting views are held on a matter it is as well to consider intermediate possibilities as well. So, let us muse upon the possible train of events if ours is just one of very few technological civilisations in the Galaxy. By very few I mean no more than, say, three in all the 10^{11}, or so, stars of the Galaxy. These will almost certainly be more advanced than we are because our science-based technology is very young, being barely 300 years old. If there are any other technologies we must be the youngest. "They" will have originated intelligent "von Neumann" type self-replicating space probes to explore the entire Galaxy in the remote past if their mode of thought bears any resemblance to ours. If it doesn't then we are effectively alone and there is nothing to discuss.

"They" will have discovered life on Earth – at least one of their probes will have – most probably long before the appearance of man but, having already explored vast regions of the Galaxy and found few or no planetary systems with any sign of life, they would be amazed and excited when the radio message from their probes near to, or on, Earth arrives. Remember, their galactic exploration will probably have been in progress for something of the order of several million years before Earth would be found. It would be a most astounding event for them. Perhaps, as their civilisation has existed for so long, they have evolved into something which we would regard as a vast collection of silicon chips programmed by their originators millions of years before.

Let me give a local example: Earth is as rare to "them" as the Chatham Island black robin was to the New Zealand Wild Life Service which, around 1975, discovered five birds remaining alive on a remote island. By heroic efforts and some novel breeding techniques, these have now (mid 1984) been increased to just fifteen birds and the species' chances of survival slightly improved. They are perhaps the rarest birds on Earth.

What will the alien do to improve the chances of Earth's life surviving and developing? Will "they" undertake a genetic engineering programme to nudge Earth's life in the direction of their own, or are they going to leave it strictly alone but observe it like we would observe the life of a new tribe of apes, but perhaps would not interfere? Clearly they can see all sorts of possibilities which might extinguish life on this amazing planet. They do not want this to happen. They might be aware of the Cretaceous-Tertiary comet or meteorite which, according to some current research, is supposed to have extinguished many vulnerable species at the end of Cretaceous times and would have extinguished all life had it been much bigger. Did they even cause this event knowing that Earth's future did not lie with the great reptiles then rampant? They would also know that a nearby super-nova could greatly damage existing life. There are many other possibilities which could bring disaster to our amazing planet. The alien's number-one priority may be to prevent this while they observe life evolve with perhaps just a very subtle nudge now and then in the right direction, as they see fit.

Can we see any sign at all of interference from outside? In the Solar System there are a lot of unanswered puzzles like why is there a belt of asteroids between Mars and Jupiter? Has someone been doing some mining there and taken a small planet apart, or did Jupiter simply prevent one forming as most astronomers believe? Why does the Earth have such a relatively huge Moon and would life have originated here without its influence on such phenomenon as the tides and plate tectonics? Aspects of this problem are

discussed in Ref. 4. To me, one of the most strange puzzles is why does our Moon eclipse the Sun so perfectly? That is, why are the angles subtended at the Earth's surface by the Moon and by the Sun almost equal? So close are they that we sometimes get annular eclipses, as well as total ones. No other planet-moon pair in our Solar System comes anywhere near satisfying the necessary geometry. The chances of this happening on a planet which also has an emerging technological civilisation seem to me to be infinitesimal unless the two are connected. A similar conclusion was reached by Mendillo and Hart [5] who facetiously implied that divine providence must be invoked to explain it. Again, we are attempting to do statistics with just one example, our own Solar System. Until we have good data on at least a few other planetary systems we won't be able to evaluate the significance of the Earth-Moon geometry, and even then we may not reach a conclusive answer.

Did "they" move the Moon with respect to the Earth and leave it in such an orbit so that by the time man became interested in such things it was producing rare but wonderful total eclipses? Superficially, it seems a fantastic notion. Was the Moon moved into Earth orbit just to start plate tectonics going, to produce mineral concentrations for future mankind to mine? One can, of course, invoke a "God" to explain any strange phenomenon but this is the basis of religions, not science. Merely invoking Occam's Razor is important in such cases – one ought not to believe a complex explanation if there is a good simple one. But I have not heard of a simple explanation for the eclipses except that the Earth-Moon geometry came about by chance. The Moon has been slowly receding from Earth apparently since close to the time they were formed according to orbital dynamics extrapolation backwards in time from the present. But the near coincidence of apparent angular diameters came about only in our present geological era. Just a chance occurrence?

Occam's Razor neatly demolishes the arguments that UFO's are aliens visiting us. If "they" regularly observe Earth then it is certain that we are not meant to be given any obvious or even subtle indication. Probably it is futile to ask how they might do it. A dolphin might as well ask how do submarines, which dolphins may regard as big fish, reproduce.

In 1945 as event took place which would, on this thesis, cause great alarm to the alien; mankind exploded his first fission bombs followed just a few years later by fission-fusion bombs. If the velocity of light is the limiting velocity in "their" physics, as it is in ours, then they cannot yet know of this on their home worlds which are presumably very remote from us. Their probes or local intelligences, hidden from us but closely studying us have been programmed to act against any menace to the survival of unique homo sapiens. Now they see a real chance that we could self-destruct. Previously, wars have been minor affairs from their point of view, just tribal affrays. There was no possibility that sapiens would disappear, now there is. What to do?

"Their" edict of "no interference" has to be broken, perhaps not for the first time, but it must be done very subtly to avoid skewing mankind's natural development. For example, we would probably not give our hypothetical new tribe of apes unlimited supplies of bananas but we might well shoot a few marauding lions which were killing them off. We must not know or guess that we are being manipulated or helped through these difficult post-nuclear years to more stable times.

In the 1950's some of the greatest minds of this century, men like Bertrand Russell, Albert Einstein and C. P. Snow forsaw the near certainty of disasterously destructive nuclear wars in the near future. The 1980's were then a quarter of a century away and they gave mankind little chance – Snow once implied an infinitesimal chance of reaching 1980 unscathed by nuclear destruction. Russell was just as pessimistic and in 1961 [6] wrote that, "it is impossible to know whether the human race will last long enough for what I write to be published." Yet here we are well into the 1980's and, while the international situation is still black it is at least no worse than in the alarming times of the Cuban missile crisis over two decades ago.

Are we in a celestial zoo being manipulated by a very powerful being some would call God? This is not a very original idea but I submit that the arguments advanced here should lead us to take the possibility more seriously than most of us do. The final paradox is that such a being might well have the capability of reading articles as this and would then presumably ensure that they are not taken seriously enough for mankind to begin a "find the alien" project!

