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The central portion of the Rosette Nebula in Monoceros, NGC 2237.

Kitt Peak National Observatory.

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SPACE RESOURCES AND THE LIMITS TO GROWTH

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Natural resources are finite in any closed system. Sooner or later they will be depleted to a level where problems with energy production and environmental change will force a "limit to growth." It does not matter whether the population is increasing, exponentially or otherwise, or whether it is static. Neither does a policy of recycling manufactured goods and waste products help. Over some period of time, long or short, the available resources will be consumed.

However, while the Earth is a closed system in the 20th Century there is no reason for it to remain so. Space provides a supply of energy and raw materials which is essentially unlimited, and an almost infinite sink for pollution. Once the exploitation of the resources of the Solar System is under way, then all limits to growth are removed.

The impact of space resources and their utilisation upon the population of Earth, and its standard of living, is traced over the next five hundred years with the aid of computer simulations. The results of delaying the exploitation of space, and the long-term impact this will have on conditions on Earth, are explored. What can and should be done is clear, but problems in achieving this goal of infinite resources are already perceived.

1. INTRODUCTION

In 1798 the Rev. Thomas Robert Malthus published (anonymously) the first edition of "An Essay on the Principle of Population as it affects the Future Improvement of Society." Malthus argued that the growth of population will always tend to outrun the growth of production, and that any hopes that society haboured for happiness were held in vain. Population will always expand to the limit of subsistence and will be held there by famine, war and disease. There will never be enough produced (in terms of food, material, goods, wealth, etc.) to remove the condition of poverty being mankind's inevitable and inescapable fate [1].

The Malthusian theory of population had a great influence on social policy. The "Essay" appeared in six editions, with substantial material and argument added, and Malthus himself achieved world fame as a political economist.

In the early 1970's a string of events took place which were also to cause a measure of influence on contemporary policy and doctrine. Jay Forrester, working at MIT, developed a methodology for the continuous simulation of systems which possessed highly interactive feedback characteristics. That is, a change in one of the parameters of the system has an effect upon many other properties of the system. This methodology, known as "Systems Dynamics," consisted of a statement of the objectives and guiding philosophy, together with a generalised model structure that served efficiently in representing the inter-relationships of any dynamic system. Forrester applied Systems Dynamics to the world economic situation, calling the result "World Dynamics" [2]. A group led by Dennis Meadows, also working at MIT, suggested various changes and extensions to the model and the results from this study received worldwide attention in the book "The Limits to Growth" published in 1972 under the auspices of the Club of Rome [3].

The conclusions drawn from these computer models by their authors were that the world was in trouble, and that drastic measures were needed to correct matters. Forrester wrote "we may now be living in a 'golden age' when... the quality of life is, on the average, higher than ever before in history and higher now than the future offers."

The Club of Rome used the publication of "Limits to Growth" to attempt to influence a wide spectrum of influential political, industrial and intellectual leaders. In an assessment in 1978 of global modelling, John Richardson noted that "the impact of this activity on public opinion, on the scientific community and on national leaders is difficult to appraise and impossible to measure, but it has certainly been significant" [4].

In some senses, however, the warnings of a coming collapse in world society had all been voiced before, by Malthus. The same problem of insufficient production was at the root of the system instability, and only the words used to describe the situation had changed. Again to quote Forrester "within the next century, man may face choices from a four-pronged dilemma- suppression of modern industrial society by a natural-resource shortage; decline of world population from changes wrought by pollution; population limitation by food shortage; or population collapse from war, disease, and social stresses caused by physical and psychological crowding" [2].

In his book, Forrester gave details of the computer model (WORLD-2) which he used in his studies. This was subsequently elaborated and added to by the Meadows group (WORLD-3) and used as the basis for the work presented in "Limits to Growth." In the present paper, a version of WORLD-2 written by Tim Grant [5] will be used, firstly to review the trends and world responses leading to the Forrester/Meadows prophecies of doom, and secondly to investigate an alternative path away from societal restraint and any limits to growth.

I am, naturally, aware of the substantial body of criticism of the work of Forrester and the Meadows group, and the more general criticism of the validity of the use of such computer models as a whole [6]. However, simply because the impact of "Limits to Growth" (especially) has been so large, any exercise which can show an alternative to the strategies demanded by these groups is thought to be a valuable one. Leaving aside questions as to the validity of such modelling itself, can we invalidate the conclusions previously derived from these models, by using the models themselves?

The route that I will take into the future is a high technology path. In their original work Forrester and the Meadows group both showed to their own satisfaction that technological fixes. applied under the conditions associated with their models, were not enough on their own to solve

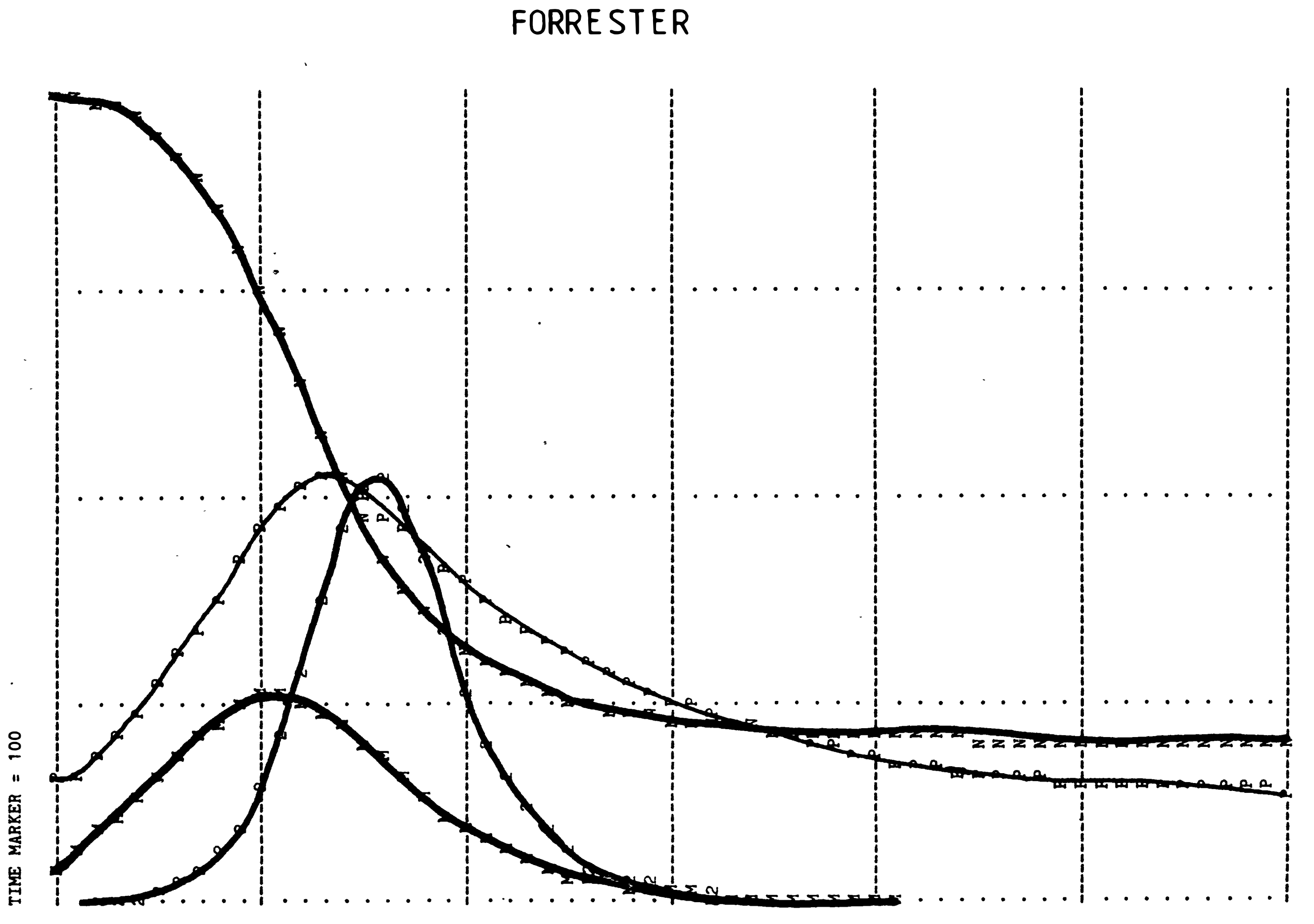

Fig. 1. The original predictive world model presented by Forrester [2]. The time scale is in centuries, from 1900 to 2500 AD.

the problem. For example, Forrester showed that control of "natural resources usage" led to a pollution crisis, control of the pollution rate led to overcrowding and a fall in the quality of life, suppression of the overcrowding factors by birth and death rate control led to food shortages, and so on. "Exponential growth rates do not continue for ever. Growth of population and industrialisation will stop. If man does not take conscious action to limit population and capital investment, the forces inherent in the natural and social system will rise high enough to limit growth. The question is only a matter of when and how growth will cease, not whether it will cease" [2].

The difference between these statements and the outcome of the modelling that I have carried out lies in the concept of the future base for technology and its implementation which we employ. Forrester and the Meadows group were conceptually limited to applying their ideas to a closed system based on the Earth. I apply my ideas to a system which involves the use of space and its resources, as well as the Earth. The difference that this introduces should become clear as the discussion progresses.

2. THE ORIGINAL PREDICTIVE WORLD MODEL

Figure 1 shows the results of computer simulation of the original predictive world model presented by Forrester [2]. The start of the simulation is 1900 AD, and the model is followed through to 2500 AD. Four quantities of interest are plotted. These are:

(a) The fraction of natural resources remaining at any particular time, N, with a full-scale value of 100.

(b) The population of Earth, P, with a full-scale value of 10 milliard (ten thousand million; ten US billion).

(c) The level of pollution, 2, with a full-scale value of 40 milliard units.

(d) The material standard of living, M, defined by Forrester as the effective capital investment per person and a measure of the wealth of the society, with a full-scale value of 4 units.

These full scale values will be kept constant in subsequent figures, for ease of comparison.

Forrester commented [2] upon his version of Figure 1: "The system... is discovered to be one in which growth is reversed by the pressures arising from declining natural resources... Population rises to a peak in the year 2020 and thereafter declines... The falling natural resources lower the effectiveness of capital investment and lower the material standard of living enough to reduce population... Well before natural resources disappear, their shortage depresses the world system because of the natural-resource extraction

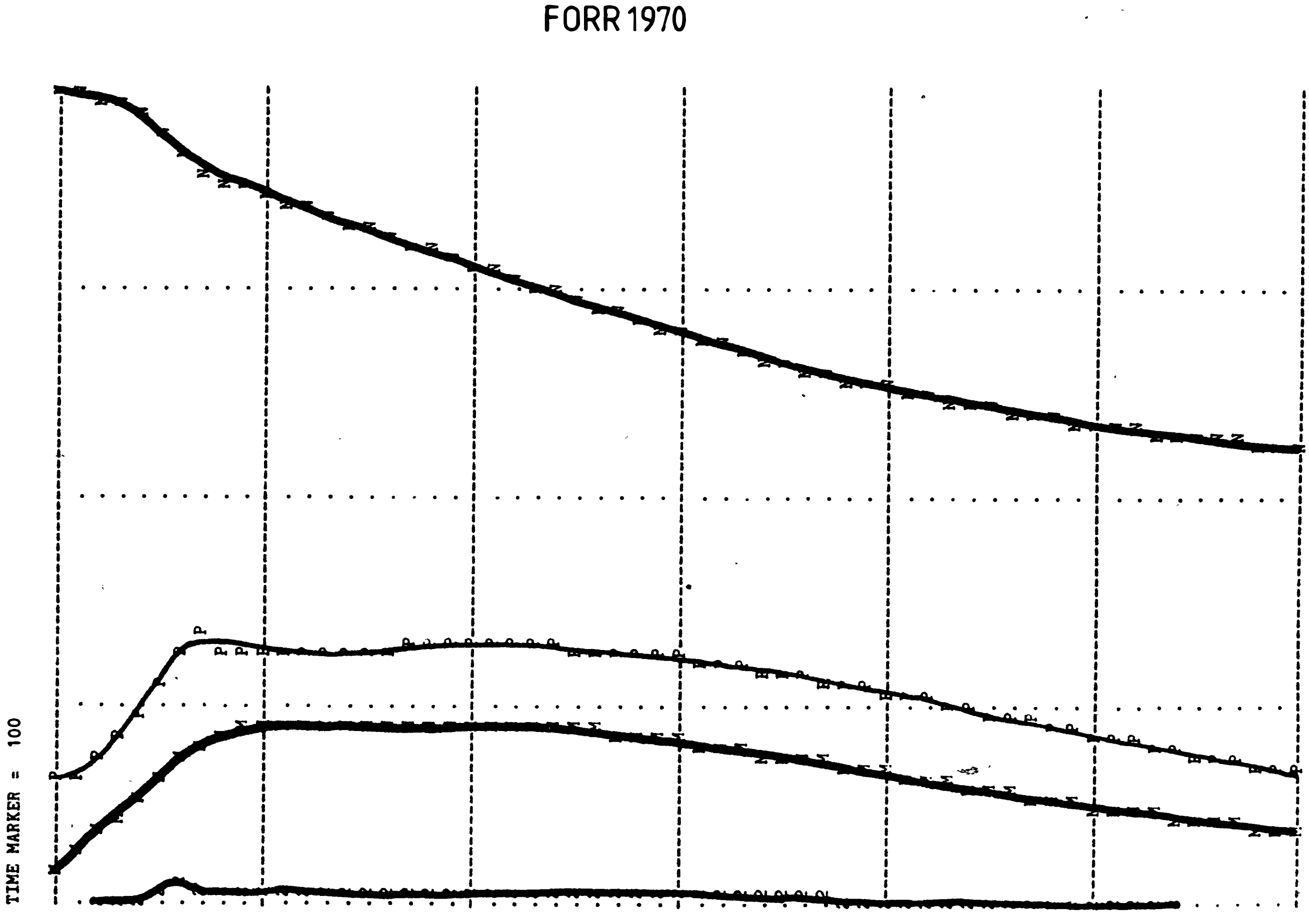

Fig. 2. The result of implementing Forrester's proposed solution in 1970.

multiplier... that introduces the more difficult extraction task resulting from depleted and more diffuse stocks of resources."

The maximum population is some 5.3 milliard, with a material standard of living only just above that of 1984. This latter quantity is related to the amount of natural resources remaining in the system, the fraction of available capital that does not have to be allocated to agriculture (and therefore relates to population level and food ratios), and the total capital investment itself.

The material standard of living has decreased to values of lower than those in 1900 by the year 2150, and to a fifth of that level by 2300.

Although the population is essentially static, at a level of some 1.5 milliard by 2500, this has only been achieved by an equalisation of the birth and death rates at an unacceptably high level of mortality. The global average life expectancy, reflected by a high death rate, is only some 18 years. The total "wealth" of the society is almost an order of magnitude lower than that of 1984, even with a population almost three times smaller.

The "Limits to Growth" group also summed up the outcome of their version of this standard predictive run [3]: "The collapse occurs because of non-renewable resource depletion. The industrial capital stock grows to a level that requires an enormous input of resources. In the very process of that growth it depletes a large fraction of the resource reserves available. As resource prices rise and mines are depleted, more and more capital must be used for obtaining resources, leaving less to be invested for future growth... *We can thus say with some confidence that, under the assumption of no major change in the present system, population and industrial growth will ceratinly stop within the next century, at the least.*" [Italics theirs].

3. THE ORIGINAL SOLUTIONS

The solution offered by Forrester [2] to the problems illustrated in Figure 1 was based on the following changes to the model, all of which were assumed to be implemented, simultaneously, in 1970:

- Natural resource usage rate reduced by 75 per cent.
- Pollution generation reduced by 50 per cent.
- Capital investment generation reduced by 40 per cent.
- Food production reduced by 20 per cent.
- Birth rate reduced by 30 per cent.

The result of computer simulation of the world model with the above changes is shown in Fig. 2. Forrester comments [2]: "Resources are still declining slowly and in time will depress the system unless there is sufficient recycling of waste products and substitution of less critical materials...

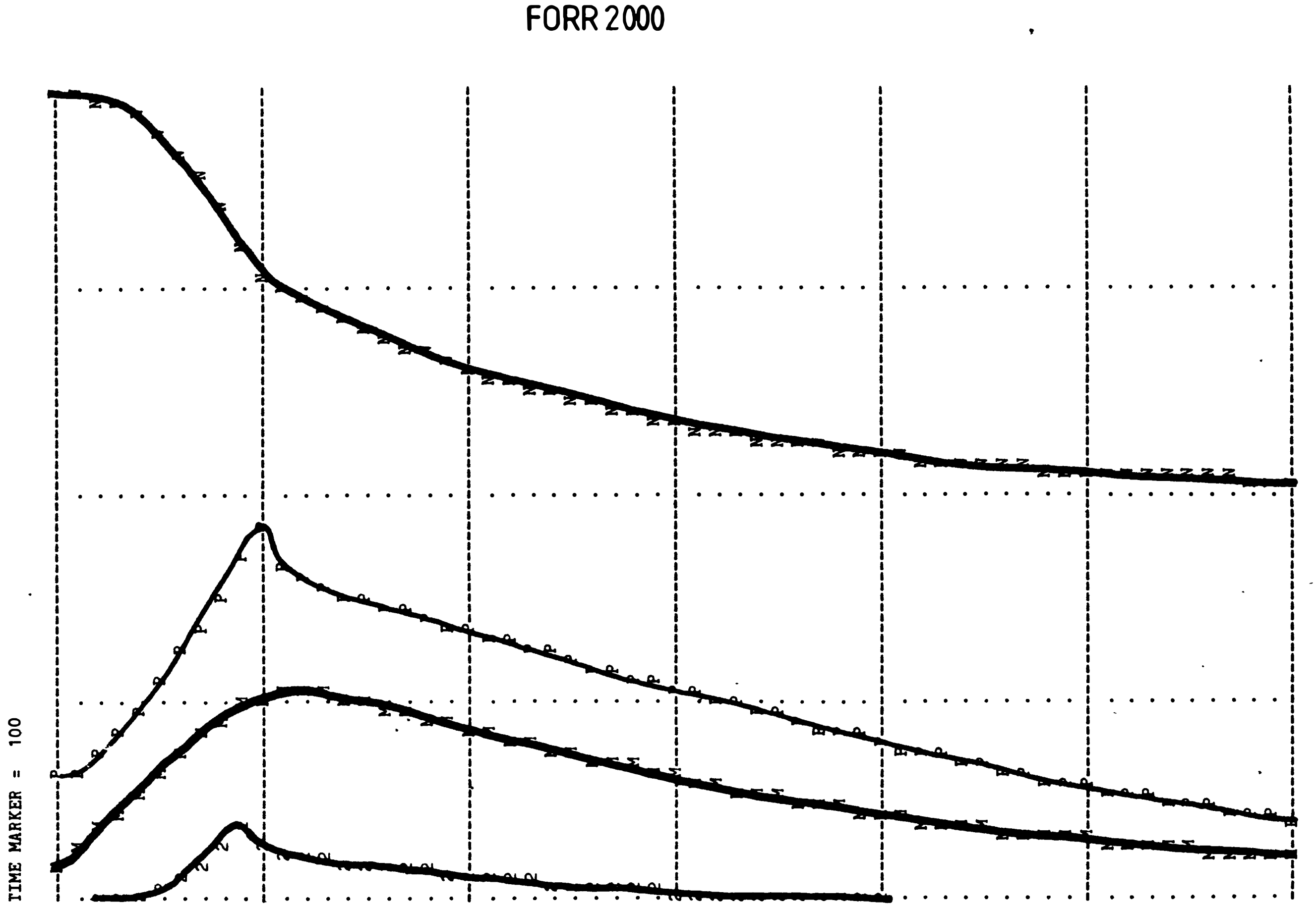

Fig. 3. The result of implementing Forrester's proposed solution in 2000.

[The figures mean] an end to population growth and to rising standard of living. They suggest a reversal of the emphasis on economic development."

The "Limits to Growth" group [3] use a more detailed, more complicated representation of the world, and their solution (Stabilised World Model II) was correspondingly more comprehensive. The following changes to the model were assumed to be implemented, again simultaneously, in 1975:

- 100 per cent effective birth control.
- Average desired family size is two.
- Average industrial output per capita maintained at 1975 level.
- Excess industrial capacity produces consumption goods.
- Resource consumption per unit of industrial output 25 per cent of 1970 value.
- Economic preferences shifted towards services (health, education) and away from material goods.
- Pollution lowered to 25 per cent of 1970 value.
- Capital diverted to food production, even if "uneconomic."
- Soil enrichment and preservation is a priority.
- Average lifetime of industrial capital increased.

The group commented [3]: "Many people will think that the changes we have introduced into the model to avoid the growth and collapse behaviour mode are not only impossible, but unpleasant, dangerous, even disatrous in themselves... *Indeed there would be little point even in discussing such fundamental changes in the functioning of modern society if we felt that the present pattern of unrestricted growth were sustainable into the future.*" [Italics mine].

The possibility of long-term sustainable growth represents the basic, fundamental disagreement between the outlook of these groups and that of the present author.

4. DELAYED IMPLEMENTATION OF THE SOLUTION

Now, of course, the changes that Forrester suggested taking place in 1970 have not happened, and it is almost 15 years later. What effect does delay have upon the model predictions? Figure 3 shows the effect of applying the elements of Forrester's solution after another 15 years of delay, that is at the turn of the Century.

The maximum population is now some 4.6 milliard. However, pollution is higher and natural resources are more depleted. The 30 year delay has, in effect, consumed about 150 years of resources when compared to the simulation of Figure 2.