Someday when we, or "they", have got our society on to a stable footing, though perhaps not until we have mastered interstellar travel, will they let us discover them. By then, we will be their near equals technologically and may also be no more (or less) than millions of space-faring silicon chips, the remaining homo-sapiens being kept at home on Earth and a few other congenial planets, not in a zoo

REFERENCES

1. C. Sagan, "Cosmos," p. 301, Macdonald, London (1980).
2. F. J. Tipler, *Physics Today*, **34**, (4), 9 (1981).
3. A. Bond, *JBIS*, **35**, 195 (1982).
4. G. W. Pace, *JBIS*, **35**, 504 (1982).
5. M. Mendillo and R. Hart, "Resonances," *Physics Today*, **27**, (2), 73 (1974).
6. B. Russell, "Has Man a Future?" p. 120, Penguin, London (1961).

* * * * *

Journal of the British Interplanetary Society, Vol. 38, pp. 139-142, 1985.

SUSPENDED ANIMATION FOR SPACE FLIGHT

JOHN HANDS
67 Battledean Road, London, N5 1UX, England.

The idea of suspended animation for humans is generally regarded as science fiction. Yet recent research into hypothermia in humans has demonstrated the body's ability to endure, and be resuscitated from, extended periods of very low temperatures; recent research into hibernation has demonstrated the ability to induce low-temperature hibernation in normally non-hibernating primates. Drawing together these two strands of research suggests that a concerted research effort would have a reasonable chance of demonstrating the feasibility of putting humans into suspended animation for prolonged periods. Such a breakthrough would have considerable implications for the work being undertaken into space flight to the planets and the stars.

1. INTRODUCTION

The vast majority of work undertaken on future space flight to the planets and the stars deals with modes of propulsion; a small element is concerned with the bio-medical effects of prolonged weightlessness on humans; an even smaller element is devoted to speculation on the psychological and sociological implications of long-duration manned space flight.

The assumption underlying the work on interplanetary flight is that either it will be unmanned or else a human crew will continue to function normally during prolonged periods of weightlessness and boredom (for which much more physiological and psychological research is needed, coupled with research into post-flight readjustment). The assumption underlying the work on interstellar flight is that either the mission will be unmanned or else will take the form of a multi-generation space ark on a one-way trip. In both cases payload calculations assume either storage of, or means of producing and/or recycling supplies of, air, food, etc.

Drawing together strands of research in the fields of hypothermia and hibernation, however, questions these assumptions and suggests another option for long distance space flight.

2. HUMAN SURVIVAL AT LOW TEMPERATURES

It is generally considered that, at a body temperature of 20°C, the tolerance of the brain to loss of blood supply – and therefore oxygen – is increased tenfold compared to that of a body at the normal temperature of 37°C. Two recent reports raise the question: is this an underestimate?

Felix and colleagues from Boston describe techniques they have used to resuscitate people who have nearly drowned in cold water [1]. Their first conclusion is disarmingly simple. *A patient who is not both warm and dead should not be considered dead.* They have revived people who have been totally immersed in cold water for as long as 40 minutes, and quote other instances of people surviving for as long as an hour. These victims of near-drowning were cold, pulseless and areflexic, yet survived without neurological damage. Felix's technique is immediate and continued heart-lung resuscitation on removal from the cold environment. He then warms the core of the victim by using heated oxygen at 44°C, followed by peritoneal lavage (putting warm fluid in the cavity surrounding the intestines inside the abdominal wall) with a warm, balanced salt solution at 54°C.

Perhaps an even more dramatic pointer to the feasibility of suspended animation is evidence from Switzerland of the body's ability to survive without oxygen while deep frozen. A group of surgeons, headed by Mühleman, have reported on methods used to revive three people buried under avalanches [2].

All three victims were in a state of profound hypothermia, with no signs of heartbeat or breathing when rescued. The Swiss surgeons also come to a startingly simple conclusion: *Every profoundly hypothermic patient, even in the state of clinical death, has the potential for full recovery.*

The first case quoted was a 41 years old man who was trapped under several metres of packed snow for 2½ hours. By the time he was rescued he had stopped breathing and had lapsed into cardiac arrest. He was helicoptered to an emergency centre where he was found to have ventricular fibrillation (instead of the heart muscle contracting regularly and efficiently, it twitched without performing its functions), a core temperature of 22°C, and dilated, fixed pupils. Closed chest defibrillation proved unsuccessful. His chest was opened and the surgeons say that "at the beginning of active rewarming his heart was found to be as hard as stone..."

Although his heart had stopped two hours previously, he was worked on for a further one and a half hours. At the end of this period, having had complete cardiac arrest for 3½ hours, he revived. He was discharged two weeks later having made a complete recovery and went back to his normal job.

Rewarming was achieved in this case by opening his chest and continuously irrigating the pericardial cavity (the sac that surrounds the heart) with warm fluids.

A second method was found to be even more efficient with another of their patients. This was a 42 years old man who was covered by seven metres of snow and ice for five hours before being freed. When he was rescued he was unconscious, pulseless and not breathing. No attempt was made to resucitate him and he was flown off to hospital. There he was found to have an electrocardiagram showing asystole (no contraction whatsoever of the heart muscle), a rectal temperature of 19°C, and fixed, dilated pupils. Seventy minutes after rescue it was decided to try and resuscitate him. Active rewarming started three hours after rescue. He was put on a heart-lung machine and the blood was warmed and pumped round his body. But when his chest was opened his heart was found to be motionless and frozen stiff.

So successful, however, was the extracorporeal method of warming the core that, within half an hour, his heart was started again by electrical defibrillation (the use of electrical

shocks to stimulate the regular heart contractions). This patient, too, fully recovered his intellectual and physical abilities, despite some four hours of complete cardiac arrest.

The Swiss surgeons warn of the problems which may be incurred by rewarming patients externally, for example, using blankets or immersing in a warm bath. This could cause "rewarming shock" due to peripheral vasodilation. Here the blood vessels at the outside of the skin dilate and take too much of the pool of blood, and not enough blood comes back to the heart to keep it going. But, the surgeons believe, if the heart is warmed first before the shell, preferably by extracorporeal warming using a heart-lung machine or, failing that, by continuous irrigation of the pericardial cavity with warm fluids, then most profoundly hypothermic patients should recover, even when they show symptoms which would indicate irreversible cellular damage in a body at normal temperature.

The recognition that low temperature reduces the oxygen requirements of the body and, specifically, of the brain, has formed the basis of hypothermia techniques used in neuro and cardiac surgery in recent years. Here the objective is not to revive someone already frozen but deliberately to cool the patient to reduce his or her need for oxygen.

Eight years ago a group of surgeons at Yokohama in Japan reported that, because of certain disadvantages attached to the extracorporeal perfusion technique employed in open heart surgery (that is, directing the blood out of the body, oxygenating it, and putting it back in the body while the heart is opened up), they have performed most of their open-heart operations under profound hypothermia induced by body surface cooling [3].

Essentially they put the patient to sleep with an intravenous injection, insert a tube down the trachea and induce deep anaesthesia by introducing ether. They then cool the patient by putting him in an ice water bath, carefully adjusting the speed of ether inhalation in order to avoid extremely slow cardiac rhythm or cardiac standstill during the cooling process. Their target body temperature is 20°C and as they approach this temperature the patient is removed from the ice water bath at 23°C.

The patient is carefully monitored throughout the procedure. The electrical activity in the brain is recorded by an electroencephalogram (EEG), the heartbeats by an electrocardiogram (ECG), and the arterial blood pressure measured from the femoral or brachial artery. The central venous pressure, together with the oxygen and carbon dioxide percentages, the blood pH, and the percentage of the blood volume which is occupied by cells, are all continuously monitored while the patient is cooled. The team comments that, as cooling progresses, oxygen consumption decreases.

To prevent blood sludging, low molecular weight dextran is given intravenously. Heparin is also given to stop blood clotting; at the end of the operation protamine sulphate is administered as an anti-heparin agent.

Once cooled to the target temperature, the aorta is clamped and the heart stopped by an injection of Young's solution. When the operation is near completion, warm water at about 45° is put into the bath and the patient is brought back to normal temperature by floating in the warm water. The rewarming process is terminated on reaching the target temperature of 35-36°C.

The Japanese surgeons claim that an additional advantage of this technique is the relative ease of post-operative respiratory control. Spontaneous respiration resumes almost at once after the operation.

A team at St. Thomas' Hospital, London later assessed five different techniques used to protect the heart muscle in 168 patients undergoing replacement of the aortic valve [4]. Two methods came out joint top: one was continuous perfusion of the heart at 32°C with a still beating heart; the other was cardioplegic hypothermic arrest.

The latter technique involves cooling and stopping the heart by injecting a solution into the root of the aorta which reduces the temperature of the heart muscle to approximately 16°C. They report that an initial coronary perfusion of Ringer solution containing potassium choride, magnesium chloride and procaine ensured rapid and uniform cooling of the heart and prevents its ATP (adenosine triphosphate) content being decreased by the heart beating itself to a standstill. Of the 14 patients operated on under these conditions, all showed good preservation of the heart muscle during the period the aorta was shut off. They add a note of caution, however, to the effect that, 'although profound hypothermia is beneficial, it has deleterious effects on a proportion of the hearts investigated'.

This theme was taken up in the Journal of the American Medical Association [5] which considered deep hypothermia for infant open-heart surgery. It was reported that some researchers claim that post-operative motor and intellectual impairment occurs, while other researchers refute the claim.

Perhaps the answer lies in the particular techniques used. Rather than using external means, or internal means with the aid of surgery, why not induce the body to perform its own cooling and re-warming processes? Better still, why not induce a natural form of suspended animation?

This is the implication of research now being carried out in the field of hibernation.

3. INDUCED HIBERNATION IN PRIMATES

This work is based on the discovery, nearly 15 years ago, of a hibernation "trigger" (HT) factor in the blood of the hibernating woodchuck and ground squirrel. Dawe and Spurrier of Loyola University demonstrated that when blood is withdrawn from the animal during the phase of winter hibernation, and is then injected intravenously into an active squirrel or woodchuck during the summer months, the recipient begins to hibernate within 48 hours [6].

Later attempts to characterise the HT molecule biologically clearly show that the factor is bound to, or closely associated with, the plasma albumin fraction [7], is a protein [8], and exerts a profound effect on blood constituents [9, 10].

Now, although profound hypothermia is a characterstic of hibernation, the two are not the same. Hibernation has other characteristics. For example, it has been shown that electrical activity and contractility can be sustained in the isolated heart muscle of hibernating animals at a temperature of 5°C [11]. Hibernating animals are unique in other ways. Unlike non-hibernators, such as primates, they show certain physiological characteristics which may protect them from the adverse effects of hypothermia. These include dilution of the blood, rapid cooling and rewarming, periodic arousal, low arterial blood pressure, an increased volume of blood and increased levels of magnesium [12].

This raises the intriguing question: can hibernation be induced in primates, like ourselves, so that not only is cooling achieved and the metabolic rate reduced, but the body protects itself against any adverse effects of profound hypothermia?

As a first step to providing an answer, Myers and colleagues at the University of North Carolina have experimented with four conscious female macaque monkeys [13]. Baseline temperature, heart rate, food and water intakes were monitored in each animal after it had been acclimatised to a primate restraining chair. Hibernating woodchuck albumin lyophilisate was infused into the cerebral ventricle of each monkey. This produced a fall in body temperature and a marked inhibition of food intake, accompanied by a decline in prandial water intake. Heart rate decreased intermittently, while respiratory rate remained unchanged. Behavi-