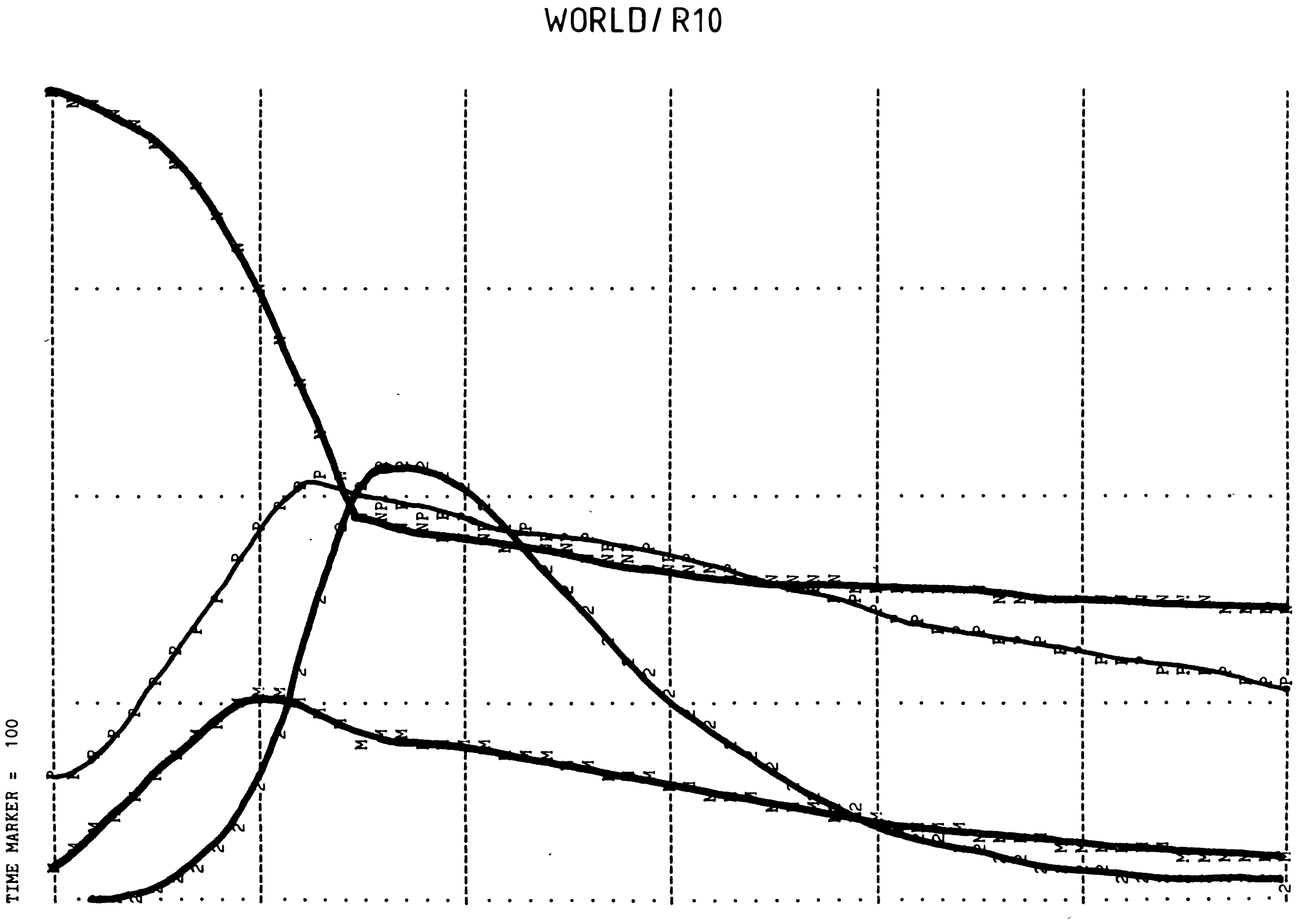

Fig. 4. The age of substitution. Natural resource usage rate is reduced to 10 per cent in 2050.

The end result is a more rapid decline in population to a level, in the year 2500, of about half that predicted by the application of the solution in 1970, and with a material standard of living also about half.

5. THE AGE OF SUBSTITUTION

Let us turn now to consideration of some alternative possibilities for the future development and growth of society on Earth.

Both the world models of Forrester and the Meadows group assumed fixed levels of natural resources, and natural resource usage rates which were essentially static before or after change. The fixed levels of resources were responsible for the eventual structure of the world models.

However, it has been argued many times that these levels of resources and resource usage rates are pessimistic, as long as the technological base is available to exploit the resources. In particular, Goeller and Weinberg [7] have made a case for the unlimited availability of resources. They foresee three stages of resource depletion and substitution:

(1) The continuation of present patterns of use of non-renewable resources, taking place over the next 30-50 years at least.

(2) A stage where there is little oil or gas remaining, but still a heavy dependance upon coal. Changes in metals usage from non-ferrous metals towards alloy steels, aluminium, magnesium and titanium occur. This stage could last for several hundred years.

(3) The age of substitutability, where fossil fuels are exhausted and society is based upon materials that are virtually unlimited.

The basic key to the fulfillment of this scenario is abundant energy. "Depletion of mineral resources per se need not create catastrophe, provided man finds an inexhaustible, nonpolluting source of energy... Moreover, the incentive to keep the price of prime energy as low as possible is immense. In the Age of Substitutability energy is the ultimate raw material. The living standard will almost surely depend primarily on the cost of prime energy" [7].

Given this proviso, the implementation of which we shall discuss below, we see no barrier to the application of the first part of the "high technology solution" to the world model:

- Reduction of natural resource usage rate to 10 per cent at the year 2050.

The result that this has on the world model is shown in Fig. 4. In the original model, a reduction to 25 per cent in 1970 led to pollution increasing catastrophically around 2050. The effect of this late reduction in usage rate is not as

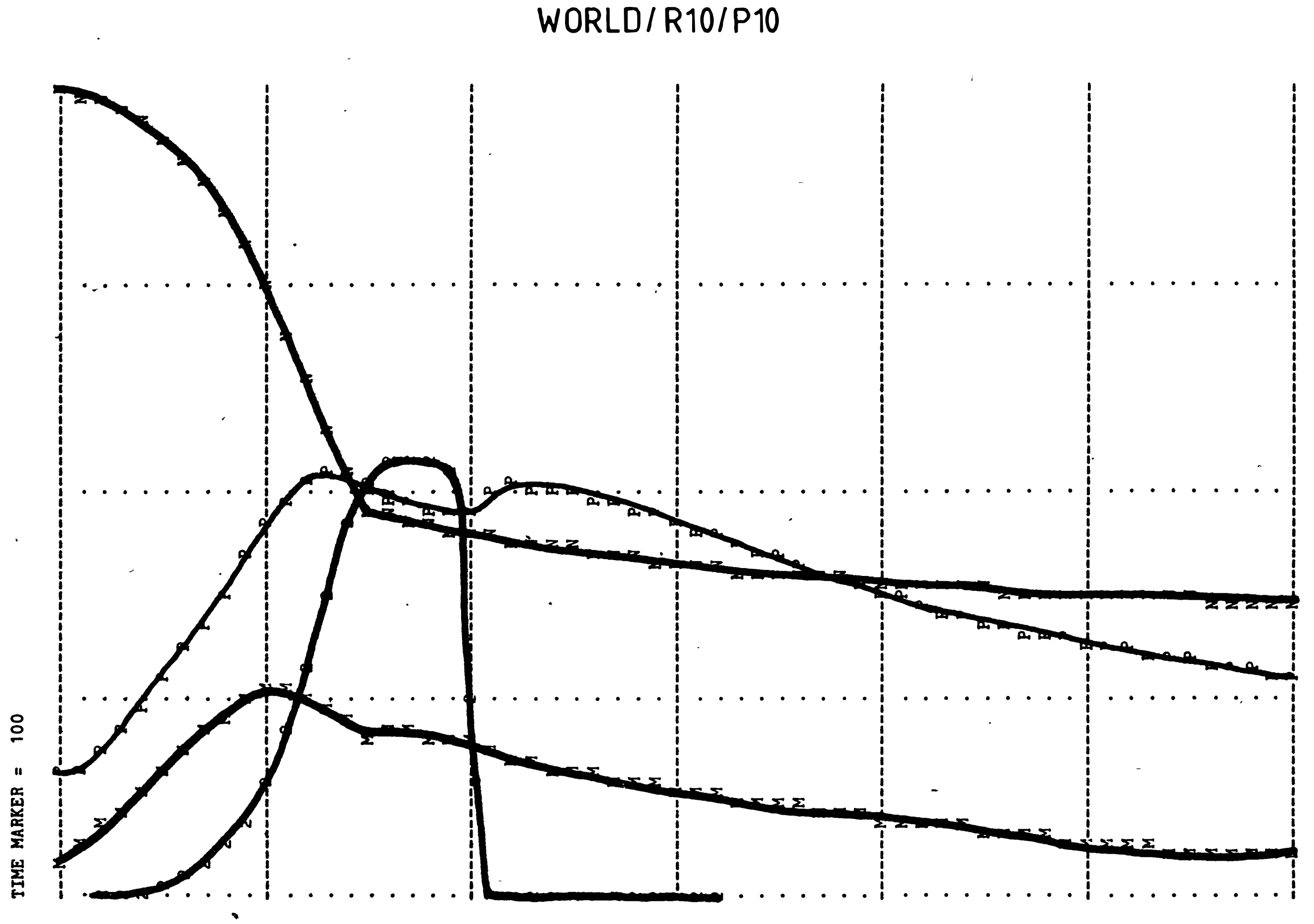

Fig. 5. The age of low pollution. As well as a resource usage rate reduction, the pollution rate is reduced to 10 per cent in 2100.

dramatic- the total resources have dropped significantly lower and the system is starting to respond to trends by producing a natural downward drift in pollution levels.

This, perhaps, is a good illustration that panic responses can do more harm than good. Sometimes the best course of action may be to do nothing for a period of time. Compared with the original world model (Fig. 1) the population in 2500 is over twice as large with about the same standard of living. It is about the same as in the Forrester solution at its peak population, although there has been a steady decline in population by a factor of two over some 500 years.

What we do see, however, is that the standard of living is only a fraction of that experienced at the end of the 20th Century. Pollution levels are also higher for longer in this simulation, as a result of the increased natural resources remaining over time and the higher population.

6. THE AGE OF LOW POLLUTION

This question of high pollution levels can be investigated by the model simulation by applying the second part of the high technology solution. The changes now become:

- Reduction of natural resource usage ratio to 10 per cent at the year 2050.
- Reduction of pollution rate to 10 per cent at the year 2100.

Fifty years after tackling the problem of natural resource depletion, the levels of pollution are brought under control. The results of the simulation are shown in Fig. 5.

The effect of this change on the world situation in 2500 is negligible. The driving factor here is the natural resource level. Although the world is a "nicer place to live in" as a result of an order of magnitude lower pollution level, this intangible is not reflected in the material standard of living, at least as it is defined by Forrester and used here.

7. IMPLEMENTING THE HIGH TECHNOLOGY SOLUTION

In Sections 5 and 6 we have assumed that a major impact can be made upon natural resource usage by a combination of increased discovery and exploitation of resources, but more importantly by implementing policies of substitution for any resources that are becoming scarce. At the same time we assumed that this could be carried out without any major environmental impact, in the form of pollution generation. We should now examine whether or not these two requirements can be mutually satisfied.

Goeller and Weinberg urged [7] "moving as vigorously as possible, not only to develop satisfactory, inexhaustible energy sources – the breeder, fusion, solar and geothermal power – but to keep the program sufficiently broad so that we can determine, perhaps within 50 years, the cheapest inexhaustible energy source."

For a world with a population of 10 milliard, and a per capita energy usage rate of, on average, one-half that projected for the United States, then the total world produc-

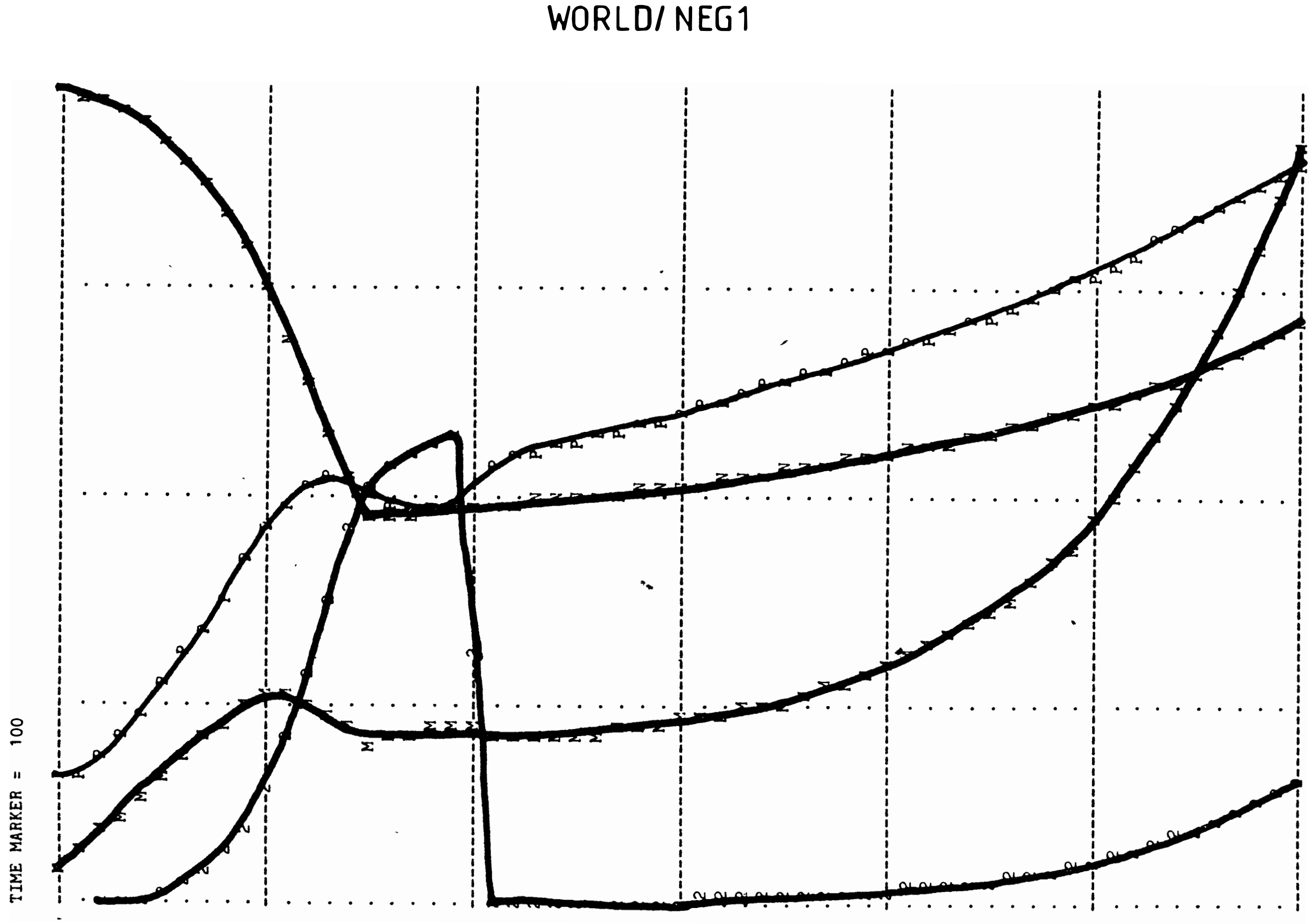

Fig. 6. The age of space exploitation. The concepts of substitution of scarce resources and reduction of pollution are still in force, but exploitation of the Solar System now leads to an increase in the effective natural resource levels.

tion of energy will need to be 75,000 GW. This is about twelve times the present level.

In principle, there is no problem with providing this level of power. Possible sources are fission breeder reactors (already operating as prototypes at the present time) or fusion power reactors (still in the experimental stage). However, if we assume a large unit size for a reactor of 5,000 MW, then we would require a total of 15,000 reactors. For a station lifetime of 30 years, then in the steady state 500 reactors would have to be built every year, that is ten reactors per week [8]. While changing the numbers alters this absolute figure, this requirement is likely to prove difficult to achieve.

The projected level of 75,000 GW is about 0.3 per cent of the solar energy absorbed and re-radiated by the Earth. Used in an unconcentrated form, with a ten per cent efficiency of conversion factor and no spacing between collectors, therefore, would require covering some three per cent of the surface of the Earth with solar arrays of some form to provide the energy requirements. While this is possible, it is again difficult to envisage.

Nor does a system based upon Solar Power Satellites (SPS) [9] help the problem much. Collection of the energy in space and transmission to the ground *via* microwaves can, in principle, give much higher power densities than those present in sunlight. However, safety factors limiting the maximum power density that can be used in a beam, and the requirement for a safety zone around the energy pickup area both serve to increase the land area requirements over the theoretical minimum. Estimates are that a factor of perhaps two could be gained over raw sunlight. Thus we would need to cover about 1½-2 per cent of the surface of the Earth with rectennae. Although these structures could, conceptually, be 70-80 per cent transparent, hopefully releasing the land underneath for agricultural purposes, again the scale of project is difficult to envisage.

The only method which appears to avoid this problem of area is the use of the power in space itself. This has two main advantages: (a) the power is higher, as atmospheric scattering, reflection and absorption losses, the day and night cycle, and seasonal variations do not apply (b) the sunlight can be converted to electricity with a higher efficiency and no conversion or transmission losses are incurred. Estimates indicate that the required global power needs could be met by 300,000 square kilometres of solar array, that is at least an order of magnitude lower than land based systems. While this is still large, it only represents an equivalent circle of radius 300 kilometres.

Here, then, we have the first two benefits given by the use of the natural resources to be found once we break away from the Earth:

- Space is an infinite source of energy.
- Space is an infinite place for expansion.

Now, most of the energy requirements we have been discussing were for the manufacturing sector, and were used

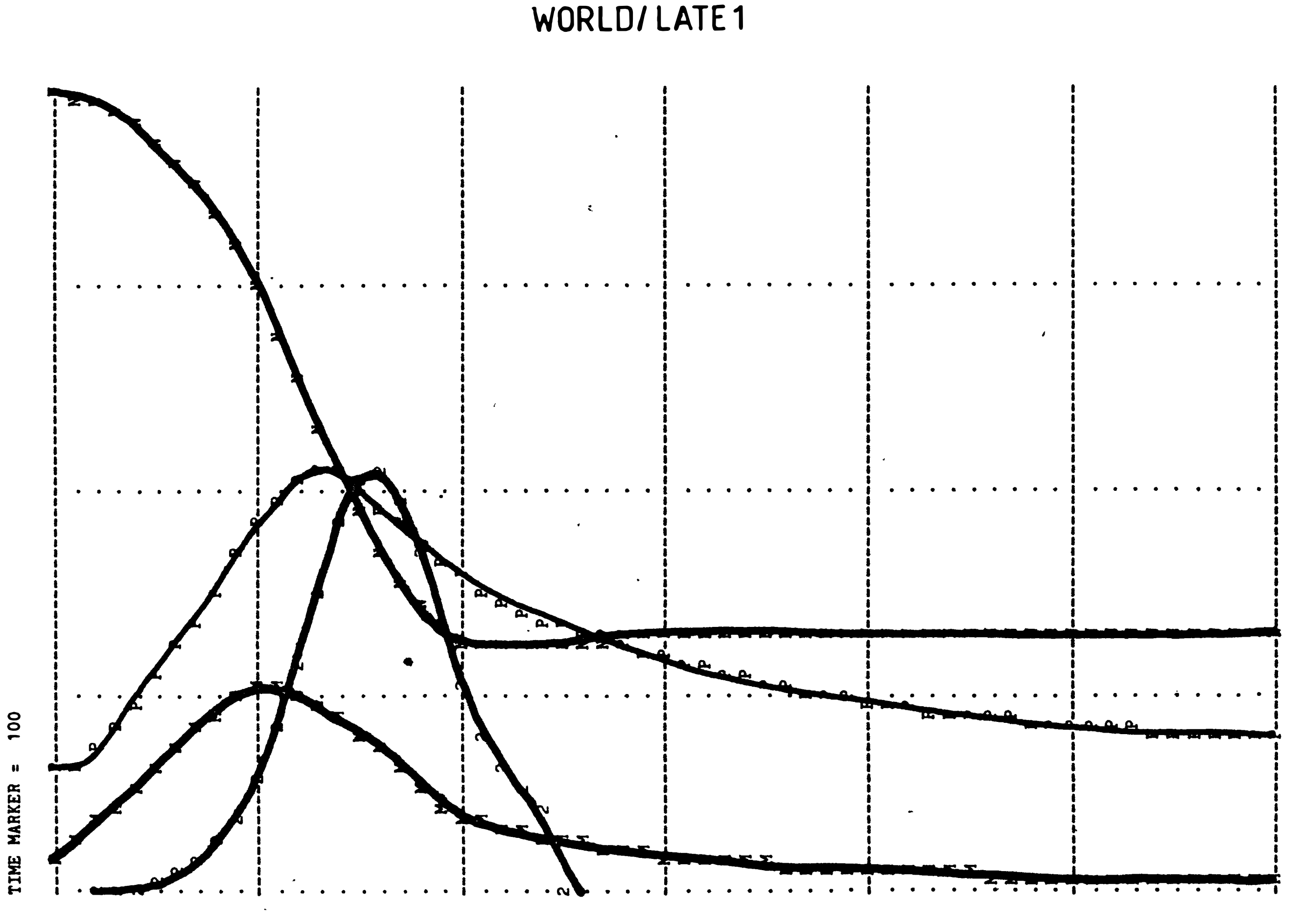

Fig. 7. The result of a 50 year delay in implementing the high technology solution.

to provide substitute materials and finished goods. There is thus no need for the per capita energy requirement to be geographically associated with that person. More locally required energy can be met, even on a global scale, with a level of energy generation capacity similar to that in existence today, if we discount the industrial requirements.

This removal of energy generation to space has another effect, this time in the pollution sector. At present the bulk of air pollution (carbon dioxide, carbon monoxide, silicon dioxide, trace elements and fly ash) is the result of burning fossil fuels for energy production purposes. In addition, about 95 per cent of all the spoil waste products by the mining industry is a by-product of coal production. With reliance on a coal energy economy in the future this percentage will not change, but the total amounts produced will.

Thus we can see another benefit of the use of space resources:

- Space is an infinite sink for pollution.

In principle then, the age of substitution could be supported by a high technology, energy intensive industrial base in space, reducing the impact of such a technological drive on the Earth to a minimum.

8. THE AGE OF SPACE EXPLOITATION

There is still a step missing in the above argument, however. The shipment of raw materials from Earth to space for processing is, in itself, as difficult to envisage as the ground-based energy production scenarios, and the transportation technology involved in such an enterprise would, in all probability, be a highly polluting one.

The missing factor is provided by the realisation that, if we are maintaining a technology base in space, then we must also take into account one further attribute of space:

- Space is an infinite source of natural resources.

The raw materials that our industries need will all be found in space, with an essentially infinite abundance. This will be true for metals, liquids and volatiles alike. Beginning with the Moon and Earth approaching asteroids, progressing to main belt asteroids, and finally to the exploitation of other moons and planets, mankind will reach the stage where the resource base is unlimited.

The effect of this situation upon life on Earth is shown in Figure 6. The concepts of substitution of scarce resources, forcing a reduction in natural resource usage in 2050, coupled with reduction of the pollution levels in 2100, are still in force. However, after a period of around 150 years, about 2300, the vicious circle of a closed system is broken as mankind truly begins to exploit the Solar System. Resource availability is now essentially unlimited rather than finite. The effective natural resource level available to the Earth can actually increase (at a rate of 5 per cent in the example shown here; the rate is not central to the argument, or the end result, however). There are no limits to growth, in terms

of potential for expansion, only limits to how this growth can proceed and to how far the system can absorb such growth.

For the first time we find that the population *and* the material standard of living are increasing. This is even the case for the population during the 150 years after 2050, where the resources and standard of living are essentially static.

At the year 2500 the population is just over nine milliard, and the standard of living is five times that of 1984. Pollution is also starting to rise again. However, the figures must be interpreted with some degree of freedom here. If we have increased the resource base by moving out into space, then the population levels must be considered as being the total on Earth and in space together. The pollution will be mainly generated in space by the mining and manufacturing areas. The increase in material standard of living is relevant to the society at large, and not just to that portion of it which still inhabits the surface of the Earth.

It is now the Solar System model which we should be investigating, and not the world model. The potential for the expansion of mankind is almost literally infinite.

9. CONCLUSIONS – A CRITICAL PERIOD FOR MANKIND

We must now sound a note of caution over the optimistic outlook that we have just described. Figure 7 shows the effect on the world model of a late application of space exploitation and the high technology solution which assumes:

- Natural resource usage changed at 2100.
- Pollution changed at 2150.

The consequences of a 50 year delay in the application of remedial measures results in barely any improvement over the standard model results – a situation that is implicit in the output from that model, in that by 2100 the decline in natural resources and the maximum levels of pollution have already indicated a decrease in the population and the standard of living. The population is only some 30 per cent higher in 2500 (2 milliard, compared with 1.5 in the standard model). Although the standard of living is about four times higher, it is still seven times lower than in 1984.