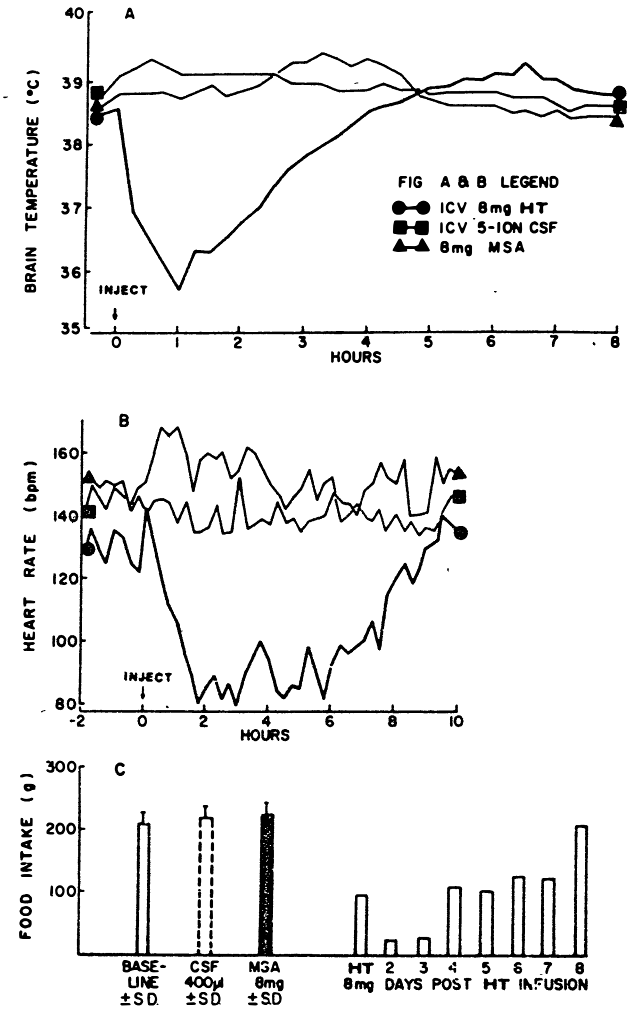


Fig. 1. (A) Brain temperature of a representative monkey following ICV injection of 8.0 mg HT in 400 μl of CSF; 400 μl of control CSF; or 8.0 mg MSA in 400 μl CSF. Abscissa is time in hours. (B) Heart rate (15 min computer averages) of a representative monkey. An interval of 48 hours or longer between each ICV injection of 400 μl CSF, 8.0 mg MSA, or 8.0 mg HT. Abscissa is time in hours. (C) Baseline intake of banana pellets of a representative monkey over five days (1st bar). Food intake at interval of 48 hours or longer after ICV infusion of 400μl CSF vehicle (2nd bar); 8.0 mg MSA (3rd bar); of 8.0 mg of HT (4th bar). Recovery from hypophagia post-HT infusion is depicted by the 5th through 11th bars. (Figure taken from *Pharmacology Biochemistry & Behaviour,* Vol. 17, p. 1272, 1982.)

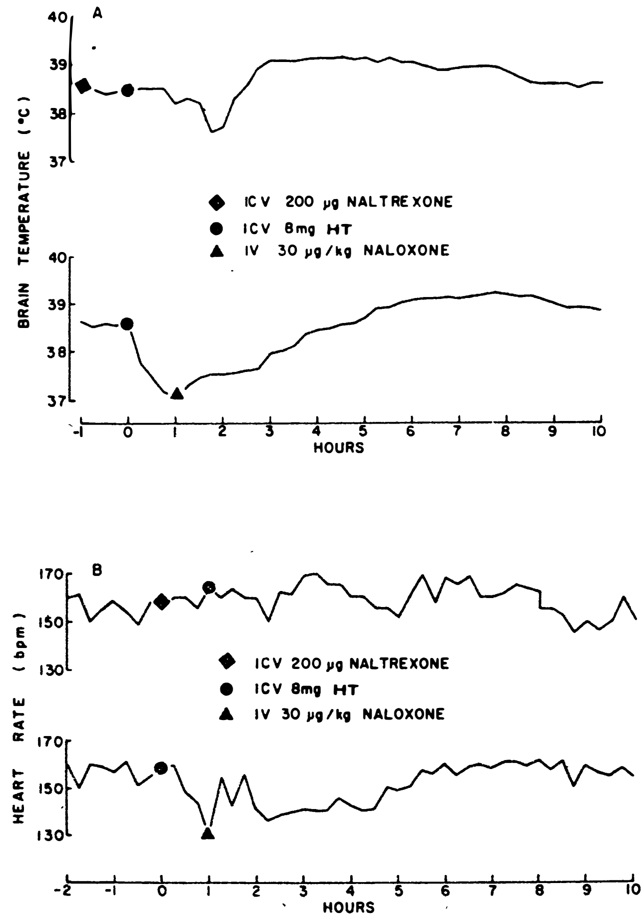


Fig. 2. The effects of opiate antagonists, naloxone (▲) and naltrexone (♦), on brain temperature and heart rate of a representative monkey either 1 hour before or after injection of HT (•). (A) Delay (top) of the hypothermic response produced by 200 μg of naltrexone ICV 1 hour prior to injection of 8.0 mg HT; reversal (bottom) of hypothermic response after intravenous injection of 30 $\mu g/kg$ naloxone. (B) Abolition of bradycardia (top) by ICV injection of 200 μg naltrexone 1 hour prior to HT injection; attenuation of bradycardia (bottom) after intravenous injection of 30 $\mu g/kg$ naloxone 1 hour after 8.0 mg HT. (Figure taken from *Pharmacology Biochemistry & Behaviour,* Vol. 17, p. 1273, 1982).

oural signs of lethargy and lassitude were observed. For comparison, summer active woodchuck albumin and bovine-serum albumin were given in the identical range of doses. These exerted little or no effect.

The experiments clearly demonstrated that a blood-borne substance obtained from a hibernating animal in torpor exerts a direct physiological action on the brain of a primate which is not normally capable of entering into hibernation. Vital metabolic, thermoregulatory and other control processes mediated by diencephalic and other systems are directly suppressed by the "trigger" factor.

Further efforts are now under way to identify the nature and mechanism of the HT molecule. In the latest series of experiments [14] three male rhesus monkeys were given infusions into the cerebral ventricle (ICV) of the HT-containing albumin fractions at twice the strength used in the previous experiments. The overall set of responses was essentially double in intensity.

Within 10-15 minutes of the infusion of HT, the monkeys closed their eyes, slumped and exhibited symptoms of an anaesthetised state which persisted for three to five hours, while their body temperatures fell and their heart rates dropped by up to 50%. Reduction in food intake persisted for five to seven days.

By comparison, ICV infusions of either a 5-ion artificial cerebro-spinal fluid (CSF) vehicle or monkey serum albumin (MSA) produced none of the behavioural or physiological modifications (See Fig 1.).

The researchers then attempted to see whether opiate receptor blockers would alter the monkeys' responses to HT. The injections of naloxone one hour after ICV infusion produced a remarkable effect in all three primates. Within minutes they became alert and the symptons of hibernation were reduced or abolished. A similar response was given to the ICV infusion of naltrexone (See Fig. 2).

These experiments lead the researchers to hypothesise that the hibernation "trigger" molecule is an endogenous opiate-like peptide; that the non-hibernating primate possesses receptor sites in the brain that are capable of responding to this potent molecule; and this its effects can be reversed by the injection of opiate receptor blockers.

In their view "the clinical potential for a molecule such as HT is quite extraordinary. It could be used to depress metabolism, lower body temperature, manage cardiovascular function or reduce food intake."

4. CONCLUSION

In the nineteenth century the idea of swopping somebody's heart seemed as remote as landing men on the Moon. Few space scientists now doubt that in the twentyfirst century we will have achieved controlled nuclear fusion and will be able to harness its power to drive vehicles across interstellar space. Is it any less probable that within this timeframe we could also develop the techniques to put humans safely into suspended animation for the journey?

The relatively modest cost of a concerted research programme into suspended animation *could* play enormous dividends in terms of increasing the options for manned flight, reducing payload, and reducing the physiological and psychological effects of prolonged space flight. Certainly it is too significant a field to be left to the random, uncoordinated and underfunded work being carried out at present.

ACKNOWLEDGEMENTS

The writer would like to thank Dr. Iain Dow for help in the preparation of this article.

REFERENCES

1. W. R. Felix, Jr., K. F. MacDonnell and L. Jacobs, "Resuscitation from drowning in cold water," *N. Engl. J. Med.*, **304**, (14), 843-844 (1981).
2. W. Mühleman, U. Althaus, P. Aeberhard, P. Schüpbach and B. H. Nachbur, "Management of profound accidental hypothermia with cardio-respiratory arrest," *Ann. Surg.*, **195**, (4), 492-495 (1982).
3. A. Matsumoto, S. Sato, J. Kondo, J. Kumada, H. Goto, M. Kohno, H. Natsumara and T. Wada, "Use of profound hypothermia induced by surface cooling in open-heart surgery," *Ann. Thorac. Surg.*, **22**, (4), 330-337 (1976).
4. S. Čancović-Darracott, M. V. Braimbridge, B. T. Williams, L. Bitensky and J. Chayer, "Myocardial preservation during aortic surgery. Assessment of five techniques by cellular, chemical and biochemical methods," *J. Thorac & Cardiovac. Surg.*, **73**, (5), 699-706 (1977).
5. E. Rasche González, "Deep hypothermia for infant open-heart surgery: pros and cons," *J.A.M.A.*, **241**, (24), 2585 (1979).
6. A. R. Dawe and W. R. Spurrier, "Hibernation induced in ground squirrels by blood transfusion," *Science*. **163**, 298-299 (1969).
7. P. R. Oeltgen, W. A. Spurrier, L. C. Bergmann and S. B. Jones, "Isolation of a hibernation inducing trigger(s) from the plasma of hibernating woodchucks," *Prep. Biochem.*, **8**, 171-188 (1978).
8. P. R. Oeltgen and W. A. Spurrier, "Characterisation of a hibernation induction trigger," in *Survival in the Cold, Hibernation and Other Adaptations*, Chapter 8, edited by X. J. Musacchia and L. Jansky. New York: Elsevier/North Holland Inc., pp. 139-157, 1981.
9. P. R. Oeltgen, W. A. Spurrier and L. C. Bergmann, "Hemoglobin alterations of the 13-lined ground squirrel in various activity states," *Comp. Biochem. Physiol.*, **64B**, 207-211 (1979).
10. W. A. Spurrier and A. R. Dawe, "Several blood and circulatory changes in the hibernation of the 13-lined squirrel," *Comp. Biochem. Physiol.*, **44A**, 267-282 (1973).
11. W. A. Spurrier and A. R. Dawe, *Comp. Biochem. Physiol.*, **57A**, 457-469 (1977).
12. Popovic and Popovic, *Hypothermia in Biology and Medicine*, New York: Grune & Stratton Inc., 1974.
13. R. D. Myers, P. R. Oeltgen and W. A. Spurrier, "Hibernation "trigger" injected in brain induces hypothermia and hypophagia in the monkey," *Brain Res. Bull.*, **7**, 691-695 (1981).
14. P. R. Oeltgen, J. W. Walsh, S. R. Hamann, D. C. Randall, W. A. Spurrier and R. D. Myers, "Hibernation "trigger": opoid-like inhibitory action on brain function of the monkey," *Pharmac. Biochem. Behav.*, **17**, (6), 1271-1274 (1982).

CORRESPONDENCE

Colonisation and Cultural Drift

Sir, The application of concepts such as cultural drift to interstellar colonisation [1] is indeed valuable. However, the detailed simulations presented by Bainbridge are perhaps less so, largely due to the difficulties of modelling a large enough system.

For 1000 units in diameter the distance between neighbouring stars is about 100 units. To allow six generations or so of colonisation without major problems due to edge effects, the maximum ship range was also put at 100 units. Unfortunately, this is equivalent to assuming only marginal interstellar flight capability, so it is hardly surprising that the colonisation pattern turns out to be patchy.

I have carried out some simplified simulations using equally-spaced stars on a cubic lattice. For a range of one stellar separation (1 st), equivalent to Bainbridge's 100 units, very similar results were obtained. However, even so small an improvement as doubling the range to 2 st made a major difference to the colonisation pattern: irregularities were greatly reduced, holes were rarely left for more than one generation, and the colonisation front progressed at a steady rate of about 1.5 st/gen (slowly increasing with time).

Doubling the range also made the natural selection of colonisers more effective, particularly when the initial colonisation probability was set very low. In one 2-D simulation a row of 19 starter sites, with $C = 0.05$, colonised out to a distance of 28 st in only 20 generations, the mean colonisation probability at that distance having risen to 0.743; in 3-D the effect is even larger.

The random spacing of stars will make little difference if ranges of 2 st or more are allowed, and after the first few generations the colonisation fronts are approximately planar: these simplifications allow computer models to be made more powerful, using more stars and greater ranges.

Thus even if Bainbridge's pessimistically low estimate of "normal" colonisation probability (zero!) and his cultural drift equation are accepted, they are significant only when interstellar flight is technically marginal. However, there is no reason to suppose that there is any technological limit on the possible range of a starship, and we should expect this range to increase with time for any starfaring society: any model using a fixed ship range is therefore ignoring the fact of technological progress. But for the Hart-Viewing argument [2] to work, only a very modest improvement (if

any) on the first marginal interstellar missions is needed – it is almost inconceivable that this would never occur.

Many people [1, 3] still do not appreciate the strength of the Hart-Viewing argument. It does *NOT* assume that ETIs must obey universal social laws, follow certain specific scenarios, or use particular starship technologies. It doesn't care how much ETIs may differ from us or each other, how much social variety there is or how their societies may develop, how much cultural drift there is, how many alternative scenarios CETI supporters can invent – the more the merrier. All it asks is that some one group or individual begin the process of interstellar colonisation; someone, of any society, of any race, anywhere, at any time in the history of the Universe.