In this sense, then, Forrester and the Meadows group are perfectly correct. Depletion of natural resources will cause an end to population growth and prosperity. There is a point of no return, after which the society will not be able to recover to its previous standard.

We saw in Section 5 that too early an application of remedial measures could lead to disaster (in that case, a pollution crisis). Here we see that one can also be too late in attempting corrective action. There is, therefore, a critical period for mankind during which time measures are necessary in order to avert a decline away from the levels our society has reached.

The models are not precice enough to identify this period accurately. Using the above figures for reduction in resource usage rate and pollution levels, however, they suggest that change of the resource base much before 2040 leads to a pollution crisis, and that delay until much after 2070 results in falling population levels as a result of resource depletion. Although these dates must be treated with a certain amount of flexibility, it is clear from the results of the computer simulations that the high technology solution which promises a complete and final break away from any limits imposed over our growth must be implemented during this period if it is to be a feasible and workable solution.

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Paper presented at Space '84, Brighton, England, 16-18 November 1984, organised by The British Interplanetary Society.

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WORLD SHIPS: PROSPECTS FOR NON-NUCLEAR PROPULSION AND POWER SOURCES

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A number of options for non-nuclear propulsion and power for world ships are investigated, after it is demonstrated that the minimal world ship will have a mass comparable to that of an O'Neill Model III space habitat. World ship acceleration from a hyperbolic solar orbit using high performances and baseline solar sails is evaluated. A more effective form of propulsion is to utilise a solar-electric rocket and giant-planet gravity assists to propel the world ship on a photosphere-grazing trajectory. During the interstellar cruise phase of the voyage, which will most likely be longer than 1000 years, on-board power could be provided by a perforated solar sail or a light sail windmill. Initial world ship deceleration can be accomplished by electrostatic drag techniques. For velocities below 0.0008c, world ship deceleration can be accomplished using a perforated solar sail pointed towards the destination star. Finally, certain aspects of world ships demography are considered. As an alternative to very small initial populations or a steady-state population level maintained throughout the interstellar voyage, a moderate initial population of a few thousand can be allowed to gradually increase to the 100,000 people or so necessary to begin development of the destination star system.

1. INTRODUCTION

The world ship as an interstellar space habitat is a significantly greater undertaking than the interstellar ark. An ark, such as thosed based upon the early work of Shepherd and Strong [1, 2], would carry hundreds of people to the stars on flights requiring 100-1000 years. Living conditions within the ark would be, of necessity, artificial.

Bernal's early work on world ships [3], which are larger space communities containing tens of thousands of people in "natural," Earthlike conditions, has recently been expanded upon by O'Neill, de San, and Martin and Bond [4-8]. These miniature planets, which would be totally independent of terrestrial and solar-system civilisation, would be equipped to develop a variety of habitats within the target star system. Total duration of a world ship's voyage could be several millenia.

In the publications previously cited, it is assumed that the only available propulsion option for world ships is the thermonuclear pulse rocket, such as the Helium-3/Deuterium drive proposed for the unmanned Daedalus probe. Grant, however, has suggested that the solar drives recently suggested for interstellar ark propulsion could be adapted by world ship designers [9].

With the assistance of Eugene Mallove, we have previously explored the utility of solar propulsion and power sources for interstellar arks. Utilising close solar flybys, high-performance solar sails and payload subdivision, an ark can be accelerated to Alpha Centauri on a trajectory requiring less than 1000 years [10, 11]. Application of solar-electric drives, perforated solar sails, and planetary gravity assists can reduce the flight times required for a small interstellar ark to reach Alha Centauri to about 800 years [12-14]. The light sail windmill can be utilised to supply on-board power during the long interstellar transfer [15-16].

The analysis presented here applies similar non-nuclear technologies to supply the propulsive and power requirements of world ships. We first present an attempt at the calculation of the size of a typical small world ship.

2. THE SMALLEST WORLD SHIP

To estimate the size of the smallest world ship, we utilised Ref. 17. On p. 173 of this reference, it is noted that as a space community's size approaches diameters of several kilometres and individual land areas of 100 km^2, cosmic-ray shielding provided by the habitat's structure, land area, and atmosphere becomes great enough that such extra shielding is not required.

For a cylindrical habitat with length L/radius R = 10, (such as O'Neill's designs [4] and those presented in Fig. 3-4 of Ref. 17),

$$2\pi RL \approx 10^2$$

or (1)

$$20\pi R^2 \approx 100,$$

TABLE 1. Population Densities of Several terrestrial Locations (1984 Data).

Location	Area	Population	Population Density
Channel Islands	194 km^2	130,000	670 km^{-2}
Gibraltar	6	30,000	5000
Malta	320	360,000	1125
Monoca	1.9	27,000	14211
Bermuda	53	55,000	1038
Barbados	430	254,000	591

TABLE 2. World Ship Cable and Sail Parameters Used to Calculate Figs. 1 and 2.

	Baseline Sail	Perforated Sail
Areal mass thickness	6×10^{-5} kg/m^2	1.2×10^{-6} kg/m^2
Emissivity	0.5	0.47
Reflectivity	0.9	0.63

Cable = Diamond
Density = 3.52×10^3 kg/m^3
Tensile strength = 5.3×10^{10} N/m^2

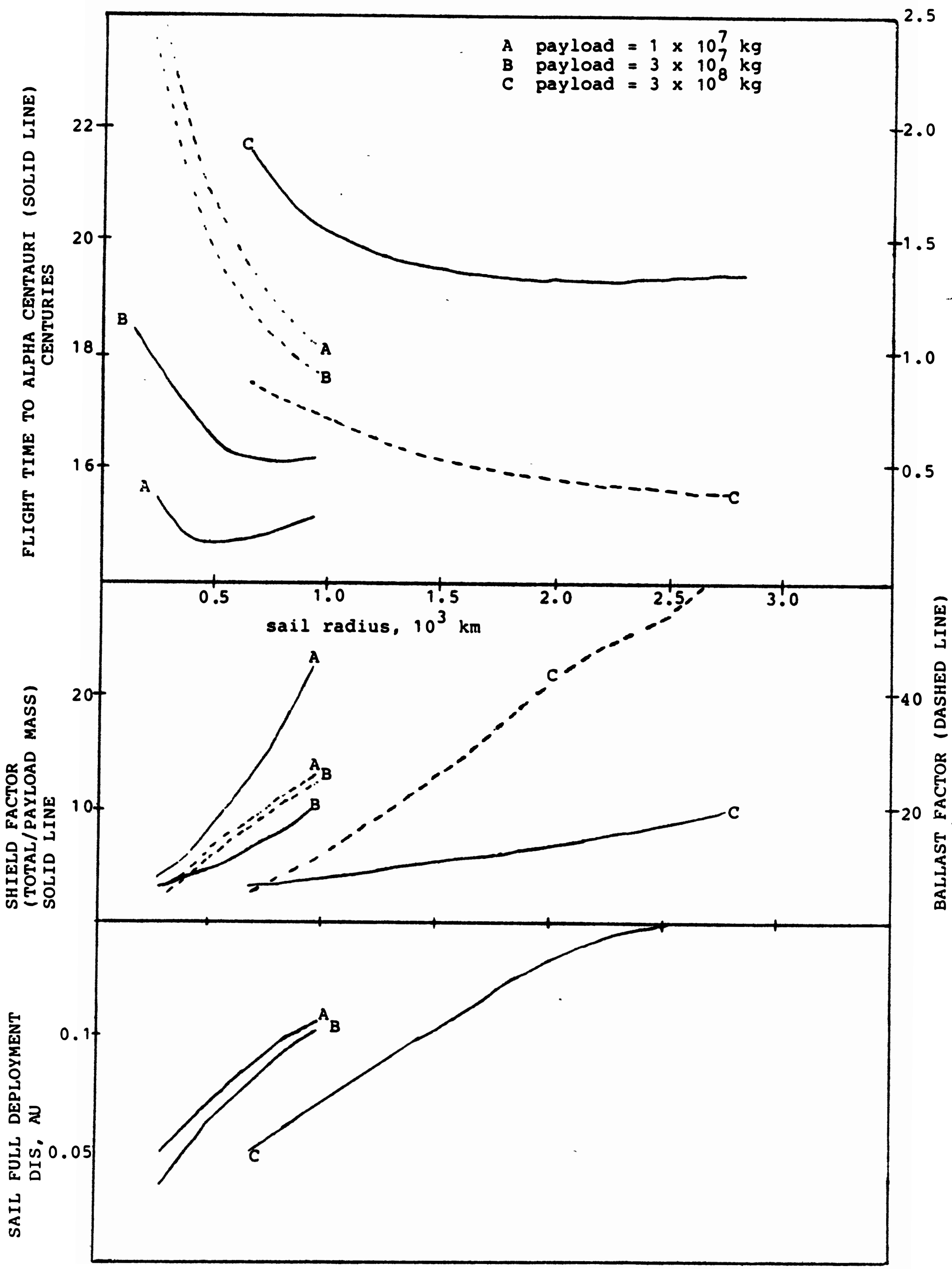

Fig. 1. Performance characteristics of the baseline solar sail accelerating payloads from hyperbolic 0.01 AU perihelion solar orbits.

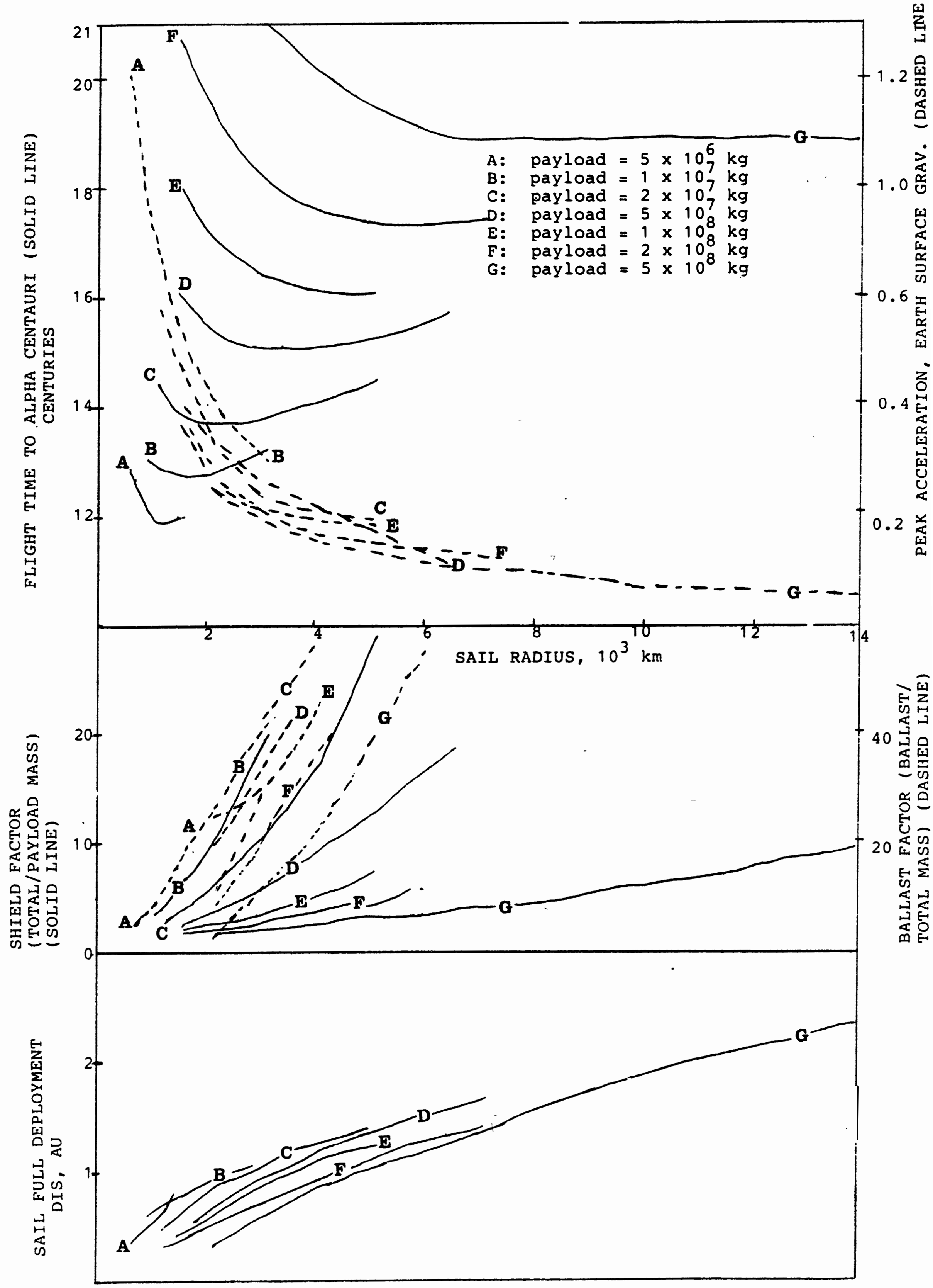

Fig. 2. Performance characteristics of the perforated solar sail accelerating payloads from hyperbolic 0.038 AU perihelion solar orbits.

where R and L are both measured in kilometres. Thus, R $\approx$ 1.26 km and L $\approx$ 12.6 km satisfies the requirement for no additional cosmic ray shielding. From Fig. 4-3 of Ref. 17, a wall thickness of 1 m for an aluminium wall is suitable for the cylinder's shell. This is close to the wall mass thickness requirement calculated using Fig. 2 of Ref. 7.

The shell mass can be estimated for a cylinder with two end caps:

$$M_{shell} = 2\pi RL\rho + 2\pi R^2\rho, \qquad (2)$$

where R and L are here measured in metres and ρ is the shell mass density in kg/m^3. For a one metre aluminium shell, ρ = 2700 kg/m^3 and $M_{shell} \approx 4.7 \times 10^{10}$ kg, which is close to the 5×10^{10} kg mass of an O'Neill Model III Space Habitat [4].

This mass allotment must be taken as very approximate. Reduced apparent gravity or increased population density would decrease the mass; internal atmosphere, soil, and water would increase it. Dimensions and depth of internal water bodies and atmospheric density and composition (if not Earth sea level standard) must be taken into account by world ship designers.

From Chap. 3 of Ref. 17, we see that the minimum size for a world ship's population is $\sim 10^5$ people. For a 10^2 km^2 surface area, the population density is approximately 10^3 people/km^2 within the world ship.

This population density is 3-4 times greater than those reported for representative industrialised nations listed in Ref. 8. Demographic data, presented in Table 1, indicates that a population density of 10^3 km^{-2} is not uncommon is some island nations or territories [18].

The projected population density is considerably less than those observed in cities or towns or projected for early space colonies [17]. Space colony designers could reduce the apparent population density still further using such techniques as constructing underground homes for the inhabitants. People residing in world ships with a 10^3 km^{-2} population density will therefore not be deprived in terms of living space.

We next turn our attention to the acceleration of world ships utilising solar sails.

3. SOLAR-SAIL ACCELERATION FOR WORLD SHIPS

We will consider solar-sail accelerations of world ships which have been accelerated towards the Sun at hyperbolic excess velocities of 0.0006c (180 km/sec). It has been pointed out that voyage duration for world ships in unaccelerated (parabolic) pre-perihelion trajectories are prohibitively long [19].

In Figs. 1 and 2, we present the performance of the baseline high performance and perforated solar sails, as discussed in Refs. 11 and 13. This data has been generated for sail and cable parameters listed in Table 2, using the optimisation programme in Ref. 11.

As in Refs. 11-13, the shield factor is total starship mass (payload + cable + sail)/payload mass and the ballast ratio is ballast mass/total mass. Note that the largest payloads considered are 5×10^8 kg, which corresponds to an O'Neill Model 1 mass allotment. With a shield factor of 10, the total mass would amount to one O'Neill Model 2. Post-perihelion rendezvous of 10 of these starships would be required to construct a world ship.

Note that the use of the perforated sail results in trajectories a few centuries shorter than application of a baseline sail for the same payload. Perforated sails are larger than baseline sails for similar payloads. For the largest payloads considered, sails of planetary dimensions are required for voyages of about 2000 years duration to Alpha Centauri.

The solar sail clearly becomes less effective as the payload mass is increased. Because of the necessity to accelerate the sail towards the Sun (probably using an electric rocket [12], we have investigated the possibility of dispensing with the sail entirely during the perihelion pass and utilising a solar gravitational assist. This approach, which is further discussed in the following section, is not payload-mass dependent, does not require payload subdivision and post-perihelion rendezvous, and dispenses with the requirement for ballast mass.

4. SOLAR GRAVITY ASSISTS AND PRE-PERIHELION ACCELERATION

To consider the effects of a close solar flyby with no perihelion acceleration upon a world ship's interstellar cruise velocity, we start with Eqs. (3) and (4) of Ref. 14.

$$e_p = \left(\frac{V_p}{V_{cp}}\right)^2 - 1 \qquad (3)$$

and

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

In Eqs. (3) and (4), e_p is the eccentricity of the approach hyperbola, V_p is the world ship velocity at perihelion, V_{cp} is the circular velocity at perihelion, and V_∞ is the post-perihelion world ship velocity.

We can combine Eqs. (3) and (4) to obtain:

$$V_\infty = V_{cp}\,\left[\left(\frac{V_p}{V_{cp}}\right)^2 - 2\right]^{1/2} \qquad (5)$$

Since $V_p = 1.4\,V_{cp} + \overline{\Delta V}$, where $\overline{\Delta V}$ is the pre-perihelion hyperbolic excess, Eq. (3) can be modified to:

$$V_\infty = (2.8\,\overline{\Delta V}\;V_{cp} + \overline{\Delta V}^2)^{1/2} \qquad (6)$$

Because a high perihelion circular velocity produces a high post-perihelion cruise velocity, it is advantageous to minimise the Sun-spacecraft separation at perihelion. In Refs. 10-12, we considered a 0.01 AU perihelion distance after Ehricke [20]. The perforated sail considered in Ref. 13 can operate at a perihelion distance of 0.038 AU.

We might consider operating at a Sun-grazing perihelion distance of 0.005 AU if the world ship were shielded from solar irradiance. Solar-irradiance shielding has already been considered in the design of the "Starprobe," an unmanned mission to 0.02 AU from the solar centre planned for the 1990's [21]. An aluminium shield with dimensions 20 km x 2 km and a width of 0.01 m would have a mass of 10^9 kg, about 2% of the total world ship mass.

The closest reasonable perihelion approach distance is a few thousand kilometres above the photosphere, just above the top of the chromosphere. There are approximately 10^{15} atom/m^3 at such a location, which is at the base of the solar corona [22].

At closest approach, the particle drag deceleration on the world ship, $\dot{V}_d$, can be estimated:

$$\dot{V}_d = \dot{M}_p V_p / M_s \qquad (7)$$

where $\dot{M}_p$ is the particle mass encountered each second, V_p once again is the world ship's velocity at perihelion and M_s is the world ship's mass. Assuming most of the particles are

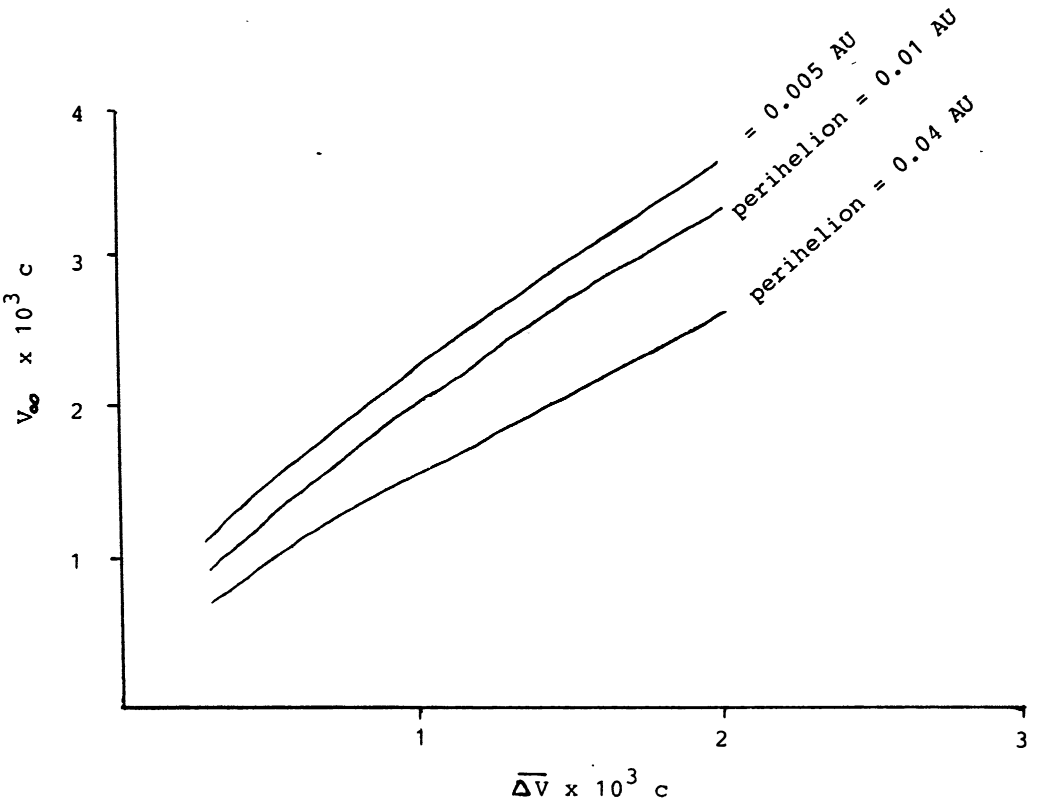

Fig. 3. Interstellar cruise velocity V_∞ *versus* hyperbolic excess at perihelion, for three perihelion distances. Solar sails or other non-gravitational acceleration devices are not deployed at perihelion.

hydrogen atoms or protons,

$$\dot{M}_P \approx 1.67 \times 10^{-17} A_C \rho \text{ m/sec}^2 \tag{8}$$

where ρ is the particle density in m^{-3} and A_c is the world ship's cross sectional area in M^2 along the line of flight.

Assuming $M_s = 5 \times 10^{10}$ kg and $A_c \approx 6 \times 10^6$ m² from Section 2 of this paper, $\dot{V}_d \approx 2 \times 10^{-16} V_p$. If $V_p = 0.003c$ ($\approx 10^6$ m/sec), $\dot{V}_d \approx 2 \times 10^{-10}$ m/sec². For a three-hour perihelion duration the world ship's velocity will decrease by less than 10^{-6} m/sec due to coronal drag.

The shield temperature during a 0.005 AU perihelion pass can be estimated utilising the arguments presented in Refs. 10 and 11. For a 0.01 m thick shield, an emissivity close to 1.0 and a reflectivity of 0.9 do not seem unreasonable. If the angle between the normal to sunlight and the shield is 45°, the peak shield temperature will be about 1300°K. For a composite partially metallic shield this temperature is not unmanageable.

In Fig. 3, we present solutions of Eq. (6) with V_∞ plotted *versus* $\overline{\Delta V}$. Circular velocity at perihelion, V_{cp}, has been calculated for perihelion distances of 0.005, 0.01, and 0.04 AU. For a perihelion pass of 0.01 AU, a hyperbolic excess of 0.0015c results in an interstellar cruise velocity of 0.0027c. The same hyperbolic excess velocity for a 0.005 AU perihelion pass results in an interstellar cruise velocity of 0.003c.

To obtain a pre-perihelion hyperbolic excess of 0.0015c (450 km/sec), we might consider combining giant planet gravity assists with an electric rocket. As discussed in Ref. 14, gravity assists by Saturn and Jupiter can accelerate a spacecraft moving towards perihelion by more than 50 km/sec.

The additional 400 km/sec required by the world ship before perihelion can be supplied by an electric rocket similar to the one considered in Ref. 12. This rocket has an exhaust velocity of 200 km/sec. From the rocket equation, a 5×10^{10} kg spacecraft accelerating from rest to a velocity of 400 km/sec using this motor requires about 3×10^{11} kg of fuel.

If the world ship accelerates under electric propulsion for 10 years, it exhausts about 1000 kg/sec of electric rocket fuel. Assuming a constant acceleration rate, the energy required is about 2×10^{13} watt. For an electric thruster-system specific power of 1 kg/kW, as in Ref. 14, the thruster-system mass will be 2×10^{10} kg. The acceleration will be 1.3×10^{-3} m/sec² (1.3×10^{-4} g Earth). During the acceleration run, the world ship will travel approximately 6×10^{13} m, or about 400 AU. Assuming a 10% conversion efficiency of collected solar energy to thruster exhaust kinetic energy we find that an 8×10^4 km radius solar collector is required to provide the thruster energy. The collector radius could be decreased as the ship accelerated sunward.

The perforated solar sail considered in Ref. 13 has an areal mass thickness of 1.2×10^{-6} kg/m². If this sail material is utilised as the world ship's solar collector, the mass of the solar energy collection system will be about 2.4×10^{10} kg.

Thus, we see that currently foreseeable technology can propel a 5×10^{10} kg mass to 0.003c utilising giant planet gravity assists, electric rocket acceleration, and a solar gravity assist during a 0.005 AU perihelion approach. Only 10% of the mass, equivalent to an O'Neill Model 2 space habitat, would be useful payload mass during the 10-year pre-perihelion acceleration run. The balance of the mass could be utilised for shielding and structure during the post-perihelion phase of the flight, as the O'Neill Model 2 is

expanded into an O'Neill Model 3 habitat.

As a less extreme case, let's examine a 5 x 10^{10} kg world ship accelerated to 0.001c (300 km/sec) using this 200 km/sec exhaust velocity electric rocket. The fuel mass required to achieve this velocity is approximately 1.7 x 10^{11} kg. If Jupiter and Saturn are used to increase world ship pre-perihelion hyperbolic excess to 0.00117c, Fig. 3 indicates that the post-perihelion velocity for a 0.005 AU perihelion distance will be 0.0025c. Approximately 1700 years will be required for a voyage to Alpha Centauri.

For a 20-year duration electric rocket acceleration period, the thruster will exhaust 300 kg/sec. The energy required for thruster operation will be 6 x 10^{12} watt and the constant world ship acceleration will be 5 x 10^{-4} m/sec^2 (5 x 10^{-5} g Earth). During acceleration, the world ship will travel about 600 AU. The thruster mass is 6 x 10^9 kg.

A 10% energy conversion efficiency for energy collected from a $\approx$ 6 x 10^4 km radius perforated solar sail (as in the above case) satisfies thruster energy requirements. The sail-collector mass will thus be approximately 1.6 x 10^{10} kg. Thus, for this less extreme case, less than 50% of the total world ship mass is required for thruster and sail-collector.

A further reduction in thruster and sail-collector mass is possible if grazing flybys of Jupiter and Saturn are used instead of the 2-planetary-radius flybys considered in Ref. 14. The combined increase in velocity from these two planets for 1-planetary-radius flybys is, from the analysis presented in this section and in Ref. 14, approximately 95 km/sec.

For an interstellar cruise velocity of 0.0023c, which results in an $\sim$ 1800 year flight time to Alpha Centauri, a perihelion pass of 0.005 AU requires, from Fig. 3, a hyperbolic excess at perihelion of about 0.001c. Thus, if 200 km/sec is provided by an electric rocket with a 200 km/sec exhaust velocity, 1.7 times the world ship's mass, or 8.5 x 10^{10} kg is fuel.

If this fuel is exhausted over a 20-year period at 140 kg/sec, 2.8 x 10^{12} watts must be supplied to the thruster. The mass of the thruster (assuming 1 kg/kW) will be approximately 3 x 10^9 kg.

Assuming a 10% energy-conversion efficiency as before, the sail radius will be about 4 x 10^4 km and the (perforated) sail mass will be about 8 x 10^9 kg. Thus, the combined thruster-sail mass for this configuration will be less than 25% of the total world ship mass.

Obtaining electric rocket fuel should not be a major problem, at least conceptually. As Oberg has noted [23], oxygen can be utilised as an electric rocket fuel. This element will be quite abundant in the Oört comet belt where the world ship will begin its sunward drive.

As electric-drive technology improves, we can expect some corresponding performance improvements. It seems unlikely, however, that the time required to reach even the nearest star by a world ship can be reduced below a millenia. Therefore, some consideration of world ship power sources during the long interstellar cruise is in order. World ship power options for the cruise phase are considered in the following section.

5. WORLD SHIP POWER FOR THE CRUISE PHASE

In Ref. 16 we considered various non-nuclear options for supplying power to an interstellar ark during the cruise phase. It was estimated that 10^4 watt/person are required. For a peak world ship population of 10^5 people, this corresponds to a peak power requirement of 10^9 watt.

We could certainly provide this power from spacecraft kinetic energy, since a 5 x 10^{10} kg spacecraft moving at 0.003c has a kinetic energy of $\sim$ 2 x 10^{22} joules. This is about 1000 times greater than the total energy required by the crew during a 1000 year voyage. Electrostatic and electromagnetic techniques for partially converting ship kinetic energy to satisfy cruise power requirements have been considered [24, 25].

If spacecraft deceleration during the cruise phase is undesirable and nuclear techniques are not utilised, we can investigate utilisation of the perforated light sail and the light sail windmill [16]. Light sail calculations will assume, as in the last section, a 10% energy conversion efficiency, and a Sun-world ship separation of two light years (1.26 x 10^5 AU).

Since 1400 W/m^2 is the incident solar energy at the orbit of the Earth [22], the power available from a 3 x 10^4 km radius perforated solar sail two light years from the Sun will be $\approx$ 2 x 10^7 watt. This could supply the energy needs of 2000 people. Of course, it would be preferable to utilise the sail for cosmic ray shielding during the interstellar cruise phase. We will therefore turn our attention to the light sail windmill considered in Ref. 16.

The specific energy of this windmill is 3 x 10^{10} joule/kg. During a 10^3 year interstellar cruise, 3 x 10^{19} joule of energy are required to support 10^5 persons. The required windmill mass is therefore about 10^9 kg, which seems quite reasonable. Perhaps the sail could be utilised to produce some illumination. Most power requirements would be satisfied by the windmill.

Late in the mission, when deceleration at the target star begins, there will be ample energy for the world ship's population. Details of the final interstellar phases of the world ship's trajectory are considered next.

6. DECELERATION UTILISING ELECTROSTATIC DRAG

As the destination is approached, deceleration of the world ship will commence. Although electromagnetic deceleration is possible [24], the large effective field radius of an electrostatic scoop will render it superior [25].

From Ref. 26, the world ship's deceleration under electrostatic or electromagnetic drag can be written:

$$\dot{V}_e = \frac{-1.6 \times 10^{17} A_S \rho_i V_e^2}{M_S} \text{ m/sec}^2 \tag{9}$$

where A_s is the effective scoop area, ρ_i is the ion density of the interstellar medium, and V_e is the spacecraft velocity during acceleration. Substituting $\dot{V}_e = dV_e/dt$, we can integrate Eq. (9) between the interstellar cruise velocity V_o and V_t, the velocity after electrostatic deceleration time $\overline{\Delta T}$:

$$\overline{\Delta T} = \frac{M_S}{1.67 \times 10^{-27} A_S \rho_i V_o} \left[\frac{V_o}{V_t} - 1\right] \tag{10}$$

In Fig. 4 we present solutions of Eq. (10) for M_s = 5 x 10^{10} kg, ρ_i = 5 x 10^4 m^{-3} [24-26], and two values of scoop field radius. The cruise velocity is 0.003c. The 3 x 10^5 km radius scoop is greatly superior to the 10^5 km scoop. The larger scoop radius requires approximately 200 years to decelerate from 0.003c to 0.0008c.

Note that electrostatic deceleration becomes less effective for lower velocities. A world ship utilising a 3 x 10^5 km scoop radius decelerates at 3.5 x 10^{-4} m/sec^2, at V_e = 0.001c.

From Section 8, of Ref. 25, we see that such low accelerations pose no problem to the operation of the scoop. The scoop charge would be about +20 coulomb, with a much smaller negative charge on a 5 x 10^5 km long 10^{-5} m diameter cable in front of the spacecraft.

For the final stage of interstellar deceleration, it is possible to use a partially unfurled perforated solar sail. Details of this approach are considered next.

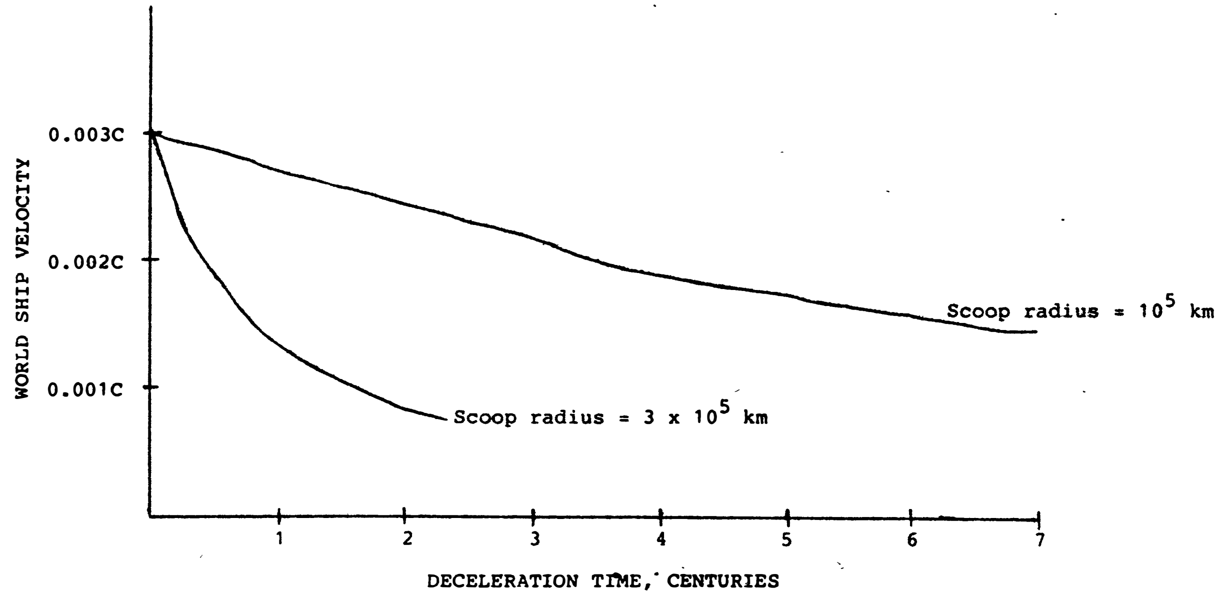

Fig. 4. Initial deceleration of a world ship using an electrostatic drag sail.

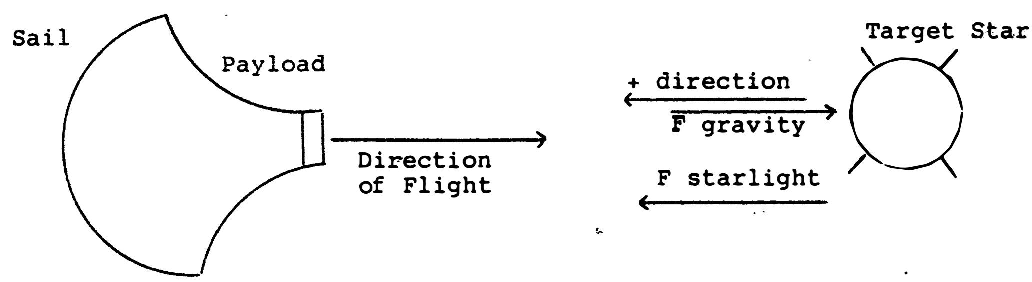

Fig. 5. Schematic of final world ship deceleration using light pressure.

7. STOPPING A WORLD SHIP USING A SOLAR SAIL

In the final stage of world ship deceleration, it will be assumed that the spacecraft is pointing directly towards and decelerating towards the target star (Fig. 5). Our derivation of final world ship deceleration begins with a modification of Eqs. (3) and (4) of Ref. 10:

$$F_{net} = \frac{1+\kappa}{2}\,\frac{6.3\times10^{17}\,R_S^2}{r^2}\,L.F. - \frac{G\,M_{star}}{r^2}\cdot M_S \qquad (11)$$

where F_{net} is the net outward force on the solar sail, κ and R_s are respectively sail reflectivity factor and radius, r is the separation between the target star and the sail, G is the gravitational constant, M_{star} is the mass of the target star and L.F. is the ratio of target star/Sun luminosity.

For a partially transparent solar sail [13],

$$\kappa = R_a/(R_a + A_a), \qquad (12)$$

where R_a and A_a are the fractional reflection and absorption for incident light. For an entirely opaque sail, $k = R_a$.

Remembering that

$$F_{net} = M_S\dot{V}_S = M_S V_S \frac{dV_S}{dr} \qquad (13)$$

where V_s is the velocity during this final phase of the interstellar trajectory and $\dot{V}_s$ is the acceleration, we can integrate Eq. (11) to obtain:

$$V_f = \sqrt{V_c^2 - \frac{2}{r_f M_S}\,(J - GM_{star}\cdot M_S)} \qquad (14)$$

where $J = (1+\kappa)/2 \times 6.3 \times 10^{17} R_s^2$ (L.F.). In Eq. (14), V_f is the final velocity; V_c has been defined in the previous section.

If we set $V_f = 0$, Eq. (14) can be manipulated to obtain:

$$r_f = \frac{\frac{1+\kappa}{2}\cdot 6.3\times10^{17}\,(L.F.)\,R_S^2 - G\,M_{star}\cdot M_S}{V_c^2\,M_S} \qquad (15)$$

which is the approximate distance from the target star at

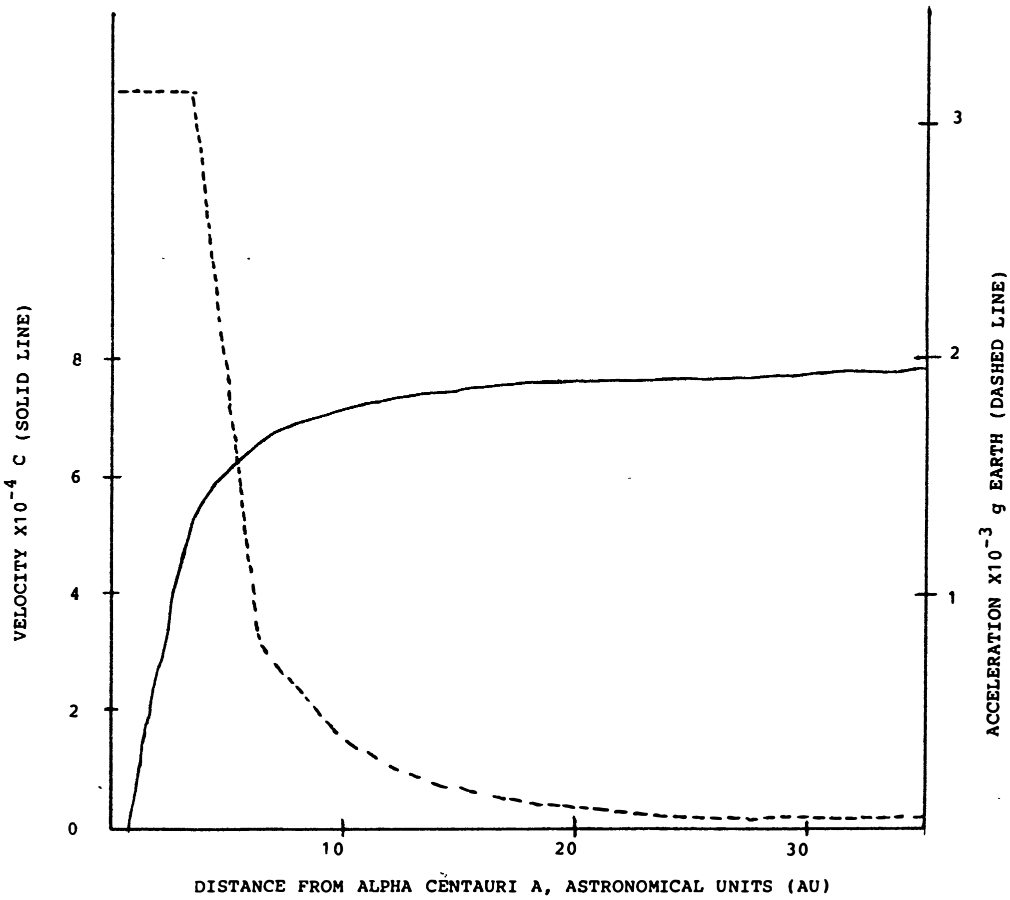

Fig. 6. Kinematics of final world ship deceleration using light pressure.

which the sail will come to rest relative to that star. Now, if r_f is substituted back into Eq. (11) for r, the peak acceleration of the world ship can be calculated during the final deceleration phase.

For sufficiently high decelerations, very high or negative cable masses can result. The cable mass, M_c, can be calculated using Eq. (15) of Ref. 10:

$$M_C \gtrsim \frac{1.4\,\rho_C R_S M_P}{\dfrac{\eta}{\dot{V}_{S_{max}}} - 1.4\,\rho_C R_S} \qquad (16)$$

where M_p is the payload mass (total mass – deployed sail mass – cable mass), ρ_c and η are cable density and tensile strength and $\dot{V}_{s_{max}}$ is the maximum deceleration experienced by the world ship during this trajectory phase. In the case analysed here, ρ_c = 3.52 x 10^3 kg/m^3 and η = 5.3 x 10^{10} Newton/m^2, the values for diamond [10].

After a number of experiments utilising a short interactive program on the Pratt VAX computer, we arrived at a configuration capable of decelerating a 5 x 10^{10} kg world ship, with a pessimistic κ = 0.5 and a perforated sail 3 x 10^4 km in radius from V_c = 0.0008c. The target star was assumed to be Alpha Centauri, with L.F. $\approx$ 1 and M_{star} = M⊙ = 2 x 10^{30} kg [10]. (For other stars, L.F. and M_{star} can be related LF $\approx$ $(M_{star}/M⊙)^{3.5}$, as discussed in Ref. 22).

Velocity and deceleration for this configuration, calculated utilising Eqs. (9-14), are presented in Fig. 5. We assumed acceleration to increase to a peak at 3.5 AU from the destination star, at which point V_s = 5.29 x 10^{-4}c and $\dot{V}_{s_{max}}$ = 3.15 x 10^{-3}g Earth. Between 35 AU and 0.7 AU from the destination star, where the world ship comes to rest, the sail is furled or detached to maintain constant acceleration. The cable mass, from Eq. (14), is approximately 4 x 10^9 kg.

We therefore see that stopping a world ship utilising passive techniques requiring no fuel is quite feasible. In the conclusions below, we review some of our results and consider certain aspects of the world ship society.

8. CONCLUSIONS

We see, therefore, that non-nuclear propulsion and power sources are quite feasible for 5 x 10^{10} kg world ships that can survive a millenia-long interstellar mission. Shorter duration missions may well prove feasible since, as Cesarone *et al* have demonstrated [27], solar-type stars occasionally approach the Solar System at distances considerably less than the present-day distance to Alpha Centauri.

Gravitational acceleration by giant planets and the Sun combined with solar-electric rocket at pre-perihelion acceleration seems superior to the solar sail as a method of launching world ships from the present-day Solar System. Electric rocket power requirements during acceleration are ~ 10^{12} - 10^{13} watts. The perforated solar sail and the light-sail windmill are both candidates for supplying power during the interstellar cruise phase.

No matter what nuclear or non-nuclear approach is utilised to accelerate a world ship, no additional fuel is required to stop it at the destination star system. A combination of an electrostatic drag sail and a perforated solar sail are adequate to the task.

Some attention must be paid to the demography/sociology of the world ship's population. Grant has taken an initial look at this with his constant-population model based on the

Club of Rome approach [9]. Holmes considers Grant's to be a worst a "worst-case" scenario [28].

Recently, Jones has considered an interstellar expedition beginning with a population of only 25 and expanding to fill the limits of the available resources as the mission proceeds [29]. Although this may be an extreme case, there is ample evidence that some prehistoric terrestrial migration, notably that of the American Indian over the Bering land bridge during the last ice age, contained small, genetically uniform pupulations [30].

Also, a world ship on an interstellar trajectory should not be thought of as a totally isolated sociological and genetic entity. Because of its predictable trajectory and resource pool it may instead be viewed as a tempting target for visits by interstellar arks and fast star ships.

One way of alleviating problems with a large constant population throughout the voyage would be to start with a small population and allow development of habitat resources as the population expands.

An initial population of 1000 expanding at 30% per century, will reach 10,000 after about nine centuries and 100,000 after about 18 centuries. If the expansion rate for the same population is increased to 50% per century, the population will rise to 10,000 after six centuries and 100,000 after 12 centuries.

During the initial generation, at least, the genetic material available to the population could be supplemented by utilising frozen embryos and sperm, or similar approaches. As the population rises and the target star system approaches, it may be wise for the population to expand into an occupied, undeveloped twin of their world ship, to begin honing the skills they will need to develop the target solar system.

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A RATIONAL GOAL FOR MANKIND: PROGENITIVE CONCEPTION

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This article presents a planetary model of development which could explain Fermi's paradox on the absence of extraterrestrials on Earth. It also proposes a long term strategy to solve mankind's problems of overpopulation, pollution, etc., and to prepare fruitful and peaceful relations with eventual extraterrestrial civilisations.

1. INTRODUCTION

In the evolution of mankind, only growth is considered as a valuable concept, and although some development schemes do not exclude it, it is probable that long term stability or decrease of world population would lead to the ultimate elimination of our species through holocaust, suicide, or otherwise. Growth may be a condition of survival, but on the other hand, most recent views agree also on necessary limits for stellar civilisations such as ours. With a very optimistic approach of growth development, long term forecasts of the world population lead to impossible figures: with the smallest growth rates, the human mass would equal that of the Earth in a few thousand years, and the mass of the Galaxy in a few million years. Thus, with strict growth control, we would ultimately arrive at a dead-lock issue which may be termed as "Fermi's reverse paradox" (Where are we to?). Even if it were possible, galactic colonisation is a false solution to long term overpopulation, and a peaceful attitude towards extraterrestrials would be to progressively reduce growth to zero in order to maintain human expansion within our own system. As growth seems vital, so, is human intelligence doomed to death anyway?

Looking the other way (expansion from the Galaxy to the Earth), such a peaceful attitude may be confirmed by the absence of extraterrestrials on Earth, as expressed by Fermi's known paradox ("Where are they?"). Considering the age of the Universe and the star population of our Galaxy, extraterrestrial visitors should already have colonised the Earth, colonisation of the whole Galaxy requiring again a few million years. This seems obvious if we admit that life is a common natural process, even if little credit is attributed to such statistical evaluations as those given by Drake's equations.