Yet the urge to colonise – to spread out and multiply – is fundamental to *ALL* forms of life. It wouldn't be life otherwise. And a successful world-dominant lifeform must have this urge in a considerable degree, irrespective of the social forms it takes (scientific, curiosity, greed, religious zeal...). So a technologically advanced culture is rather more likely than not to engage in extensive interstellar colonisation. Any sociological law that purported to make such colonisation impossible would fly in the face of the whole history of life, the laws of natural selection and the past experience of mankind.

PAUL BIRCH

REFERENCES

1. W. S. Bainbridge, "Computer simulation of cultural drift: Limitations on interstellar colonisation," *JBIS*, **37**, 420-429 (1984).
2. M. Hart, "An explanation for the absence of extra-extraterrestrials on Earth," *Quart. J. Roy. Astr. Soc.*, **21**, 267 (1975).
3. A. A. Jackson, Correspondence, *JBIS*, **37**, 430 (1984).

Interstellar Colonisation

Sir, William Bainbridge's model of interstellar colonisation (*JBIS*, **37**, 420, 1984) predicts a situation whereby the Sun could be an isolated star surrounded by colonies. However this has been arrived at by assuming that the starships will have a limited range. This assumption is not realistic.

Newton's first law will ensure that a world ship, for example, once accelerated to its final velocity and pointed in the right direction, will eventually reach its target star. Alternatively a relativistic Bussard ramjet, taking its fuel from the interstellar medium, would also have an unlimited range and would cover the distances involved rather quickly.

Removal of the constraint of ship range would mean that any star could be reached from any other, and so the filling of gaps within the volume of colonisation would not depend on the survival of civilisation on certain key colonies.

IAN CRAWFORD

Reply by Dr. W. S. Bainbridge

My simple microcomputer simulation of interstellar colonisation was meant to inspire readers to experiment with their own sets of assumptions, and the immediate research goal was to find a set of conditions that would permit the development of limited interstellar civilisations. I would like to believe that our own species is capable of reaching out across the stars, and I doubt that ours is the first star-capable species in the Galaxy. Thus I find very attractive a model of colonisation that harmonises these ideas with the apparent fact that extraterrstrials have not reached the Earth.

In the present simulation, the results are indeed very sensitive to values selected for the parameters. But it has often been pointed out that life on Earth depends on the fact that the physical constants of nature bear very particular relationships to each other. It may be that laws of social behaviour exist, every bit as determinate as those discovered by physical science, that place the parameters relevant to interstellar colonisation right in the narrow ranges for my simulation.

Actually, I think we should begin writing much more subtle and complex simulations. But to do so we shall have to develop a comprehensive theory of civilisation, something that has not been seriously attempted since the pre-war days when Pitirim A. Sorokin offered his theory, now nearly forgotten, that all civilisations go through a potentially endless series of cycles of rise and fall. Sorokin believed every civilisation begins when charismatic leaders promulgate a powerful but arbitrary ideology that becomes the principle driving an agressive and expanding society. For centuries, in what he called the *ideational* phase, citizens accept the ideology on blind faith. Then, with societal success, the civilisation enters a *sensate* period in which the ideology that gave it strength decays. Citizens turn away from faith in transcendant goals and toward the bodily senses, becoming hedonistic and skeptical of ideals.

I have suggested in previous essays, including my book, *The Spaceflight Revolution*, that ordinary utilitarian motives cannot drive a society out of its home planet, let alone across the gulfs to habitable planets circling other stars. If Sorokin's theory is correct, however, some rare civilisations may, by chance, become founded on non-utilitarian principles conducive to interstellar colonisation. If their technology is advanced enough, and the cycle of decay is long enough, they might achieve colonisation before the sensate period had brought an end to their expansion. But the sociological "launch window" for colonisation is of limited duration, setting a crucial parameter for simulations.

Among the alternatives to Sorokin's cyclical theory is a more linear one that views the progress of civilisation as a self-limiting process. Once science and technology have reached the point at which they can achieve space flight, they can also transform the species that developed them beyond recognition. If transcendent, irrational motives are required for long-distance space flight, then the social source of astronautics may die. Advanced technology is extremely dangerous if it is in the hands of independent competing groups. Nuclear war is but one way we can destroy ourselves through technology, and high-tech terrorism is not the only small-scale threat magnified by science. Thus, civilisations must quickly conquer irrationally and independent initiative, or they will destroy themselves. I view this as a tragic line of analysis, not a happy one. But if the laws of such social behaviour tend in this direction, then a civilisation will have at best one launch window in which it is both technically advanced yet disorganised enough to permit transcendent projects.

When I let the range of colonising ships be a key parameter in my simulation, I was not thinking of this range in terms like those of an ocean liner's range, determined by the work fuel must do to overcome friction through the water. Like all readers of the *JBIS*, I knew that most plans for interstellar travel involve bringing a ship up to a respectable velocity, letting it coast a practically unlimited distance to its goal at zero further cost in fuel, then expending fuel again to bring it down to an appropriate rendezvous velocity.

Several versions of the colonisation plan involve modest ships that do expend consumables for life support and electric power production, and thus would have a definite range. While some recent scenarios assume small, fast ships carrying humen genetic and technical means for creating colonists from it, traditionally it was thought very large ships would be required to transport entire communities. If so,

ships will be artificial worlds, taking lifetimes to get to nearby stars. Cultural and political drift on such a world-ship may render it socially incapable of completing its mission after a few generations. This factor would also set a range.

There may also be a socially determined range to the colonisation enterprise, if not to individual ships. Colonisation may proceed in several stages. For example, first robot survey probes will be sent to all likely systems. Then, on the basis of their reports, robot terraforming and base construction ships of great size and slow speed would be sent. Finally, after this time-consuming work, colonists follow. This scenario requires that the whole process be completed before the civilisation evolves to another phase. Thus colonisation range would be a function of rate of cultural change and of the time required for several trips to the target world.

It might be good to develop an economical model of colonisation, in which cost of colonising would replace range as a limiting factor, determining the rate at which colonies are sent out. Today, unmanned planetary probes are limited not in range – Voyager II will reach Neptune – but in the rate of launch. Civilisations that achieve cultures conducive to colonisation will be prepared to expend only a portion of their gross economic products on the effort. Dependent, of course, on the technical means available for colonisation, the rate at which colonies are sent out may not be sufficient to offset the mortality rate of such colonies. If societies are fertile only for limited periods, there will be a definite limit to the number of offspring each will produce, and a simple simulation such as mine can be rewritten so that number of offspring rather than range is a key parameter.