Where are they? This apparent paradox is generally met with answers such as: superiority of human over extraterrestrial intelligence; lack of interest of extraterrestrials for colonisation; self-destruction of stellar civilisations through uncontrolled technological development resulting in pollution, nuclear conflicts, etc. Looking at the Earth, self-destruction could be an answer, but extraterrestrial coherent beings may also have decided to limit colonisation within their own-systems. As growth seems vital, then, has extraterrestrial intelligence been doomed to death anyway?

Finally, are relations with extraterrestrials only possible on a conflictual basis? This is difficult to admit. It is also hard to accept that human intelligence is condemned to die without leaving any trace, and that after our death, the process of intelligence development will begin all over again with a new species, without any reference system to transmit the experience already acquired by man. Aiming at immortality or at least wishing to leave some posterity, a more attractive goal for mankind would be to prepare a reference system destined to the next intelligent species reappearing after us, and we may expect the same aspirations from other extraterrestrial civilisations.

2. A RATIONAL GOAL FOR MANKIND

Since the beginning of the Space Age, we have reached a technological level which could be regarded as a potential threat by extraterrestrial civilisations. Unlimited growth leading not to survival, galactic colonisation would be regarded as incoherent and agressive, and would not be tolerated. Conflictual relations should not be risked, and mankind should prepare these relations on a rational basis in view to avoid wrong messages. Extraterrestrials will not await human colonisation of the Galaxy to react, and after Voyager's raid out of the Solar System, it is not too soon to care about the image we are presenting to galactic observers, and to the form of messages we are going to address. Relations between mankind and extraterrestrials should not be conducted on a cultural, but only on a rational basis, and this means that all messages shall be confirmed by well established facts, and by the rational image of our civilisation. For instance, our peace talks will not be convincing if we have been unable to develop a growth model to solve our populational, relational and ecological problems. If we are not wanted as partners, we will be either ignored, or smashed if we represent a potential threat to the galactic community.

Being compelled to limit growth within our own systems, how are extraterrestrials and ourselves going to foster our aspirations for posterity and for relations with all other intelligent beings in the Galaxy and beyond? Taking into account all preceeding considerations, as well as man's instinct for growth, we can imagine another model of development for mankind, which would allow fruitful and peaceful relations with eventual extraterrestrials, as well as a rational issue to man's yearning for immortality, or at least to posterity. And again, we may expect extraterrestrials to have developed such a model before we start to do it.

3. PROGENITIVE CONCEPTION

Growth is vital to man, but it seems that its actual concept is leading mankind to disaster through overpopulated areas, uncontrolled pollution, depletion of natural resources, etc. Much more could be done to reduce these ills, but seen at the very long term, there is no solution with our present notion of growth. As we should limit growth within our system – that is, the Earth, or the Solar System if it is confirmed that we are the only intelligent species within it – we must not forget that space and energy are limited in any system, even if much can be done in optimisation and

if there is anyhow no problem for the next few thousand years. It could be argued that there is plenty of time to think about! But long term projects shall be initialised long before, to prepare the technology and the conditions which are to be vital to their ultimate realisation. As man is aiming at immortality, what about a few thousand years! And how are we going to convince extraterrestrial observers that we will be able to stop growing in due time?

Still, growth is essential to survival. Without it, life would probably not be worth living. So, is there no issue for mankind with or without growth?

When we think of mankind's posterity, we only look at a distant future, at an old and developed mankind. But in current life, mankind prepares its posterity well before death, and gives birth to an inexperienced being. It roughly consecrates the first part of life to becoming adult and conceive progeny, the second to assist and bring it up, and both generations live soon separately and independently. Why should mankind await the end to prepare posterity? As mankind's existence within the Solar System will come to an end, we can imagine to divide it into two cycles of development, the first one consecrated to growing up and progenitive conception, and the second to assistance and education of the new-born species.

Growth being a condition of survival and bearing also in itself a destructive potential, these cycles of development could be made independent. Thus, abortion of one cycle should not jeopardise the whole process, and posterity could be assured even if mankind is to disappear because of growth problems. If we are wise enough to prepare such a model of separate link development, intelligence should then become immortal once realised.

Progenitive conception could in itself be a sufficiently attractive goal for future generations, but the realisation of such a project would also open new perspectives to mankind's yearning for immortality, or at least to further development. In giving birth to a new species, mankind could also be born to a new existence in another reference system.

4. PROGENITIVE GRAFTING

The problem is: how is mankind going to realise progenitive conception? What kind of reference system will we transmit to a new selected species in order to save the experience acquired by man after mankind's death, and how are we going to elaborate separate environments allowing individual development of the new species, and of mankind as well?

The choice of the appropriate species is similar to a horticultural selection: only parent plants are suitable for grafting, and an advanced animal species such as gorillas seems the most appropriate to receive human grafts. But what kind of reference system shall we use to obtain a genuine progenitive grafting?

This question cannot be answered with present scientific knowledge, but science is advancing rapidly in all directions. If serious progenitive grafting cannot yet be considered, it will certainly become possible in the long term, after expected progress in scientific domains such as biology, medicine, computers, etc., and after mankind's intelligence synthesis has been realised in a reference system.

For this reference system to be grafted on the new species, we can imagine a sort of memory containing all the expereince acquired by mankind, and destined to be used as a "mirror" brain to compare past experience images with the images of current life registered by the normal brain. The behaviour of the new being would be guided by a compromise between both brains, the final behavorial decision belonging to the normal brain. The new being would thus not be dispensed from acquiring his own experience, but he would also dispose of a reference system to balance his decisions and prevent him from going too much astray. The mirror brain would anyway remain inactive in the absence of personal experience, thus leaving the new individual total freedom. On the other hand, cerebral discomfort would be felt if the mirror brain's views are ignored.

5. INTELLIGENCE SYNTHESIS

How would we proceed to elaborate this reference system and to transform it into a biological mirror brain? Only future science will answer this question; but taking into account all preceeding considerations on growth, and actual scientific tendencies, we can imagine the following scenario.

Suppose that our present technological development continues at a reasonable pace, that medical sciences progress (replacement of organs, members, etc.), that we learn to know how our brain really works – then we can imagine a time (in a few hundred years?) when man has lost his biological structure, i.e. has become totally technological. This could be reached without any loss of personality if care is taken concerning the preservation of individual history.

Such technological beings would have a computer-like brain and could then associate themselves (marry!) to form collective beings. This kind of marriage could intervene between candidates in love: for instance, two partners decide to "marry," i.e. to wholly invest themselves in the "construction" of a third being who would be the synthesis of both. This would be possible with technological beings when all information (souvenirs, knowledge, sensibilities, etc.) contained in their brains are already under the form of binary data. A protocol established prior to marriage may agree on the elimination of redundant data for the new-born who is the only one to be left alive, both partners being "cannibalised" through its birth. Furthermore, this new-born collective being could also associate with other simple or collective beings to form more complex beings, and we can imagine that this process continues to include whole communities, nations, or even mankind as a whole, thus reversing the actual course of overpopulation.

Such collective beings would require little energy, and space and interstellar travel would be facilitated. To reduce the risks of such adventures, they could even be "duplicated" or "stored" through pure technological means for renewal in case of accidents in the short term. And we can imagine that in a few hundred years, science will make possible the conversion of technological-to-biological data. Such a synthesised intelligence could then be integrated into a mirror brain grafted besides the normal brain of an advanced animal species. Progenitive conception would then be realised.

6. SEPARATE DEVELOPMENT

Progenitive conception would be aimed at assuring mankind's progeny, and not at acquiring robots. As there is no place for two intelligent species in a closed environment, only separate link development is possible. Living with mankind, the inferior beings would never develop, but would remain animals or robots, and separate link development would therefore be a condition of development for the new species. This should not exclude initial surveillance and corrective interventions, but separation should become more effective as intelligence grows, and to accentuate it, man should be considered as an ideal model (God!) by the new species. Mankind's progeny would anyhow not be able to have a clear conscience of its origin and should be totally free to acquire experience through responsibility.

7. CONCLUDING REMARKS

Progenitive conception might well be a normal step in Nature's rational progress to more complexity, a step as common as the fecundation of flowers by insects or bees, but an intelligent step for the human species. Mankind might be the result of such a chain development, and extraterrestrial civilisations as well. This could elucidate Fermi's paradox on the absence of extraterrestrials on Earth, and the reported unwillingness of eventual extraterrestrial visitors to engage relations with us: we are not interesting partners as long as we remain biological beings! Communication between collective and biological beings would almost be impossible, harmful to mankind's development and anyway prohibited by mankind's progenitors. Furthermore, such a model of development would not be in contradiction with present knowledge in science and history, philosophies and religions, traditions and legends, etc. It would be a solution to most problems of mankind, and make possible peaceful and fruitful relations with extraterrestrials for further intelligence synthesis in the Galaxy and beyond.

Following old pretentious human traditions, we could also claim that man is the one and only fruit of the Universe, and that the present model is new in an eternal system. But on a rational point of view, it would anyway offer the same potentialities!

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FAILURES, SETBACKS AND COMPENSATIONS IN INTERSTELLAR EXPANSION

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Interstellar colonists and explorers will be vulnerable to accidents, vehicle fires and plagues, and because of their isolation and limited numbers may not be well placed to deal with their effects. The inhabitants of recently-terraformed planets, and of the large vehicles known as world ships will be particularly vulnerable, because of the immensity of the task of correcting climatic excursions in their mastable environments, following damage by fires wars and other disasters. Experience gained in successfully dealing with colonial disasters may be usable in Solar System emergencies.

1. INTRODUCTION

There has never been a time when exploration was a safe activity, or one when pioneering in engineering has been a reliable route to wealth. From the earliest times ships have been lost, commercial ventures have failed and seamen and traders, surveyors and test pilots have died in horrifying ways. Progress has always been inordinately expensive.

This gloomy picture will certainly continue into space, and into interstellar expansion if that follows. Some of the failures of every size of space vehicle and habitat which must be expected will be due to errors in design, or to unappreciated defects in materials, in controls and in suitability for new purposes. These failures will be a simple continuation of the grisly history of aircraft. There will also be failures of kinds which are well known on Earth, but take on a special importance in the space environment, and failures of kinds not known on Earth. By their very nature, it is not possible to list all of these. This paper is meant to give a non-exhaustive survey of some dangers which can be foreseen, operating either at the level of threats to the survival of an interstellar colonisation venture or at that affecting a single vehicle and its contents.

Interstellar travel and colonisation will be marginal activities for many, if not most, of the societies which have to pay for them. Consequently the causes of ruin discussed below are considered to be taking place in an isolation in which there is no prospect of unpremeditated help. Marginal activities are always vulnerable when spending is cut, so during the decades, or centuries, needed for the smallest interstellar project reversals of decisions and changes in policy are to be expected. The ships, and settlements, discussed below must be thought of as existing in physical isolation, linked to prosperous civilisations by communication links that take several years for an exchange of question and answer, and the settlements as having been established by a succession of projects, with gaps between, rather than by a coherent development.

2. FAILURES AFFECTING INDIVIDUAL INTERSTELLAR VEHICLES

Irrespective of whether they travel alone, or in company interstellar vehicles of every size will be liable to failure from internal causes. Loss of a single vehicle in a fleet may be bearable, but loss of several can only be a damaging setback for the expedition of which they form part. Planners will try to make loss of several vehicles from a single cause, within a short time, as unlikely as possible. There are several causes which will constantly threaten destruction.

2.1 Conflict Aboard

Interstellar spacecraft will be as far from civilised authority as the ships of Henry Hudson and Captain Bligh. If some person, of group of persons, attempts to usurp authority aboard, the remainder of the crew will have to choose between submitting, with all the dangers that that is likely to lead to, and resisting the usurpers with whatever weapons they can find at hand. This is, perhaps, the greatest threat to long-duration spacecraft with small crews. The usurpers may have become mentally disturbed, or have gone through religious conversions during the voyage, or in a spacecraft which is in flight for more than a human life they may belong to factions which have separated out during the education of children born aboard. The only remedy for conflict of this sort seems to be to choose crew carefully, if the flight is one of a few years or decades in a relativistic vehicle, and to make certain that the number of persons travelling in a slower expedition is large enough for help to be available from other ships when the problem becomes apparent.

2.2 Structural Decay

Rust and corrosion will affect the interiors of spacecraft, residential habitats and O'Neill colonies alike. The very fact that they are meant to carry human beings, or the animals that man shares the Earth with, will mean that their internal atmospheres carry water vapour, and probably salt. That will not make much difference in habitats and O'Neill colonies within the Solar System, where the inhabitants are always within reach of large manufacturing capacity, but interstellar craft will have no easy means of repair, and will have to tolerate decay for much longer.

An unmanned interstellar ark [1] of the sort which will have to be used to carry ecological communities for use in "terraforming" barren planets, may take 500 years or more to reach its target star. That is a time equal to that which separates us from Columbus. Very few mechanisms survive from Columbus' time, and those which do are not in daily use. By the time that it arrives, an ark may still have an exterior structure, and propulsion and control areas, in near-new condition, but all parts to which life has access will be worn, rotten and encrusted. Some of the parts of the ark which are worn, rotted and encrusted will never have been intended to be reached by life from the cargo, but will have been contaminated accidentally, for example, when disinfecting chambers for robotic attendants broke down.

After some centuries of unmanned flight, the interior of an ark may be very different from its state when it started.

If all has gone well, the differences will be of an understandable and straightforward sort. Trees will have grown bigger, and new ones will have seeded. Bridges used by the people who established life in the ark will have rotted and fallen, and artificial rocks will have become covered by real lichen. Alternatively, a forested interior may have been replaced by a sterile, fire-blasted heath, or a few species only may survive in an atmosphere far from Earth-like. The first thing that settlers entering an unmanned ark must do will be to assess its condition, and the likelihood that it will be fit for some centuries, at least, of further use. Many arks may not be.

2.3 Fire

There is no form of travel, no building and no vehicle on Earth which is not threatened by fire. Fires in ships, aircraft, factories and refineries kill hundreds each year, and forest fires in time of drought often devastate large areas.

An immense amount of attention is given to preventing fire, and to minimising its effects, but ruinous fires still happen.

Fires will certainly happen in space. The danger of fire is so great that no designer will neglect it, but fires of all sizes will happen in spacecraft and arks, just as they happen among the ships on Earth's present seas.

When a fire takes place in a confined space, with less than some hundreds of feet of headroom, the heat produced cannot escape, and the structure surrounding the space becomes the wall of a stove. That simple statement is a well-known rule on Earth, and the equally simple principle that the presence of large amounts of combustible material in a fire allows the fire to become larger is equally well-known. Between them, these childish phrases sum up the reasons for some of Earth's greatest disasters. The Great Fire of London and the Great Fire of Chicago are two examples of conflagrations in which whole districts of cities burned in "a single flame," as radiant heat from an already out of control fire set light to wooden houses and stores of hay and straw. In these great open air fires the temperature goes higher than in smaller outbreaks, and an air circulation pattern develops with flames rising in the centre and winds rushing in around the edges, blowing the fire like a forced draught. If there is a roof over a fire, hot air cannot escape and radiant heat is reflected downwards, with strange and horrifying focussing effects.

Spaceships will be liable to fire in much the same way as sea-going ships and aircraft. The absence of gravity may help to prevent fire spreading in them, but there is some reason to believe that there are fire-oxygenating processes which are not gravity-dependent. Most of the currently-proposed space habitats, O'Neill colonies [2] and interstellar spacecraft will be vulnerable.

Within the Solar System, this vulnerability will not be fatal, although it may be distressing. O'Neill [2] gives some attention to this point. He suggests that the fire hazard may be minimised in a space colony by a combination of lush green vegetation in a colony interior with buildings of non-burning materials similar to brick or cinder block on Earth, and with reduced atmospheric pressure, large total volume and plenty of water.

Other investigators are less concerned. Some suggest that housing in space colonies may include large amounts of aluminium [3]. Many designs for space colonies and interstellar vehicles contain structural aluminium in contact with internal air.

Aluminium is a marvellous structural metal, but it has two large faults. It melts at 660°C, and softens below that temperature. Also it has such a voracious appetite for oxygen and burns so relentlessly in air once it is lit that it is very difficult to put out an aluminium fire.

It will not be possible to make the interior of an O'Neill colony, or an interstellar vehicle based on one, completely balanced ecologically. Instead, its vegetation will grow under conservatory-like conditions, and there will be little or no destruction of dead wood. With abundant carbon and water available from carbonaceous chondrite asteroids and the outer Solar System there seems to be no reason why the "wilderness" areas of an established space colony should not carry as much biomass as present day woods and forests.

There are two aspects to fire on Earth. Much of the surface of Africa, for example, is swept by grass fires that do little or no immediate harm, but carry fire to tangles of grass and trees which have not been visited by fire for many years. That can result in a "hot burn," which destroys trees and shrubs as it blazes. Great precautions are needed in all the warm countries of the Earth to prevent fire from devastating homes, towns and villages. They are not always successful.

If the "wilderness" areas of a long-established space colony or world ship, or the whole interior of an unmanned "ark," carries the same combustible biomass as a temperate forest on Earth, it may have as much as 500 to 1000 trees to a hectare, and a combustible biomass of 250 or 300 tonnes to a hectare. That is quite sufficient, on Earth, for a fire during a drought to cover large areas with glowing charcoal and to ignite structural aluminium. If a town or village with a moderate amount of wood and aluminium in its buildings is set fire to by a forest fire, it may blaze hotter and longer than the forest.

On Earth most of the heat produced is lost by dilution, in a large volume of air, as the combustion products rise and entrain surrounding air. In a space colony there may be much less dilution. "Gravity" and buoyancy fall off sharply with height above "ground" in a space colony design of less than nation size, and both up-draughts and down-draughts will be much affected by Coriolis effects, which interfere with the formation of the ring vortices that are the main means of entrainment on Earth. There is no question of a total failure of dilution and heat dispersion, but it seems that a fire in a medium-sized space colony may produce more local heating than one on Earth. Even although the heat capacity of the atmosphere, on one side, and the artificial regolith and hull on the other, may be large enough to absorb the entire output of the fire, transfer to them may be so inefficient that the fire heats its immediate surroundings more strongly than on Earth. The immediate surroundings are, therefore, more likely to blaze themselves, and the conditions governing spread of the fire are the little-known ones applicable to hot fuel surfaces, rather than the cold ignition ones which rule fire regulations on Earth.

Unless great care is given to the interior detail of a space colony, or large interstellar vehicle below world ship size, there is a danger that reflections from surfaces which acts as mirrors for infrared radiation may add up to give hot spots which spread fire, or even cause structural damage by melting. There is a great temptation to use modular techniques in building, so that a few conventionalised roof angles, for example, repeat indefinitely. Surfaces which are parallel to the local direction of "gravity," or at 15°, 30°, 45° and 90° to it, or to the local "land surface," are likely to appear throughout any habitat or space colony in which there is no deliberate attempt to avoid them. The surfaces which are usually given to metal sheets, or even painted walls, are quite smooth enough to reflect infrared. If a large vehicle, or small colony, has an internal shape which is more or less cylindrical, or toroidal, with spherical or ellipsoidal end-caps in the cylindrical case, careless installation of buildings, imitation rock surfaces, roads and internal structure may provide a focussing mirror for infrared heat.

If there is a large fire in one of the internal towns of a world ship or an O'Neill colony, it may be accompanied by

secondary forest fires, miles away from the original blaze. If there is an extended forest fire, similar to those which have recently taken place in South Australia, reflecting surfaces may combine momentarily to act in reverse manner to a bad telescope mirror. They can so concentrate perhaps 1% of the heat of a widespread fire into a small area, just as the mirror smears a star image into a blob. Concentrated heat of this sort may melt through structural members.

Such effects can, of course, be avoided by making the interior of the spacecraft rough on a variety of scales, with convex infrared-scattering surfaces wherever possible. That will result in the heat of a fire being directed into as large a fraction of the interior as possible. If the spacecraft is large, that may be enough to prevent any disasterous effects to the vehicle as a whole, but considerable areas may be devastated.

A small habitat or colony can, of course, be fitted with a local cooling system to fight fire, probably using the same sprinklers which provide the "rain." Just how effective such a system can be expected to be is doubtful. The amount of heat generated by burning buildings in a large town fire is likely to overload any local cooling system which depends on mixing with the general colony atmosphere or circulation of hot air through radiators, and the alternatives of bleeding off hot air, and substituting cold air from a store, and spraying the whole interior of the colony with enough cold water to suppress satellite fires seems likely to be almost as damaging as the fire.

When an O'Neill colony in the Solar System suffers a major fire, it will certainly have other colonies within reach. There will be emergency evacuation agreements between colonies of the same political unit, and perhaps more widely, so that the inhabitants can be evacuated until the fire is extinguished, the interior surface cooled, the structure checked for damage and the life support system rehabilitated. There will be very little difference between the effects of such a fire and those of a natural disaster on Earth. An explorer's habitat in another planetary system, or an isolated O'Neill colony, will have no such opportunity. Its people will have to evacuate into spaceships, with the strictly limited opportunities and habitability time of any crowded transport, and try to save their home themselves. Explorers may be forced to return early by losses of this sort, even with extensive robotic help available to help them rebuild.

Fires in unmanned arks converted from annular or small-diameter habitat designs will be even more devastating. They will take place in spite of precautions taken by the designers to rule out any possible cause of fire, and their unforeseeability will make it difficult for robotic control mechanisms to deal with them. Arks with temperate forests in them are probably the most vulnerable, but any ecology which includes, or is threatened by, forest fires on Earth will be liable to destruction in any ark which is less than 100 metres or so in air-filled radius or annular radius. Even if the unmanned arks travel in company, and have robotic crews capable of mimicking a human level of decision making, it will not be possible to evacuate wild animals and plants while the fire is dealt with. Fires may come about by spontaneous combustion of plant matter heaps, as they do on Earth, or by friction of tree branches, and static electricity sparks are likely to be as common, and as lethal, as they are on Earth. Also the robotic attendants may cause electrical fires, or scrape aluminium feet on rusty steel, as they age and wear out mechanically. They may try to repair ark systems, and start fires with their welding equipment, as human workmen do.

2.4 Modal Changes

The interior of a space habitat or world ship [4] which mimics surface conditions on the surface of the Earth will, of necessity, be a highly artificial environment, which needs constant attention to prevent it from reverting to a simpler and less desirable state. Its Earth-normal atmospheric pressure will, in the larger world ships, be accompanied by a considerable fall-off in atmospheric pressure with height. In normal operation it will be a transparent atmosphere, through which a considerable light and radiant heat flux passes on its way to heat the inner surface. The interior surface will, in its turn, give off as much infrared radiation as an Earthly land surface, but there will be no way for that radiation to escape into space. Instead, the world ship will have infrared absorbing surfaces in its central structure, shielded from the light sources which are also mounted in the central structure. World ships which do *not* have central structures, such as the "Valley and Sky" and the "Three Continent" one with shielded light sources in islands in its seas, will also have to have absorbing surfaces if they are to avoid an unearthly overheating.

The lowest kilometre or so of atmosphere will have rain, mists and thermal upcurrents, sea breeze effects and at least some clouds. They are unlikely to have cumulonimbus clouds in normal circumstances, but large town and forest fires will be as likely to start thunderclouds as they are on Earth, and these will include powerful up-draughts and down-draughts.

On Earth the largest thunderclouds burst through the tropopause into the stratosphere, where they decay to spread ice particles and, in some cases, entrained dust and smoke.

The well-known "Nuclear Winter" scenario for the destruction of Earthly civilisation [5] does not depend primarily on injection of light-blocking dust and smoke into the stratosphere by nuclear explosions, but on the carrying up of great amounts of smoke and dust by thunderclouds caused by fires. Large volcanic eruptions also trigger cumulonimbus activity, and both the original outbursts and the clouds dump numerous kinds of slow-settling particle into the stratosphere, so that eruptions of the very large size sometimes found in the geological record rival nuclear war as a potential destroyer of the present planetary civilisation.

A world ship will not, of course, have a stratosphere, but it will have a central zone in which "gravity" is low, and scavenging of suspended particles is not efficient. When fire-caused thunderclouds dump ash and smoke into the atmosphere of the world ship these are likely to reach greater heights than can be accounted for by the buoyancy of their carrier clouds. The intense up-draughts and down-draughts in the clouds will cause gentler compensating movements that are not purely convectional, and these will be enough to move at least some of the particles distributed by decay of the thunderclouds into the central zone. Neither thunderclouds nor formation of a particulate haze in the central zone will be a normal feature of the world ship, and it is unlikely that many of the people aboard will have seen either effect in their lifetimes.

A particulate haze in the central zone of a world ship is likely to include particles larger than any that remain suspended in the stratosphere of the Earth, and unless it is artificially removed it is likely to be persistent. The particles will intercept light and heat from the central sources which the haze surrounds, and a smaller amount from any off-axis sources. They will also intercept re-radiated infrared from the whole of the interior land surface, and direct radiation from any continuing fires. Both kinds of infrared will be focussed into the haze, in the manner of a furnace. As a result the particles, and air containing them, will be strongly heated, and a strong, stable inversion will be produced in the atmosphere of the world ship.

Unless the particulate haze is removed within a few days, the drastic blanketing of light at the surface which it causes will damage plant life severely. In the worst case, the haze may thicken after its establishment, as the largest ash particles disintegrate on further heating. There is a possibility of a reversion from the lighted, transparent-atmos-

phere, land surface-heated convective mode which is the habitable one to a stratified, smoggy, ill-lit non-convective one in which the "land" on the inner surface of the outer shell receives little light or direct heat, and is eventually chilled by loss of heat into the low-temperature hull. Neither human beings nor the plants and animals of an Earth-type ecology are likely to survive such a change.

If such an ecology-damaging, or ecology-destroying, change of internal mode is to be prevented from going to completion, processing of several thousand cubic kilometres of atmosphere within a few days may be needed. To do this in the presence of continuing fires without creating damagingly strong winds, it will be necessary to provide many inlet and outlet vents in the central structure, where they can clear the low-gravity central zone, and probably in the land surface of the outer shell as well.

During the long flight of an unmanned ark there will probably be a few occasions when internal fires threaten the survival of its cargo. Ability of the ark and its robotic crew to overcome these threats will be a critical requirement.

3. FAILURES AFFECTING ESTABLISHED INTERSTELLAR COLONIES

When an interstellar colony is fully established, it will no longer be vulnerable to the murderous or crazed acts of individuals in the same way as in its early days. The surface of a terraformed planet will be large enough, and well-enough forested, to allow thousands or millions of people to escape from the most efficient dictator. Nuclear war will always be a menace, as it is and will be to Earth, but it will be a threat that is hardly different in kind or degree from that with which present-day people are familiar.

There are, however, some possible causes of extinction of a planetary colony which are shared with Earth, but may be more devastating under colonial conditions.

3.1 Volcanic Eruptions

In spite of a century and a half of geological surveying, it is not possible to say with any confidence how many dangerous volcanoes the Earth has, or to forecast eruptions. Written history is only some 5,000 years old, and in that time the greatest outburst that has been identified was the Bronze Age explosion of the Greek island Thera. That appears to have done considerable damage to the Minoan civilisation of Crete, and may be the cause of the Atlantis legend. More recently the Indonesian island volcanoes Tambora and Krakatoa have filled the whole atmosphere of the Earth with dust, and have caused crop failures as far away from Indonesia as North America. There are plenty of signs of still greater eruptions in the geological record, and the largest of these must have darkened the Earth for months and caused large die-offs of vegetation. They still threaten the Earth, but there is some comfort for its inhabitants in their infrequency: there are gaps of 500,000 years or more between such eruptions.

Planetary settlers on a terraformed planet will have no comforting statistics to contemplate. Their planet will probably have had its current unloaded of a deep atmosphere during "terraforming," and may have suffered deliberate asteroid impacts and the start of previously-unknown continental drift. These may result in violent volcanic activity on a planet with no previous record, and blight its plants and people a few hundreds of years, or a few millenia after its settlement.

3.2 Population-threatening Epidemics

From time to time, on Earth, a new disease appears and sweeps through the whole human race. Bubonic plague once killed a quarter of the population of the Earth in a few years. There are vague records of other great plagues (some of which may, in fact, have been bubonic plague), but for really devastating epidemics (or rather epizootics) one must turn to animals and the fossil record. One example is the great rinderpest epizootic of the 1980's, among cattle and hooved animals in East, Central and Southern Africa. After the rinderpest had passed through, there were huge areas with no cattle and no hooved game, until restocking from untouched territory.

Epidemics and epizootics can certainly cause extinctions. Until the early years of this century the Tasmanian Wolf (alias Tasmanian Tiger, or Thylacine) was in no immediate danger of extinction, although a bounty was paid on it as a stock killer. Then the number of claims fell, and the bounty was ended to avoid encouraging killing a creature which had become a rare animal. A disease much like distemper had appeared among the Tasmanian Wolves, and killed so many that the animal was soon announced to be extinc.. (There have been many sightings of single Tasmanian Wolves since, including some recent ones, and from time to tine one is photographed. Apparently the disease flares up again if their numbers rise beyond some critical density, and that density is very low. Announcements that the Tasmanian Wolf is extinct are almost as common as reports of sightings.)

If an animal population is cut by disease, and is affected by some form of predation, competition or exploitation which does not fall off with its numbers, it may easily become extinct. The Tasmanian Wolf is so attractive to zoologists that they, alone, are a major menace to it as they search the bush, and disturb the animals and their prey. Similarly many African populations of elephants have become extinct because of the killing of the survivors of an epizootic. An elephant is such a prize to a hunter that he will follow a single animal, even an immature one, for weeks until he gets a chance to kill it. Even if the elephant is the last one in the district, it offers some thousands of pounds of meat for use or sale in a continent where most of the people hunger for it.

Several extinctions and local extinctions of the past are suspected to have been due to epizootics. The extinction of the American horse in both North and South America, in territory so suitable for horses that a few introductions by Spanish explorers soon turned into great feral herds, impressed Charles Darwin [6]. Some of the extinct animals of the Americas may have been destroyed by Palaeo Indian hunters, but the animals which have become extinct in the Americas in the last 15,000 years have included not only the wily, wary horse but several forms of elephant, the American lion and cheetah, large camels and rhinoceroses. All of these have survived, in spite of hunting, in other parts of the world. Other extinctions have affected Siberia, where the present animal life is much less rich than in the past, although the population seems too sparse to have destroyed all that have vanished. Even at the present day there are tigers in Siberia, and there are tales of their crossing over the ice to Alaska in the 19th century. The quick end of these immigrants is explainable by their fur, but the fact that no tigers of pre-gun centuries established themselves in Alaska needs explanation. It is at least possible that the reason is to be found in some local reservoir of a tiger-killing infection, much as certain farms cannot keep cats, because they are infected with "cat flu." Certainly both lions and tigers are liable to fatal infections at the present day, both in captivity and in the wild, and there is every reason to believe that the severest of these may break out from small areas in the same way as human influenza, and spread until they reach a sea crossing or an area barren of possible victims.

There is, also, a possibility that Man once became extinct in the New World as the result of epidemics which either did not affect the Old World or had a much smaller effect

there. Long before the incredibly worked Clovis and Folsom points were used to kill mammoths and giant bison, there were people in Northern Canada, and probably further south, who used simpler weapons. There is very little evidence of their culture, for their stone tools have been found in small numbers only, and usually in settings that are hard to date. Some bone tools from Northern Canada have been carbon dated: these people were certainly hunting in Canada 25,000 years ago, and they may have entered North America long before that. In spite of the human tendency to breed freely, these early Canadians seem to have been a sparse, scattered people, who left no great accumulations of tools, such as are found in Africa and in the gravels of Europe. They seem to have never increased beyond a modest number, and may have vanished altogether some time before the Palaeo Indians crossed from Siberia.

There may be an explanation for this, and a warning for interstellar settlers, in the varying susceptibility of human races, groups and individuals to particular diseases. Some of that is due to the absence of immunity in populations never before exposed to a disease, as with the ravages of measles among American Indians and of syphilis among Europeans after 1492. A part, however, is certainly due to the intricate polymorphism of the human race, as that is expressed in blood groups, in tissue types and in such matters as being able to smell or taste particular chemicals. That polymorphism has survived in such detail shows that each variant must carry a benefit in some circumstances, so that they survive in roughly constant ratios. In other circumstances, they have correspondingly important disadvantages. Human polymorphism, and the polymorphism of animals, is inherited genetically, and half-serious investigators have suggested that such improbabilities as a "music gene" (or high musical ability precondition gene) can be identified in the Bach family, or scientific ability among the Struves.

The dark side of polymorphism can be seen in differential susceptibility to particular diseases, including both infections and deficiency diseases. Far too many people live on the edge of malnutrition, and far too many suffer recurring gastro-enteritis. Children who have an inherited susceptibility to these are more likely to die of them, although they may have advantages in other ways if and when they live to grow up.

The early Canadians are likely to have been descended from a small group, who wandered widely, among abundant game and wild foods. At that time there were no boats, as were used by later imigrants across the Bering Straits to reinforce their numbers again and again, so the early Canadians' ancestors probably crossed the Straits by some unlikely ice blockage, or on a land surface later submerged by the rising sea. In either case, the genetic base of the crossing party, and so of their descendants, was probably very narrow indeed. If they had a tendency to die of some animal-carried disease, rather than suffer and recover, or to develop scurvy easily, that tendency, and the vulnerability that goes with it, will have been passed to most groups of their descendants.

Interstellar colonists are likely to have a narrow genetic base, for the same reasons, and the populations which they build up will be more uniform than any on Earth. This effect has been made use of in Science Fiction: in one well-known novel the time travelling hero finds most colony planets of the future populated by human beings who are all clones of a few selected types. For safety's sake, a few "wild type" planets are kept as sources of new varieties. Real life interstellar colonies are not likely to be quite as uniform as these fictional ones, but they may be uniform enough to suffer plagues which affect all, or almost all, of those who fall victim to them to a single, devastating degree. The rich polymorphism which has made certain that there have always, in the past, been some survivors somewhere on Earth will not have been carried to the interstellar colonies.

4. COMPENSATIONS

There is only one predictable compensation for the disasters which will accompany attempts at interstellar travel and colonisation, and it is typical of Earth experience that it will not be the sufferers who receive the compensation, but their relatives, the rest of humanity.

If colonisation is successful, and communication is kept up after, each member system of the interstellar community will be able to learn from the experience of the unlucky. Codes of spacecraft construction and terraforming practice, to name only two examples, will benefit from failures at great distances. Also the opportunity for failure in a multi-system community will be greater, and will allow a more searching review of the codes than is possible in a single system where the failure guarded against has not, yet, happened. Interstellar expansion may be exceedingly slow, or totally unsuccessful for millenia, without complete forfeiture of these advantages.

Successful colonisation will add the further advantage that humanity is no longer restricted to the neighbourhood of a single unpredictable star. It is by no means impossible that after a major war, an unexpected flaring of the Sun, or a darkening of the Earth by volcanic eruption the people of the Solar System may welcome arks with supplies of undevastated life forms with which to re-establish tropical jungles or coral reefs. There may one day, be an estalished procedure for rescuing damaged planets and solar systems, and that procedure will owe a great deal to disasters elsewhere which have made rehabilitation necessary.

5. SUMMARY

Many of the possible causes of failure and disaster in interstellar travel and colonisation are analogous to events which take place on Earth at the present day, or are known from the historical or geological record. Earthly experience can be used in estimating the likelihood of these, and in minimising their consequences. In turn, failures and disasters in the larger community which will result from successful interstellar colonisation may assist the people of Earth in guarding against Earthly disasters, by providing experience not otherwise available, and in the event of a large disaster on Earth techniques which are used in preparing planets for habitation may be applied to help recovery.

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A MANNED INTERSTELLAR VESSEL USING MICROWAVE PROPULSION: A DYSONSHIP

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1. INTRODUCTION

Freeman Dyson [1] has recently proposed a scheme for using a highly collimated beam of microwave to accelerate a sail made of thin wires woven at a spacing of roughly the microwave wavelength. The low surface density of the sail would permit substantial accelerations. Forward [2] has done a detailed analysis of a low-mass (kilograms) interstellar probe launched by means of the microwave output of a standard 10 GW (gigawatt) Solar Power Satellite (SPS). However, if a Dyson Sail were to be used to accelerate a manned vessel to a fraction of lightspeed, the required tensile strength of the sail materials and of the cables attaching the ship to the sail would be of the order of hundreds of kilobars; a strength far in excess of ordinary materials. Fortunately, thin fibres (whiskers) made of silicon carbide (SiC) which approach the required strength can be grown in the laboratory [3]. In this short paper, I will outline a means of achieving interstellar settlement voyages using microwave propulsion. Conceptually, this scheme resembles the Solar Sail Starships sketched by Matloff and Mallove [4].

2. MISSION PROFILE

Although the least expensive "settlement" voyages would involve sending genetic materials to the stars under the care of robots and computers, the human elements of such a mission are missing. While an interesting technical exercise, such a scheme has little to offer the adventurous spirit of our species [5]. Let us explicitly assume that by a "settlement voyage" we mean a party of flesh-and-blood human beings embarking on a voyage to a nearby star, and that the one-way trip must be completed in less than a human lifetime. We will assume that the emigrants will have adapted to living in space from several generations of experience living in extraterrestrial habitats and that on arrival at the target star the party will mine asteroids or small moons for the materials to build habitats for an expanding population.

If it is assumed that the target must be a single, solar type star, so that it is likely to have the requisite building materials, then Barnard's Star at a distance of 5.9 light years would be a candidate. A coasting speed of one tenth lightspeed would permit the journey to be completed in about 60 years. If we assume acceleration at ten per cent of terrestrial gravity, the vessel could achieve such a speed in one year. Deceleration might be achieved through electrostatic means, through use of a fusion engine, or some combination of these and other techniques.

3. THE EMIGRANTS

A group of emigrants embarked on a one-way voyage must be not only materially self-sufficient, but socially and genetically self-sufficient as well. These are historical examples of communities grown from very small beginnings. These include the descendants of the Bounty Mutineers and their Polynesian women, and the people of Tristan da Cunha in the Atlantic [6, 7]. On a large scale it is plausible that the Hawaiian population, which numbered a quarter million at the time of the Cook voyages, was descended from about two dozen people who had arrived in Hawaii centuries before in a single canoe [8]. Although we might imagine an interstellar party of very small size, a voyage lasting a lifetime suggests the need for larger communities. Anthropological studies suggest a minimum community size in surviving hunting and gathering populations. The typical breeding community is about 500 [6, 9]. For example, among Australia's aboriginal population tribal groupings defined by dialect and marriage boundaries have about this size [6]. Similar patterns are found among the San peoples of Africa's Kalahari Desert [9]. I choose this common model. The party that actually leaves the Solar System might be somewhat smaller, with few small children, but I will assume that by journey's end the community will be at about the 500-person level.

4. THE INTERSTELLAR VESSEL

Following Matloff [10], a plausible ship configuration would be a torus with the dominant mass requirement given by the need for protection from cosmic rays. In a toroidal design, the area available for human habitation is

$$A = 2\pi RW \qquad (1)$$

where R is the outer radius and W is the width parallel to the rotation axis (Fig. 1). The radius is dictated by the chosen values of rotation period (P) and the fraction (f) of terrestrial gravity (g) to be experienced by the emigrants:

$$R = fg\left(\frac{P}{2\pi}\right)^2 \qquad (2)$$

The habitat volume (V) is given by the equation

$$V = \pi W[2RH - H^2], \qquad (3)$$

where H is the thickness of the toroidal perpendicular to the rotation axis.

Following the NASA design study of space settlements [11], plausible design constraints are: 1) P equals 60 seconds; 2) V equals 2000 N m^3, where N is the population; and 3) A equals 70 N m^2. We will further assume that an effective gravity of 0.1 g will be comfortable for a party of emigrants

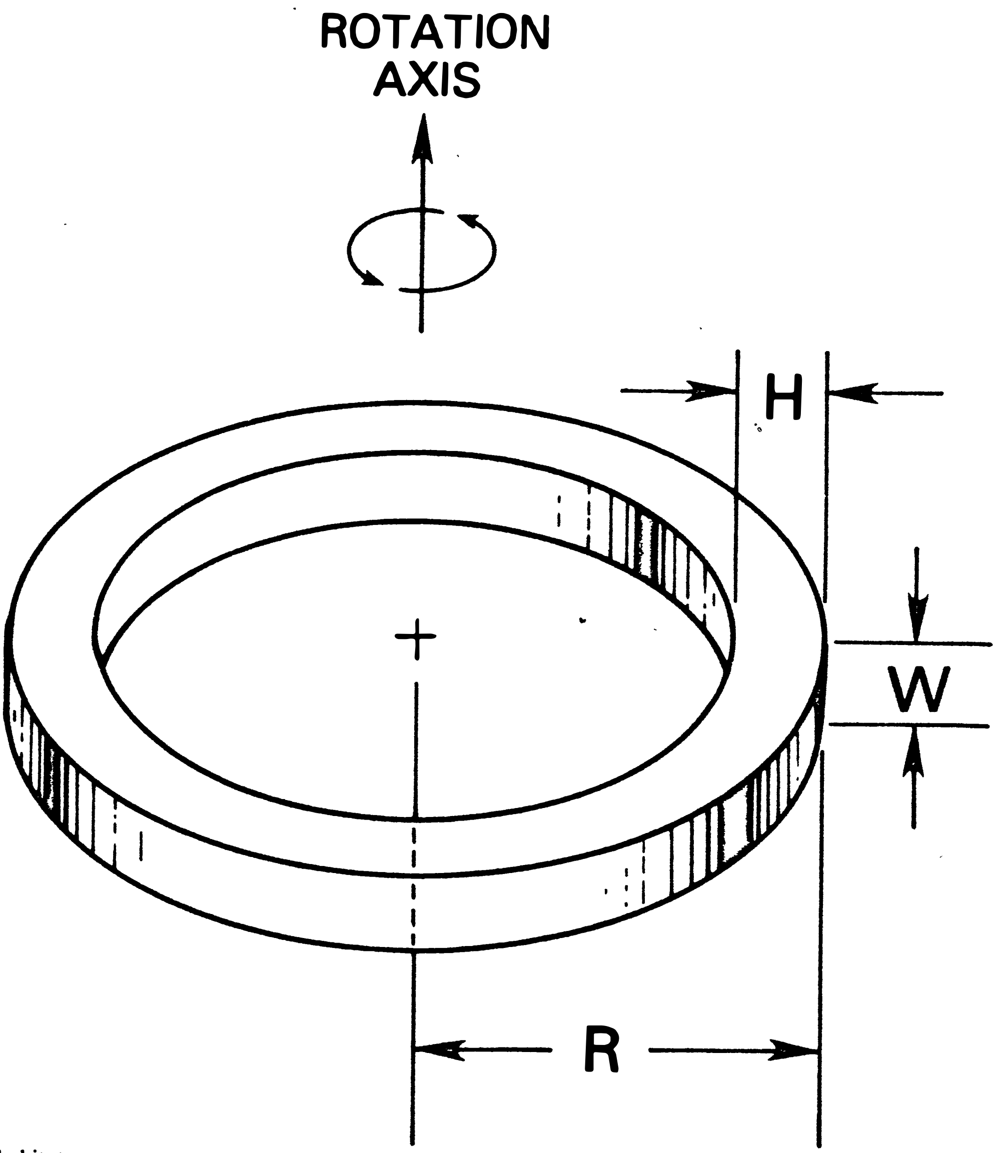

Fig. 1. A toroidal habitat.

long adapted to living in space. The shielding mass required is then set by the relationship

$$M_S = 2\pi R\sigma(2 - \frac{H}{R})(W + H) , \qquad (4)$$

where σ is the surface density of the shielding material. Because R is much larger than W, H can be approximated as

$$H = \frac{V}{2\pi RW} , \qquad (5)$$

and thus,

$$M_S = 2\sigma[A + \frac{V}{A}\frac{fgP^2}{2\pi}] , \qquad (6)$$

or

$$M_S = 240\ \sigma[N + 230]\ m^2 . \qquad (7)$$

Following Matloff [10], if an acceptable cosmic ray exposure is 0.5 rem, than σ is 5000 kg/m^2 and M_s is 7 x 10^5 [N + 230] kg. Development of laternate shielding methods [12, 13] or acceptance of higher exposure levels would reduce the mass requirements, but for the purposes of the present anaylsis we will assume this "worst case." We will also assume a biosphere mass of 5 x 10^4 N kg.

With a party of 500, the total mass (excluding deceleration fuel) is 5.4 x 10^8 kg, R = 900 m, W = 62 m, and H = 28 m. Deceleration fuel would increase the mass by a factor of four to 2.2 x 10^9 kg.

5. ENERGY REQUIREMENTS AND SAIL DESIGN

Acceleration of the ship to 0.1 lightspeed at 1 m/s^2 requires an acceleration distance (d) of 4.5 x 10^{14}m or 3000 astronomical units. Collimation of the microwave beam is limited by dispersion and, if the transmitter and sail have comparable diameters (D), d and D are related to the photon wavelength (λ) by the expression

$$D^2 = 2.44\ \lambda\ d . \qquad (8)$$

Following Forward [2], I will assume for convenience that

the transmitter operates at X-band (λ = 3 cm); for a 3000 AU acceleration distance the sail diameter is then about 6000 km. If the sail wires (metal-coated silicon carbide) have a 3.0 micron diameter and are spaced at 0.3 cm (hexgonal weave), the effective surface density is about 1.7 x 10^{-5} kg/m^2 and the sail mass is about 4.9 x 10^8 kg, which is comparable with the ship mass.

The required transmitter power (P_T) is determined by the equation

$$P_T = M a c / \epsilon \tag{9}$$

where M is the total mass of vessel, sail, and deceleration fuel, a is the acceleration (1 m/s^2), c is lightspeed, and ϵ has a value of about 0.7. For the vessel described above the power requirement is about 1.2 x 10^{18} watts or 1,200,000 terawatts (TW). We have assumed that the sail is discarded after launch to reduce the required mass of deceleration fuel. For comparison current world installed capacity is about 40 TW.

6. ENERGY GENERATION

Because the Dyson sail scheme uses an external source of power for the launch phase of the mission, that portion of the system can be reused, reducing the capital costs of subsequent expeditions. This is particularly true if the power source is the Sun. Arthur C. Clarke [13] has suggested that large "light traps" could be placed close to the Sun to supply the energy needs of a human society spread throughout the Solar System. If we imagine mirrors placed at 0.1 AU (=20 solar radii) from the Sun, the solar flux is 140 kilowatts/m^2. Producing 1.2 x 10^6 TW for an interstellar mission would require a collector radius of 3700 kilometres if the overall sunlight-to-microwave conversion efficiency is 20% [15]. The most massive component of a Clarke Station (as we might call such a facility) would probably be the collecting mirror. Assuming an effective surface density of 0.002 kg/m^2, the mass of the Clarke Station would be about 8.8 x 10^{10} kg.