This consideration reminds us of the serious issue facing advanced industrial nations today. The birth rate in the United States is already so low that the population will actually begin to contract as soon as the age distribution adjusts to the limited production of children. The fact that the same is true for East Germany as well as West Germany suggests that this is not merely some defect of Capitalism but a feature of advanced industrial societies regardless of economic system. Some demographers believe the cruicial factor is the cost of children. In earlier societies, children could offer parents many benefits to offset the costs of rearing them, including help in agricultural work, allies in defence against enemies, and economic security in old age. Today, when children are a huge economic net drain on the adult generation, and return nothing to them in economic terms, it is not surprising that there is less willingness to invest in them.

On the interstellar level, there may be costs beyond the economic associated with colonisation. Cultural drift may occasionally produce societies that seek to destroy their neighbours. Any ships capable of delivering even modest colonies can deliver cobalt bombs instead – or a fusilade of neutron bombs if the attacker wants subsequently to recolonise the world. Indeed, if the transport ships use hydrogen fusion to reach velocities a significant fraction of the speed of light, then they need carry no bombs at all, but need only impact the target planet's atmosphere to destroy its civilisation.

With this possibility in mind, a civilisation will think twice about colonising the stars and inadvertently planting the seeds of its own destruction. For our simulations, we can write in subroutines to model both self-destruction and occasional fratricidal cultures.

A civilisation that has developed very efficient technical means for colonising may choose not to colonise the nearest worlds, but to place colonies at vast distances. While one reason for this strategy might be fear of destruction by a rogue colony, another might be that the long-term goal of colonisation of the entire Galaxy might be speeded. It would be interesting to develop simulations that explore colonisation with economically limited rate of colonising but long ship range, under various expansion strategies.

The appendix to my article suggested that one might model interstellar expansion down a cylinder, essentially as a planar wavefront, but I am wary of doing this unless the computer can handle a cylinder with radius of cross section much greater than the ship range. The *JBIS* program was limited by the widely-known dialect of BASIC in which I wrote it (without machine language routines), and was designed for 46K machines. Now that many of us have 512K machines with faster CPUs and access to more efficient languages, we have more scope for experimentation. If rate of colony sending is the limiting factor, rather than ship range, we may need that scope.

But the present simulation design permits several variations, including increasing the normal colonisation probability and incorporating a probability of self destruction. If one abandons random spacing of colonisable star systems, then extremely fast simulations can be written, but I would have less confidence in their results. Indeed, I would like to see experiments that retain the general concept of random distribution, but introduce variations in the density, as undoubtedly exist in our real Galaxy. When we can build simulations around actual data about the world, then realism demands it.

The crucial idea of my article remains the most difficult to handle: Our opinions about interstellar colonisation must be informed by social science. Unless we have a good theory of civilisation, all our speculations will be in vain. If universal laws of civilisation exist, they will play decisive roles in determining the possibility and extent of interstellar colonisation.

I often hear one or the other of two naive ideas about the sociology of colonisation from people interested in the subject. First, some agree with Paul Birch that an *urge* impells all life to explore or to multiply. This is excessively teleological thinking. What our innate drives will lead to outside the environment in which they evolved is anybody's guess. Many people confuse urges or instincts possessed by individual members of a species for a motivation somehow acting at the level of the species itself, and thus they are ready to believe that a species will find new ways to expand when it reaches the traditional limits of its environment. Species do not have urges, individuals do. Sexual urges can be satisfied without reproduction, and individual territoriality and inquisitiveness cannot translate into colonisation without very special social conditions.

Second, the argument that only one colonising species is required – and surely one must expect one of everything in this vast universe – clearly debates the issue under a different set of rules from those currently used in the physical sciences. An astronomer who, without confirming data, claimed that there existed somewhere in outer space a stable chemical element with 150 protons and 20 neutrons in each atom would not command much respect. The fact that we do not know the universal laws of sociology does not mean such laws do not exist.

Social science has not yet become systematic and rigorous, and it cannot give us definite parameters for our speculations about interstellar colonisation. I happen to think that social science is just now in the process of transforming into a mature natural science, but even if I am wrong we should turn to it at least for ideas to refine our thinking. All the arguments about the anomalous lack of extraterrestrials on Earth make implicit sociological assumptions. Microcomputer simulation is a good means for making our assumptions explicit, and for exploring their consequences. Even if limited interstellar colonisation is possible only under very restrictive assumptions, it may happen that they describe the real Universe with precision.

NOTICES OF MEETINGS

Lecture
Theme: **COMMERCIAL LAUNCH VEHICLES**
by G. M. Webb

To be held in the Society's Conference Room, 27/29 South Lambeth Road, London, SW8 1SZ on **20 February 1985,** 7.00-9.00 p.m.

Admission is by ticket only. Members should apply in good time enclosing a stamped addressed envelope.

Symposium
Theme: **EUROPE-US SPACE ACTIVITIES**

The **1985 Goddard Memorial Symposium,** in conjunction with the **19th European Space Symposium,** will be held at the NASA Goddard Space Flight Center, Maryland, USA on **28/29 March 1985,** organised by the American Astronautical Society and co-sponsored by The British Interplanetary Society in association with other Societies.

Offers of papers are invited. Further information is available from the Executive Secretary and registration forms will be available in due course.

One-Day Symposium
Theme: **SPACE STATIONS**

A one-day symposium on the above theme, considering the technology and applications of Space Stations, will be held in the Society's Conference Room on **17 April 1985.**

Further information and registration forms are available from the Executive Secretary, 27/29 South Lambeth Road, London, SW8 1SZ.

Lecture
Theme: **PLASMA PHYSICS IN SPACE**
by Dr. D. Bryant
Rutherford Appleton Laboratory

To be held in the Society's Conference Room, 27/29 South Lambeth Road, London, SW8 1SZ, on **1 May 1985,** 7.00-9.00 p.m.

Admission is by ticket only. Members should apply in good time enclosing a stamped addressed envelope.

Lecture
Theme: **COHERENT LIGHT FROM SUPERNOVAE**
by A. T. Lawton
President of the Society

To be held in the Society's Conference Room, 27/29 South Lambeth Road, London, SW8 1SZ on **15 May 1985,** 7.00-9.00 p.m.

Admission is by ticket only. Members should apply in good time enclosing a stamped addressed envelope.

One-Day Forum

To be held in the Society's Conference Room, 27/29 South Lambeth Road, London, SW8 1SZ on **Saturday 1 June 1985,** 10 a.m. to 5.00 p.m.