One possible source of the building materials for the Clarke Station would be the planet Mercury. An O'Neill mass driver similar in design to the machine proposed for use on the lunar surface [16, 17] would be adequate to deliver materials to a building site, perhaps at one of the Mercury-Sun Lagrange points. Although Mercurian surface gravity is 2.3 times lunar gravity and would necessitate a longer acceleration distance in the mass driver, the higher solar flux would reduce the area of solar collectors needed to power the machine. If construction of the Clarke Station were stretched over a ten-year period, the throughput of the mass driver would need to be 200 kg/s. Experience will show whether one or several machines would be required. Rotation of the planet would seem to suggest at least three mass drivers. At the end of the construction phase the Clarke Station could be sailed to its duty station.

7. SAIL MATERIALS

The stresses generated in the sail and in the cables connecting it to the ship will be large. The theoretical limiting strength for sail wire and cable is obtained for diamond whiskers at about 1.9 x 10^{11} Newtons/m^2. However, it seems now that techniques for manufacturing diamond whiskers will not be able to produce suitable material. In this plausibility demonstration we will therefore restrict attention to silicon carbide whiskers for which suitable manufacturing techniques now exist, and which have a theoretical maximum strength of 4 x 10^{10} Newtons/m^2. Achievable strengths would be roughly a factor of two less, given the need for forming cables from the fibres and the inevitable imperfections in manufacturing the coated fibres to be used for the sail material [18].

Following Matloff and Mallove [4], the mass of cables needed to connect the ship and sail is set by the equation

$$M_C > \frac{1.4 \rho_C R_S M}{\frac{S}{a} - 1.4 \rho_C R_S} , \tag{10}$$

where R_s is the projected sail radius (3 x 10^6 m), ρ_c is the density of the cable materials (3.2 x 10^3 kg/m^3 for SiC), M is the ship mass including deceleration fuel (2.8 x 10^9 kg), S is the tensile strength of the cable material (4.0 x 10^{10} Newton/m^2 for perfect SiC) and a is the ship acceleration (1 m/s^2). If we define S as the product 4.0 x 10^{10} S_o, we obtain the result

$$M_C/M > \frac{1}{3 S_o - 1} \tag{11}$$

The maximum strength measured for a single silicon carbide whisker is about 2 x 10^{10} N/m^2, corresponding to S_0 of 0.5, and giving a cable mass about twice the combined ship/sail mass. For the cable mass to be half the total mass, the achieved strength should be about S_o equal 2/3. Advances in whisker technology might be expected to produce the required materials long before a Clarke Station could be built.

An additional design constraint is the strength of the wires comprising the mesh. For a rotating sail [4] the required spin velocity for stability is

$$V_S = [\frac{M_C + M_P}{M_S} a R_S]^{1/2} , \tag{12}$$

or V_s of 5 x 10^3 m/s for S_o of 2/3. The required strength of the mesh wire is given roughly by

$$S_m = 2 \frac{M_S h}{\pi^2} (\frac{V_S}{R_S b})^2 , \tag{13}$$

where h is the mesh spacing (0.003 m) and b is the wire diameter (3 x 10^{-6} m). We obtain S_M = 10^{11} Newtons/m^2 which exceeds the maximum possible strength of SiC whiskers by a factor of about 2.5. The simplest solution using this configuration would be to increase the diameter of the mesh wires. However, that would increase the sail mass to a value greatly in excess of the payload mass, and seems an unacceptable solution.

Alternatively, we can adapt a second solution proposed by Matloff and Mallove [4] for their solar sails: using inward curvature in the sail to balance the cable tension (Fig. 2). The stress in the sail wire is then set approximately by the expression

$$\sigma_M = \frac{(M_P + M_C)a}{\pi R_S^2} R_C \frac{h}{2\pi b^2} , \tag{14}$$

where R_C is the radius of curvature of the sail. For S_o of 2/3 we obtain an R_C of 1.2 x 10^{-4} σ_M, and hence, a required curvature of 3.2 x 10^6 m.

8. WIRE BREAKAGE

T. D. Kunkle, whose comments greatly improved this paper, raised a concern about wire breakage due to impacts with interstellar grains. This would be a concern only during the year-long launch phase. We can bound the threat by assuming that all of the heavy elements in the local inter-

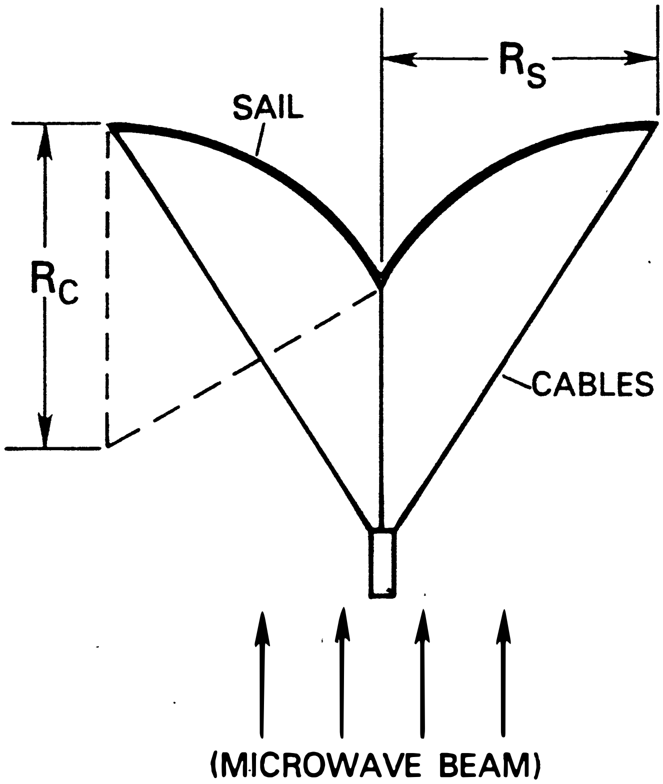

Fig. 2. Non-rotating microwave sail after Matloff and Mallove [4]. The radius of the sail projected into the microwave beam is R_s and the radius of curvature is R_c.

stellar medium are tied up in micrometer-sized grains. If we take an upper limit of 10 hydrogen atoms per cubic centimetre for the total density and a heavy element fraction of 0.04, the number density (N) of micrometer grains is approximately 2×10^{-13} cm^{-3}. If we assume that each wire segment (0.3 cm long by 3×10^{-4} cm diameter) is independent, the probability of its breaking during the launch is is $N\sigma d$ where σ is the projected area of the wire segment (9×10^{-5} cm^2) and d is the acceleration distance (4.5×10^{14} cm). We then have a breakage probability of less than one per cent, and possibly much less. A loss of one per cent of the sail wires seems acceptable although better estimates would be required before detailed engineering studies could be undertaken.

ACKNOWLEDGEMENTS

These ideas owe their existence to Freeman Dyson. Robert Forward brought Dyson's beautiful idea to my attention and supplied a copy of his book detailed analysis of Dyson's concept. My debt to both is great. This work has been supported by the Los Alamos National Laboratory which is operated by the University of California under contract to the US Department of Energy.

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SETI AND INTERSTELLAR MIGRATION

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SETI and Interstellar Migration may have more in common that their sometimes antagonistic partisans realise, or will admit. Both stem from the same basic human urge for exploration. Both reflect a desire to see the Galaxy full of intelligent life. And the two complement one another as integral parts of an expansive strategy for our species. Furthermore, the opposition of SETI and Interstellar Migration may indicate more about the workings of the human mind than the manifold possibilities for the incidence and dispersion of intelligent life in the Galaxy.

1. INTRODUCTION

To many the Search for Extraterrestrial Intelligence (SETI) and Interstellar Migration (IM) are mutually exclusive creeds. If you believe in one you generally do not believe in another. For example, SETI advocates often claim that IM would be too expensive by far to be feasible, and that the rational interstellar activity for any intelligent civilisation would be the establishment of radio communication with other intelligent civilisations – which have arisen, they hypothesise, in many places and at many times throughout the Galaxy [1, 2, 3]. In contrast, many IM advocates hypothesise that we are alone in the Galaxy, and that it makes little sense to sit and listen for civilisations that may not exist when the priority task for us is to go out there and populate the Galaxy [4, 5, 6, 7].

That these two groups might be in conflict should perhaps not be surprising, given the common human tendency to divide into separate camps, and then to oppose one another, especially when funds or other needed resources are scarce. However, as even the bitterest of conflicts often have a way of eventually fading into obscurity, so may the opposition between SETI and IM prove ephemeral. Let me go further, and propose that SETI and IM may at present have much more in common that many of their partisans realise – or will admit.

2. THE DRIVE TO EXPLORE

To begin with, there are both SETI and IM advocates who claim that their activity is a natural expression of a basic human drive to explore. For example, a couple of year ago Eric Jones, a leading IM theorist, and I wrote an essay in which we traced the development of the human capacity for migration from those first steps taken some 5 million years ago in the African savannah by our then newly bepedal ancestors, to the initial steps taken upon the Moon's surface by Neil Armstrong, and proposed that moving out into space is now the logical outlet for our bio-cultural urge to explore [8]. Unbeknownst to us at the time, in a 1977 NASA publication entitled *The Search for Extraterrestrial Intelligence* David Black and Mark Stull had put forward a similar argument, but one which linked human evolution and our exploring nature with SETI instead of IM [9]. For example, they contended that:

> "SETI is a manifestation of man's drive to explore. This drive is one of the oldest and most fundamental aspects of our nature; the very origin of the hominidae as a distinct biological entity is owed, at least in part, to the boldness of our simian ancestors who abandoned their familiar forest environment to probe the savannah..."

They then went on to trace, much as Jones and I later did, the way in which hominids pushed into almost every corner of the globe, and to suggest, again as Jones and I did, that now the arena for further exploration lies among the planets and stars beyond. Where they differ from us is in their emphasis on conducting that exploration at a distance, SETI through radiotelescopes being their case in point.

As an anthropologist fascinated with both SETI and IM who has had the opportunity to observe, and on occasion work alongside, both SETI practitioners and IM advocates, I tend to see the choice of either SETI or IM as dependent more on the personal style and experience of the particular advocates than on dispassionate logic. If, as their respective partisans claim, expanding to other star systems, and probing for evidence of extraterrestrial intelligence with radiotelescopes, can be thought of as manifestations of the same basic human exploratory urge, surely these activities might also be considered as complementary rather than conflicting.

3. COMPLEMENTARITY

Michael Michoud, a diplomat turned space philosopher, makes a strong case for complementarity [10]. He proposes that SETI and manned space ventures, and also space exploration with unmanned spaceships and more traditional astronomical instrumentation, together form what he calls a "grand strategy for the species." Michoud borrows the idea of a species' strategy from biology, employing it in the sense of the characteristic pattern of how a species responds to environmental pressures and opportunities. The recent emergence of a global environmental movement indicating the growth of a consciousness that we can and should shape our destiny as a species would seem to make this concept of a species' strategy even more appropriate to us than to other, less sapient, creatures. However, unlike those environmentalists who would think only of Earth, to Michoud the arena in which our strategy is to be worked out includes the vastness of space as well as the surface of our natal planet.

Michoud's conception of our species' strategy is basically expansionary: to provide for our welfare and ultimately our survival, we should push out into space to extend our living range and access to resources. Within this strategy SETI, along with other astronomical searches, would perform a vital reconnaissance function. Unmanned probes and telescopes (on Earth and space) would be used to detect habitable planets and other suitable places for expansion, while

SETI would be employed to ascertain whether or not some form of intelligent life had already occupied other regions of the Galaxy.

At present, SETI may be an exciting intellectual challenge, but one generally considered not to be of pressing and immediate significance, as witness the low levels of funding, or lack of funding. In contrast, manned space flight – some portion of which can only be justified as preparation for actual migration into space – receives considerable funding. Should this effort to learn how to live and work in space eventually result in the spread of human settlements throughout the Solar System, a major change in human consciousness would certainly follow. The establishment of permanent human communities on other planets and in artificial biospheres in interplanetary space itself would make it apparent to all that we are not bound forever to our natal planet, and turn thoughts even more towards actually sending colonising expeditions to other star systems. At that point the answer to the question "Are we alone?" would become crucial to charting future expansions. SETI would then no longer be the underfunded child of a few daring thinkers. It would become a vital and well-financed part of our species' "grand strategy."

Yet, it is also possible that even modest SETI efforts might succeed in discovering radio signals indicating the presence of extraterrestrial intelligence well before we had gone very far towards colonising even the Solar System. In that case we would have to re-think our species' strategy. The idea popular among IM theorists of virtually unlimited prospects for expansion through the Galaxy would have to be replaced by a realistic assessment of what was occupied real estate and what was open to our migration. And, as SETI theorists are fond of pointing out [11], the benefits in terms of knowledge to be gained from civilisations of completely different origin, and the synergistic developments that could follow when two or more such independently evolved civilisations exchanged information and experience, would perhaps more than compensate for any limitation of our physical expansion.

4. A GALAXY OF INTELLIGENT LIFE

There is a third area in which SETI and IM theorists are unwittingly in a curious kind of agreement. It is almost as though both groups believe that intelligence abhors a vacuum – for they share a vision of a galaxy teeming with intelligent life. Of course, they differ on questions of origin and timing. While SETI theorists hypothesise that the Galaxy may now be populated by many intelligent civilisations of independent origin, IM theorists hypothesise that the Galaxy may be empty of intelligent life now, but not in the future when Earth-descended civilisations will spread from star system to star system. Yet, the end result of such an Earth-derived monogenetic filling of the Galaxy might not necessarily yield a picture so totally different from the polygenetic one favoured by SETI theorists. The million of years such a galactic filling would require, the extreme separation of migrant groups into small breeding isolates light years away from their nearest neighbour, the differential selective pressures of the multitudes of new environments, and the manifold possibilities inherent in genetic engineering (not to mention the blending of humans and computers), would surely interact to produce a mosaic of human-descended galactic life forms, one perhaps as startingly heterogenous as those polygenetic galaxies of intelligent species now envisaged by SETI theorists.

That possibility, however far-fetched it might sound, raises a final question. Do the simple oppositions of a galaxy now full of intelligent life or one currently barren of other sapient creatures, and of the inevitable inter-stellar expansion of intelligent life or of its penchant for staying put and communicating by radio, really exhaust all the possibilities? I do not think they do. Furthermore, I suggest that such binary oppositions may tell us more about human thinking processes than the phenomena in question [12]. Our Galaxy is vast and, if recent experience within our own Solar System backyard is any indication, highly diverse. SETI and IM may be but two of many possible ways of trying to comprehend the Galaxy. If so, they, and the associated premises concerning the incidence and behaviour of intelligent life, should not be projected upon all other intelligent civilisations – be they of completely independent origin, or descended from our own. Indeed, the Galaxy, and its sapient populations, may turn out to be much stranger and more wonderful than our limited imagination can now conceive.

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Paper presented at the 35th Congress of the International Astronautical Federation held in Lausanne, Switzerland, October 1984.

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13th INTERNATIONAL ACADEMY OF ASTRONAUTICS REVIEW MEETING ON COMMUNICATION WITH EXTRATERRESTRIAL INTELLIGENCE

ANTHONY R. MARTIN

The above meeting was held as part of the programme of the 35th Congress of the International Astronautical Federation, in Lausanne, Switzerland during October 1984.

Edited abstracts of the papers presented at the meeting are given below. The paper number is given in brackets after the paper title. Many of these contributions will appear in the Congress Proceedings or in ***Acta Astronautica.***

Michael D. Papagiannis, "The First IAU Symposium on Extraterrestrial Life." (IAA-84-235).

This paper presented a summary of the most significant results from the first Symposium of the International Astronomical Union on the search for life in the Universe, held 18-21 June 1984, in Boston, Massachusetts, USA. Its official designation was "IAU Symposium 112 Search for Extraterrestrial Life – Recent Developments," and its proceedings will be published by D. Reidel Publishing Company in their series of IAU Symposia. In addition to the IAA/IAF, the Symposium was co-sponsored by three other major international organisations: COSPAR, ISSOL and IUBS, giving it an interdisciplinary character with the participation of several experts from the life sciences, and four other IAU Commissions (15 – Comets, Asteroids and Meteorites; 16 – Planets and Satellites; 24 – Astrometry; and 40 – Radio Astronomy).

The programme included the follwoing sessions: (1) Search for Other Planetary Systems; (2) Interplanetary and Interstellar Organic Matter; (3) Universal Aspects of Biological Evolution; (4) Radio Searches – Recent Developments; (5) Technological Progress in Radio Searches; (6) The Fermi Paradox and Alternative Search Strategies; and (7) Summary and Conclusions.

Cyril Ponnamperuma, "Cosmochemistry and Life in the Universe." (IAA-84-236).

The problem of chemical evolution is central to any discussion of extraterrestrial life. We can use the Earth as the model laboratory in which we know that life has occurred. We would like to extrapolate from events on the Earth to elsewhere in the Universe. If the laws of physics and chemistry are universal laws, we could logically conclude that life exists elsewhere. The chemical elements, Hydrogen, Carbon, Oxygen and Nitrogen, which make up over 99% of the Earth's biosphere, provided the raw material for life. Great progress has been made in demonstrating that the building blocks of life can be synthesised in the laboratory. The constituents of the protein and nucleic acid molecules, which are at the basis of life, have been synthesised in the laboratory in a variety of experiments in which the Earth's primitive atmosphere has been exposed to a number of energy sources which may have existed on the prebiotic Earth. Their pathways of synthesis have also been carefully elucidated. Experiments have also been performed to show that these components can be assembled in sequences that may simulate primitive poly-peptides and poly-nucleotides. The discovery and dating of the Earth's oldest sediments at around 3.8×10^9 years has helped us to get a glimpse of the face of our planet at the very dawn of terrestrial time. Microfossils identified in rocks and sediments at 3.5×10^9 years have provided striking evidence that life evolved and flourished on the Earth very early in its history. Amino acids and nucleic acid bases have been found in carbonaceous chondrites, demonstrating that the processes which occurred on the Earth in the very early stages may be common to the early Solar System. Recent missions to the giant planets have provided us with a wealth of information that organic matter is constantly synthesised and occurs abundantly in the atmospheres of Jupiter and Saturn. Radio astronomers looking into the interstellar medium have revealed the presence of a vast array of organic molecules which may be considered intermediates in prebiotic synthesis. Chemical evolution appears to be commonplace in the Universe and cosmic in nature. If that is indeed the case, we have a strong foundation for our supposition that life may have evolved elsewhere to the point of intelligence.

J. Oro, "Major Chemical Evolutionary Phases for the Emergence of Life in Planetary Systems." (IAA-84-237).

A serious study of the question of the origin of life has only become possible during the past three decades as a result of advances in the life and space sciences. Some of the major findings made during this time were summarised as follows:

1. At present we have only evidence for the existence of life on Earth. Terrestrial life is based on the chemistry of carbon and on the interaction of macromolecules made of six biogenic elements (H, C, N, O, S, P), which together with some inorganic ions, appear to be indispensible for the replication and metabolic processes of living systems.

2. These biogenic elements have been found among the most abundant elements in the Universe and they are known to be formed from hydrogen in the core of stars by means of thermonuclear processes.

3. The interstellar medium has been found to contain a diversity of simple organic molecules made of these elements.

4. Some of these molecules have also been found in

comets, which are considered the most primordial bodies of the Solar System.

5. The atmospheres of the outer planets and their satellites, for example, Titan, are actively involved in the formation of similar simple organic molecules which are the precursors of biochemical compounds.

6. A number of biochemical monomers, such as amino acids, purines and pyrimidines, have been found in carbonaceous chondrites which are presumed to be derived from dark asteroids.

7. Laboratory experiments have shown that most of the biomonomers and biopolymers necessary for life can be synthesised under hypothesised but plausible primitive Earth conditions from molecules found in the above cosmic bodies.

8. It appears that the primitive Earth had the necessary and sufficient conditions to allow the chemical synthesis of biomacromolecules and to permit the processes required for the emergence of life on our planet.

9. It is not known whether the emergence of life occurred on any other body of the Solar System, although it is unlikely that it occurred on Venus or Mars. However, recent information obtained about the presence of subsurface oceans of liquid water in the Jovian satellite Europa and unique features of its ice-covered surface are most interesting in an exobiological context. It is suggested that this satellite be carefully studied in order to determine the possible presence of organic and biochemical compounds, as well as some rudimentary form of primitive anaerobic life in it.

10. The exploration of the Solar System during these past two decades and the recent findings made by the infrared IRAS telescope have provided additional information which can be used to refine Drake's calculations about the possible existence of extraterrestrial civilisations in our Galaxy.

On the basis of the knoweldge accumulated, it appears that within our Galaxy there are three major chemical evolutionary phases for the emergence of life in a planetary system such as our own:

(A) In a *first pre-Solar system phase,* relatively simple organic molecules such as those found in space were formed in the atmospheres of cool carbon stars, interstellar dust and gas clouds. Some of these molecules were presumably present in the solar nebula and are also found today in the coma of comets and in the atmospheres of Jovian-type planets and Titan-type satellites.

(B) In a *second Solar System phase,* more complex organic molecules, such as amino acids, purines, pyrimidines, etc., were apparently formed in small carbon-rich planetary bodies, for instance the dark asteroids and probably in most cometary nuclei. This second phase, although important in its own way, was probably a blind alley of chemical evolution toward life, because the molecular organisation stopped at the level of biomonomers or very simple oligomers, and could not continue forward.

(C) In a *third planetary phase,* which is crucial because in the case of the Earth it involved the emergence of life, it appears that an indispensable requirement was the presence of a large body of liquid water at a moderate temperature so that the formation and interaction of informational self-replicating and autocatalytic biopolymers could take place. In the Solar System this situation may have occurred for a sufficiently long time in only two places, the Earth and the satellite Europa, although it may have also occurred more ephemerally in Mars and Venus. A comparison of the conditions of the Earth and Europa with the early conditions of Mars and Venus was made in detail in order to refine the 25 requirements studied by us which we consider necessary for the emergence of life in any planetary system of our Galaxy. In the same context some of the most recent information obtained by spacecrafts, optical and infrared telescopes on the Solar System and beyond was examined.

B. A. Balázs, "The Galactic Position of our Sun and the Optimisation of Search Strategies for Detecting Extraterrestrial Civilisations." (IAA-84-238).

This contribution made use of some stellar astronomical results based on the galactic distribution of open clusters of different ages and on C. C. Lin's gravitational density wave theory of the large scale galactic spiral structure. Relying upon the cluster distribution it is possible to determine the pitch angle (i) and angular velocity (Ω_p) of the spiral pattern. It turns out that the orbit of the Sun is close to the so called co-rotation circle. Consequently, if we assume that our case is about average and accept the idea that the longevity of a civilisation might be limited with high probability by catastrophic events threatening during the crossing of the arms, then intelligent life is presumably concentrated on a belt in the Galaxy which is a narrow annulus including the co-rotation circle and the galactic orbit of our Sun. It is possible to select loci of coevality in the belt which localise the zones where societies at least as old as ours are primarily expected.

Anthony R. Martin and Alan Bond, "Is Mankind Unique in the Galaxy?" (IAA-84-239).

If intelligent life is a common occurrence in the Galaxy, then many civilisations should have arisen which by now are far in excess of mankind in both their age and their capabilities. It is to be expected on technical grounds that some of these should have crossed the threshold of their home planetary system and ventured out into interstellar space. In a time that is short when measured against astronomical timescales such civilisations could have colonised the planets orbiting every suitable star in the Galaxy.