Topic: **THE SOVIET SPACE PROGRAMME**

Subjects will include:

- History of the USSR Luna Programme
- Cosmonaut Update
- Soviet EVA Experiments
- Discussion of Recent Activities

Offers of Papers are invited. Members with a special interest in the Soviet space programme are invited to attend. A registration fee of £5.00 is payable. Forms are available from the Executive Secretary on request, enclosing a stamped addressed envelope.

Lecture
Title: **SATELLITE INSURANCE**
by R. Buckland

Launching satellites into space is a risky business. No commercial project can go ahead without insurance to cover launch and other risks. This talk will describe the role that satellite insurance plays in the development of commercial activity in space.

To be held in the Society's Conference Room, 27/29 South Lambeth Road, London, SW8 1SZ on **12 June 1985**, 7.00-9.00 p.m.

Admission is by ticket only. Members should apply in good time, enclosing a stamped addressed envelope.

Lecture
Theme: **METEORITES: SURVIVORS OF THE EARLY SOLAR SYSTEM**
by Dr. A. L. Graham
Dept. of Mineralogy, British Museum

To be held in the Society's Conference Room, 27/29 South Lambeth Road, London, SW8 1SZ, England, on **18 September 1985,** 7.00-9.00 p.m.

Admission is by ticket only. Members should apply in good time enclosing a stamped addressed envelope.

Lecture
Theme: **THE OORT COMETARY CLOUD: PROBLEMS AND PERSPECTIVES**
by Dr. M. E. Bailey
University of Manchester

The physical structures of comets, observations bearing on their sites of formation and the usual steady-state 'Oort Cloud' theory of cometary origins will be reviewed. Several apparently severe problems for this general picture will then be described, emphasising that the 'Solar System vs Interstellar' debate continues and the validity of the steady-state Solar System model remains unsolved.

To be held in the Society's Conference Room, 27/29 South Lambeth Road, London, SW8 1SZ, on **30 October 1985,** 7.00-9.00 p.m.

Admission is by ticket only. Members should apply in good time enclosing a stamped addressed envelope.

36th IAF Congress

The 36th Congress of the International Astronautical Federation will be held in Stockholm, Sweden on **7-11 October 1985.**

Members of the Society wishing to present papers are asked to notify Dr. L. R. Shepherd, Chairman of the BIS International Liaison Committee at Society HQ as soon as possible. Members wishing to present papers at the IAF Student Conference must submit them through the Society.

LIBRARY

The Library will be open to members of the Society from 5.30 to 7.00 p.m. on each of the following dates: 20 Feb 1985, 3 Apr 1985, 1 May 1985, 15 May 1985 and 12 Jun 1985.

While every effort will be made to adhere to the published programme, the Society cannot be held responsible for any changes made necessary for reasons outside its control.

BACK VOLUMES

A small number of bound and unbound back volumes of *JBIS* have come into the possession of the Society and are now being disposed of at nominal prices.

A list of those currently available can be obtained on request, enclosing a stamped addressed envelope (20p). Please order and remit promptly if you are interested as only single volumes are for sale in most cases and will be disposed of on a first-come first-served basis.

MEMBERSHIP OF THE BRITISH INTERPLANETARY SOCIETY

Travel to the stars? Exploration of the Solar System? These are both concepts pioneered by the British Interplanetary Society for half a century. The Society is known throughout the world for its forward-looking thinking, its promotion of space exploration and development. Since its formation in 1933, the BIS has become an *international* organisation, with one-third of its membership from outside the United Kingdom. It is more than an astronautical society: it is a network connecting people with space interests *at all levels* all over the world.

Objectives

The main aims of the Society are:

(1) To promote the advancement of space research, technology and applications.

(2) To serve the general community by the interchange and dissemination of technical and other information by means of lectures, symposia, visits and publications.

(3) To promote the work of those professionally engaged in space research, space technology and allied subject-areas.

(4) To discuss national and international activities in space and to formulate forward-looking policies for the advancement of space exploration and utilisation.

Application for membership must be made on the Society's official form, available from the Executive Secretary. Those with specialist qualifications may be elected immediately to the grade of Fellow. Whatever the grade, the appropriate fees must be included at the time of application. These fees allow an applicant to join the Society *and* receive one of the monthly magazines (see below for details). Other magazines and books are available at extra cost. Other membership privileges include the use of the unique space library (at the times regularly published in the magazines) and attendance of the extensive range of lectures, film shows and, at a nominal cost, study courses. The lectures and study courses are presented by leading space experts, while the film shows are always very popular.

Periodicals

The Society keeps in touch with members by two-large-format regular publications: *Spaceflight* and the *Journal of the British Interplanetary Society (JBIS)*, and the twice-yearly *Space Education*.

For those wishing to keep abreast of space activities, *Spaceflight* (first issued 1956) provides essential reading not to be found in any other publication. Present events and future plans are dealt with in news items and major articles. Extensive participation by readers is developed through correspondence, book reviews, personal accounts and histories. *Spaceflight* is not simply a magazine, it is a valuable source of information respected throughout the world.

JBIS holds a unique place in the history of space exploration. It was first issued in 1934 and is now a leading international publication in its field, well recognised for its emphasis on key topics. Many of today's developments were predicted in its earlier pages. Each issue is now devoted to a specific subject area: Space Technology, Astronautics History, Interstellar Studies and Space Chronicle. Special issues are included e.g. on Remote Sensing, Space Communications, Computer Techniques, Space Materials, Orbital Dynamics, etc.

Space Education, first issued in 1981 and published twice a year, is an example of the Society's commitment to education. Articles cover the basics of astronautics to provide an invaluable background to what is going on in space today. *Space Education* is a medium for the dissemination of information and ideas on the understanding and teaching of space topics. It is a vital source of material for teachers.

Books

The Society has now published three highly-popular books of great interest to expert and lay members alike:

Project Daedalus (192 pp) contains 24 papers that summarise the work of a four year study for a Starship Probe to Barnard's Star.

High Road to the Moon (120 pp) records, in about 150 illustrations and text, many of the Society's original ideas and discussions on Lunar exploration in the visionary drawings of the late R. A. Smith.

The Eagle Has Wings (144 pp) traces the development of astronautics in the United States from 1945 to the end of the Apollo era in 1975.

Further Information from:- The Executive Secretary,
The British Interplanetary Society Ltd., 27/29 South Lambeth Road, London, SW8 1SZ, England (Tel: 01-735 3160)

(146)