As the Solar System is relatively young in the Galaxy, there should never have been a time in our history when mankind was not aware of the presence of such civilisations. And yet, we apparently see no signs of intelligent life in the Galaxy other than ourselves!

This paradox, now well known, was first expressed by Enrico Fermi 40 years ago, and is still as relevant to discussions on the possible existence of intelligent life in the Universe and the methods of searching for signs of such life as it was then.

The authors have reviewed the many aspects of the Fermi Paradox for the last decade, and recently entered the debating chamber. This paper was an attempt to further

contribute to that debate by exploring some of the arguments prompted by the Paradox in more detail.

Ben R. Finney, "SETI and Interstellar Migration. (IAA-84-241).

To some theorists SETI and interstellar migration are contradictory concepts. For example, some argue that because interstellar migration would seem to be possible for any intelligent civilisation in the Galaxy, there is no need for SETI because if there were any other intelligent civilisations they would have reached our Solar System by now. Others who support SETI reject the feasibility of interstellar migration, arguing that intelligent civilisations will instead seek to communicate with those from other star systems by radio.

In this paper it was argued that SETI and interstellar migration are far from being contradictory notions – that in fact SETI will become part of an overall expansionary process. Rather than an expansionary strategy in which SETI is ignored, or a passive, Earth-based remote sensing strategy in which no attempt is made to expand human settlement into space, a mixed scenario seems more likely. *Homo sapiens* is an expansionary, technologically-innovating, species, and thus it seems unlikely that the opportunity to expand into space will not be siezed. However, once our descendants settle the Solar System they will become intensely curious about the existence of life, especially intelligent life, elsewhere in the Galaxy, for that inforamtion will be crucial to future expansionary plans. Thus SETI will be more than an intellectual pursuit. It will become crucial to the reconnaissance of the Galaxy for possible living sites, and thus a vital element in the expansionary strategy of the species.

U. Merbold, A. Souchier and A. Ducrocq, "SETI Experiment in Spacelab-1." (IAA-84-242).

With the sponsorship of the European Space Agency and of Radio Station Europe 1, the Paris meridian between Paris and Amiens was lit on the second orbit of the STS-9 flight (28 November 1983) and the Greenwich meridian between the towns of Deauville and Loudun on the 18th orbit (29 November 1983) and on the 34th orbit (30 November 1983).

On 28 November, 20 groups of cars, each with three 100 W headlights, were located in Paris in a 40 m wide area (Place du Pantheon). Eight groups of the same type of headlight-assembly were scattered along the Paris meridian, north of Paris around Chantilly. The Paris group should have appeared as a -0.2 magnitude spot. Each of the isolated groups north of Paris should have appeared as a 3.1 magnitude spot.

A continuous cover of clouds stayed above Paris on the 28 November precluding any observation from the Spacelab. However the lights were turned on one minute before the theoretical time of the *Columbia* flight over Paris. The lighting time was 17 h 53 min 30 s UT.

As *Columbia* was illuminated by the Sun when crossing the Greenwich meridian (29 November 1983), it was decided to offset the light beams from the meridian plane. Owing to the offset, the beams crossed each other and the *Columbia* theoretical trajectory above the town of Chambord where *Columbia* should have been in the night. As for the Paris operation on 28 November, the observation duration was limited to 17.5 s from *Columbia*.

The weather was cloudy on the Greenwich meridian that day except for the northern part: the north spot at the seaside at villers should have been seen as an 0.85 magnitude spot (eight groups at 3 x 100 W headlights). All the lights were turned on at 17 h 44 min [illegible] s UT.

On 30 November, as *Columbia* was entering the night 300 km east of the meridian, it was not possible to offset the beams to cross the trajectory in the night. The crossing point would have been too far from the meridian. So the beams were inside the meridian vertical plane crossing each other on the *Columbia* trajectory. In this plane *Columbia* was lighted by the Sun and the ground was in the night. Depending on the Shuttle attitude, this situation could make the meridian observation more difficult.

The weather was very clear that night all over the meridian. The lights were turned on at 17 h 35 min 35 s UT.

In addition, a nine-point fireworks cross was lighted on La Fleche airfield. The distance between the points was 200 or 100 m, to be compared to the 60 m limit eye resolution capability calculated from the *Columbia* altitude. The first point was ignited at 17 h 32 min UT, followed roughly at 15 second intervals by four others. When *Columbia* was visually acquired around 30° above the west horizon, at about 17 h 36 min UT, three other fireworks were ignited. Each fireworks point burned about two minutes.

Francisco Valdes and Robert A. Frietas, Jr., "The Search for Extraterrestrial Artifacts (SETA)." (IAA-84-243A).

The rationale for the use of interstellar artifacts by intelligent life in the Universe was described. The advantages of using interstellar probes as a means of exploration and communication were presented and shown to be significant enough to counter the time, energy and technology arguments generally raised against contact *via* extraterrestrial artifacts. Four classes of artifacts were defined: Those seeking contact, those seeking to avoid contact, those intended to provide a passive technological threshold for detection, and those for which detection is irrelevant. The Search for Extraterrestrial Artifacts (SETA) is based on the latter two classes. Under the assumption that an extraterrestrial probe will be interested in life in our Solar System, a near-Earth search space was defined. This search space is accessible to us now with ground and satellite observing facilities. The current observational status of SETA was reviewed and contrasted with the achievable detection limits for the different parts of the search space.

Francisco Valdes and Robert A. Frietas, Jr., "A Search for the Tritium Hyperfine Line from Nearby Stars." (IAA-84-243B).

A search for the tritium line at 1516 MHz from 108 assorted astronomical objects, with emphasis on 53 nearby stars, was conducted in June 1983. All stars within 20 light-years visible from the 26-metre telescope at Hat Creek Radio Observatory were examined using 256 4883-Hz channels. Twelve stars were also examined using 1024 76-Hz channels. The wideband- and narrowband-channel observations achieved sensitivities of 5-14 x 10^{-24} W/m^2/channel and 0.7-2 x 10^{-24} W/m^2/channel, respectively. No detections were made. The tritium frequency is ideal for SETI work because the isotope is cosmically rare and the tritium hyperfine line is centred in the traditional SETI minimum-background waterhole region. In addition to beacon signals, tritium hyperfine emission may occur as a byproduct of extensive nuclear fusion energy production by extraterrestrial civilisations.

D. K. Cullers, B. M. Oliver and J. H. Wolfe, "Sensitive Detection of Narrowband Pulses." (IAA-84-244).

Highly monochromatic signals, such as carriers of terrestrial TV stations, can be sensitively detected by using a narrow

filter and performing power accumulation on its output. If instead a low-duty-cycle pulsed signal is present, the sensitivity of a square-law device, followed by a thresholding operation (to eliminate most samples containing only noise), followed by the algorithm to be described, is greater by about 7 dB in typical cases. This is particularly interesting to SETI because such a pulsed signal is exactly what is sent by a rotating beacon with a directional antenna. Such a pulsed signal is, therefore, a good candidate for an extraterrestrial beacon. Software for detecting this signal type is now ready for field testing with the NASA Multi-Channel Spectrum Analyzer.

If the instantaneous peak-signal is large compared to noise fluctuations, and if the number of pulses detected in an observation period is of the order of 10 or less, a square-law detector is as sensitive to pulses as a matched-filter. This result is derived from the general form of the chi-square distribution. Requiring that pulses be regularly spaced in time in order to constitute a signal-like event helps keep the false alarm rate low. Overall false alarm rates can be set by a combined requirement on the minimum pulse height, total energy, and number of pulses in a sequence.

Pulse detection can be handled in near real time by a VAX 11/750 computer, processing data from the NASA prototype Multi-Channel Spectrum Analyser. Software to perform this task has been implemented in two ways. One method handles data in a pipeline, processing one observation while taking the next. A second analyses data during the observation, and can announce the early detection of a strong signal. If pulses with all regular spacings are considered, total computation with the present algorithm grows as the square of the time since the beginning of an observation. This limits the longest possible observation and, hence, the sensitivity of the techniques. Relative performances of the two methods was evaluated.

Jill Tarter, "Using the Very Large Array (VLA) Synthesis Radio Telescope to Perform a Parasitic Search for Extraterrestrial Intelligence." (IAA-84-245).

The Very Large Array (VLA) consists of 27 telescopes, each 25 m in diameter, which are operated as a multiplying interferometer to produce radio maps of the sky at four frequency bands (1.34-1.73, 4.5-5.0, 14.4-15.4, and 22-24 GHz). Since its dedication in 1980, this instrument has been in continuous use making high resolution maps having fields of view ranging from 10^{-3} to 0.2 square degrees, computed from data collected during observing times ranging from 30 minutes to eight hours (depending upon the frequency of the observation and the brightness of the source being studied). Occasionally within the field of view of some of these maps there are stars, whose existence is unimportant and generally unknown to the radio astronomer preparing the map; one of these stars might possibly be emitting a radio beacon signal of sufficient strength to be detectable if the data were properly analysed. It is more likely that any such signal, if noticed, would be interpreted as noise and systematically removed by the software that has been developed to help the astronomer produce the best possible map of the object at the centre of the field of view which he/she wishes to study. With the help of Drs. Ron Ekers and Robert Duquet, new software has recently been installed at the VLA which attempts to preserve data symptomatic of the existence of radio stars or SETI beacons and which would otherwise have been thrown away.

The Stellar Cross Identification Catalog (CSI) of the Strasbourg Stellar Data Center contains information on approximately 450,000 stars, much of it incomplete and prone to error. Nevertheless, it represents the largest available data set of machine-readable stellar identifications with positions. We have condensed this catalogue into a file of stellar positions and spectral types and stored it on disk at the VLA. Whenever a map is being processed at the VLA, background software searches through the CSI catalogue and attempts to locate any stars falling within the field of view of that map. On average, a star is found every two days and the raw data for the map is tagged and stored for future reference. At intervals (approximately every six months), maps of all fields of view containing a star are reconstructed from the raw data, and a search is made for an exact positional coincidence between the star and a point source "noise" feature in the map. The entire procedure is transparent to the astronomer and requires only consent to so manipulate the data. The processing overhead during the original map construction is trivial and does not impede the astronomer's progress. Map reconstruction and searches in the vicinity of the stellar positions are scheduled infrequently, during periods of otherwise low computer usage.

M. Subotowicz, "Threats to CETI-SETI, Possible Solutions and Anthropic Principle." (IAA-84-247).

After the paper of Cocconi and Morrison was published many scientists represented the opinion that the realisation of CETI is a matter of comparatively short time and some investments in radio telescopes. This opinion was connected with the conviction that: (1) planetary systems like that around the Sun are the common phenomena in the Galaxy, (2) life appears always where the proper astronomical and physical prerequisites like on the Earth exist.

Now it is not possible to contradict both the above statements, but they are also not confirmed in proper observations. Our problem may be treated first from the standpoint of view of the principles, namely – of the cosmological principle: "Our position in the Universe cannot be preferred in any sense" or "apart from the local irregularities the Univserse is single realisation of a stochastic process, stationary with respect to displacements in space, but probably – nonstationary in time." Life can evolve in favourable environments, as on the Earth. Taking into account the cosmological principle one could tell: what was possible on Earth, should be possible elsewhere. Really, this is the problem of the locality or non-locality of the existence of life. Life could be – till now – accepted as the "local irregularity" in the immense Universe.

Another approach to this problem represent the physicists and astronomers raising the *anthropic principle (AP).* AP claims that many properties of the physical world are determined in an essential way by the existence of homosapiens in the world. Manipulating with some fundamental physical constants one can get on the base of AP many interesting coincidences and values of the particular physical quantities. In an arbitrary way accepted in AP the direct connection between the existence of the wise being (homosapiens) and the values of the physical constants. The values of the physical constants are in close connection with the initial conditions of the evolution of the Universe: homgeneity and isotropicity, as it requires the Einstein-Friedmann-de Sitter model of the Universe, with its "flatness" and "horizon." Some corrections to the existing models of the evolution of the Universe are proposed by the Grand Unification Theory (GUT) and inflationary model of the Universe of Guth. One of the possible interpretations of AP is that already in the moment of the Big Bang should exist the "initial conditions" guaranteeing the possibility of the origin of life after many billion years, and earlier – the origin of galaxies, stars and planets of the proper chemical composition and proper physical properties in some spherical part of the Universe; this result is difficult to accept. Life would be the regular event, not a "miracle" that leads to the development of the

scientific-technical civilisations. In that case life would be the non-local phenomenon. Is it necessary to generalise AP in this way? The author is of the opinion that the physical laws describe the outer world in a satisfactory way. The assumptions of AP do not result from any fundamental physical theory.

Apart from principles concerning the existence of life we are going to enumerate other threats to CETI-SETI that can be realised – possibly – in the visible, IR and microwave ranges of the electromagnetic radiation. Detection of this radiation is threatened by the antropogenic radiation from the Earth and soon – by the satellite solar power systems. A large scale programme of SETI to scan the stars with high resolution using 10^6-multichannel analysers, and up to 1000 light years from the Sun, is a costly procedure and it will be difficult to receive the proper financial support of the governments and societies. As the momentary outcome is proposed to couple the SETI activity with that of the radio astronomy and astrophysics (idea of the serendipity and that of "archival" approach).

The discovery of extrasolar planetary systems will change the above described situation drastically.

There are several barriers not only for the manned flights to the stars, but also for CETI-SETI: huge interstellar distances, interstellar plasma and dusts, necessary power to send not only the interstellar ships but also the electromagnetic signals, high costs of the radio telescopes and other apparatus, economical and social difficulties of the civilisation, lack of interest in the society for CETI-SETI, fear that our civilisation can collapse in the nuclear war without solving its problems of survival and existence, fear of contact with other civilisations and so on.

Many cosmic planetary factors could decide about the origin and development of life by means of evolution. All these factors may influence CETI and SETI.

All the discussed phenomena and events may change very drastically the numerical values of the probabilities existing in the Drake's equation. The main of these factors would be the locality of life. But the principal answer will be given not by the theoretical consideration: only by the search for planetary systems (observations) and analysis of the different aspects of the development, evolution and metabolism in living organisms, looking also for other possible biological systems (laboratory work).

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THE SEARCH FOR EXTRATERRESTRIAL LIFE: RECENT DEVELOPMENTS. A REPORT ON IAU SYMPOSIUM 112

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This paper is a report on the International Symposium "The Search for Extraterrestrial Life: Recent Developments" which was held in Boston, Massachusetts, USA, 18-21 June 1984. It was the first IAU Symposium organised by Commission 51 of the International Astronomical Union (IAU), and was co-sponsored by the IAF/IAA, COSPAR, ISSOL and IUBS. This report describes the highlights from the seven Sessions and two special events of the Symposium, which was attended by 145 participants from 18 countries and in which more than 50 invited and contributed papers were presented. It also discusses the future plans and activities of IAU Commission 51.

1. THE ORGANISATION OF THE SYMPOSIUM

It was an important recognition for this new field when in 1982 the International Astronomical Union established a new commission (section) under the title: IAU Commission 51 – Search for Extraterrestrial Life, which rapidly grew to a membership of about 250 (210 astronomers and 40 distinguished scientists from related fields) [1].

The first IAU Symposium of Commission 51 was held in Boston, Massachusetts, USA, 18-21 June 1984, and was co-sponsored by four other major international organisations: IAF/IAA (International Astronautical Federation/ International Academy of Astronautics), COSPAR (International Committee on Space Research), ISSOL (International Society for the Study of the Origin of Life), and IUBS (International Union of Biological Sciences). The meetings were held in the new Science Center of Boston University, the home institution of the President of Commission 51 Prof. Michael D. Papagiannis. The Symposium was attended by 145 people from 18 different countries spanning all five continents, and was financially supported by the IAU, NASA and Boston University.

The twelve member Scientific Organizing Committee was headed by Michael D. Papagiannis and included the representatives of NASA (John Billingham), COSPAR (Donald DeVincenzi), IAF/IAA (Rudolf Pesek), ISSOL (Cyril Ponnamperuma) and IUBS (Otto Solbrig), as well as the representatives of the IAU Frank Drake (USA), Jun Jugaku (Japan), Nikolai Kardashev (USSR), George Marx (Hungary), Carl Sagan (USA) and V. S. Troitsky (USSR). The eight member Local Organising Committee was headed by Philip Morrison of MIT and Edward Purcell of Harvard University, and included Tom Bania and Michael Papagiannis of Boston University, David Staelin of MIT, Paul Horowitz, Ed Lilley and Stephen Jay Gould all three of Harvard University, with Gould representing the life sciences.

The Symposium opened with a welcoming reception in the elegant "Castle" of Boston University, and closed with a visit to the Harvard-Smithsonian Oak Ridge radio observatory which has now become a SETI dedicated facility. We also had a formal banquet for the Symposium in the Hall of Flags of Boston University with Carl Sagan as the banquet speaker, and a special event at Boston's Museum of Science which included a reception, a welcoming address to the Symposium Participants by the Director of the Museum, Dr. Roger Nichols, and an inspiring talk by Philip Morrison. The title of the talk was "25 years and 30 AU" and in it he recounted how far, both literally and figuratively, we have gone in our searches and explorations during the past 25 years.

During this event, IAU Commission 51 honoured Prof. Morrison with a plaque commemorating the 25 years since the publication in *Nature* in 1959 of the historic paper of G. Cocconi and P. Morrison "Searching for Interstellar Communications" [2], which ushered in the experimental era in the search for other stellar civilisations. The last sentence of their paper was a stimulating call for action. They said "The probability of success is difficult to estimate; but if we never search the chance of success is zero." This call was answered almost immediately by a young radioastronomer, Frank Drake, who is now Vice President of IAU Commission 51.

On the occasion of our IAU symposium, Cocconi wrote to Morrison from CERN in Geneva saying, "The initial opposition to our paper was similar to that met by the pioneers of aviation; Why disturb the Angels?" "Now," Carl Sagan said in his banquet speech, "it has become mainstream science."

The scientific programme consisted of seven, half-day Sessions. The topics, chairmen, and highlights of these Sessions are discussed in the sections that follow.

2. THE SEARCH FOR OTHER PLANETARY SYSTEMS

This was the first Session of the Symposium, and was chaired by Carl Sagan of Cornell University and Jun Jugaku of the Tokyo Observatory. George Aumann of JPL reported that about 20% of the more than 300 nearby sunlike stars observed with the Infra-Red Astronomy Satellite (IRAS) appear to have extensive dust envelopes or disks, possibly indicating planetary formation. Steven Beckwith of Cornell University reported also the presence of dust envelopes in some young nearby stars from ground observations using speckle interferometry.

The development of photoelectric and interferometric devices for the detection of large planets in nearby stars is progressing very well and we can expect important results before the end of this decade. Optimistic were also the reports on the potential use of the 13.2 metre long, 2.4 metre diameter Space Telescope for the detection of planets, especially in cases of star occultations by asteroids. The Space Telescope is expected to go into orbit in 1986.

Fig. 1. A group of prominent IAU Symposium 112 participants, from the Symposium Banquet. From left to right: Edward M. Purcell, Nobel laureate, co-discoverer of the 21 cm hydrogen line; Philip Morrison, co-author of the 1959 pioneering paper on SETI that ushered in the experimental era; Carl Sagan, distinguished scientist and author, Banquet speaker; Michael D. Papagiannis, President of IAU Commission 51 and organiser of the Symposium; Frank D. Drake, conducted the first radio search (Project Ozma, 1960), and Vice President of IAU Commission 51.

Boston University Photo-Service

3. PLANETARY, INTERPLANETARY AND INTERSTELLAR ORGANIC MATTER

This was the next Session and was chaired by William Irvine of the University of Massachusetts and Donald DeVincenzi of the NASA Headquarters. There is now ample evidence that organic matter is quite common both in our Solar System and in interstellar space. Carl Sagan discussed the presence of organic matter in the outer Solar System focussing especially on the moons of Saturn, Iapetus and Titan, the last one having also a dense nitrogen atmosphere and possibly on its surface seas of liquified hydrocarbons. Cyril Ponnamperuma confirmed the presence in meteorites, that most probably are of asteroidal origin, of all five of the nitrogen bases of DNA and RNA.

R. D. Brown of Monash University, Australia discussed his work with organic matter in interstellar clouds, and J. Mayo Greenberg of the University of Leiden, Holland, discussed his work on interstellar grains. Greenberg discussed also some laboratory experiments which indicate that in the vacuum and cold temperatures of interstellar space, bacterial spores may survive the ultraviolet radiation of interstellar space for a few thousand years. This is still too short a time for spores to travel from star to star, but if the parent star was passing through a dark cloud the spores could acquire an additional coating from the molecular cloud and survive for millions of years "I do not say that Panspermia exists" he told the meeting, "but we can now begin to talk about it in quantitative terms."

4. UNIVERSAL ASPECTS OF BIOLOGICAL EVOLUTION

This was a strongly interdisciplinary Session and certainly one of the most interesting of the Symposium. It was chaired by Lynn Margulis of Boston University and John Billingham of NASA-Ames. Papers by Leslie Orgel of the Salk Institute, Cyril Ponnamperuma of the University of Maryland, and Andrew Knoll of Harvard University emphasised the point that primitive microorganisms appeared very early (3.5 and possibly 3.8 billion years ago) in the history of the Earth. "We find life in the first rocks capable of holding it" said Stephen Jay Gould of Harvard University. Of great interest was also the report on the periodic extinctions of large numbers of species, by John Sepkoski of the University of Chicago. From fossil records, Raup and Sepkoski [3] have deduced that these extinctions occur every 26-27 million years. By suddenly eliminating many species, these extinctions make room for the emergence of new ones, thus providing an external impetus to the process of biological evolution.

The most impressive of these extinctions was the Cretaceous-Tertiary event 65 million years ago, which among others produced the sudden disappearance of the dinosaurs. This in turn triggered the rapid expansion and evolution of mammals which filled the created vacuum. Louis and Walter Alvarez [4], have found that sediments from that period contain a thin, Iridium-rich layer, which they believe is the calling card of comets or asteroids. Richard Muller of the

University of California-Berkeley reported that the record of large, old craters on Earth shows also a periodicity of 26-28 million years with its peaks coinciding rather well with the extinctions. Muller and his colleagues believe that these periodic massive bombardments of the Earth are triggered by a companion star, on an elliptical orbit around our Sun, which every 26-28 million years passes through the Oort cloud sending an avalanche of comets toward the inner Solar System. Muller's group at Berkeley has already started the search for this low luminosity companion star, which now must be close to its furthest point from the Sun at a distance of 2.0-2.5 light years.

Muller and his colleagues [5] have proposed the name "Nemesis" for this star, after the Greek goddess for disaster (disaster, by the way, in Greek means "bad star"), but Harlan Smith of the University of Texas suggested at the meeting that since these catastrophies fuel also the evolutionary process and open the way for the appearance of new species, a more appropriate name might be "Siva" the Hindu god for destruction as well as for rebirth.

5. RADIO RESEARCH - RECENT OBSERVATIONS

This was the fourth Session of the Symposium and was chaired by Edward Purcell and Edward Lilley, both of Harvard University. It is interesting to note here that Purcell, a Nobel Laureate, was also the co-discoverer in 1951 with H. I. Ewen (his thesis student) of the 21 cm radio line of Hydrogen. This was the wavelength that Cocconi and Morrison proposed in 1959 to use in our searches, because it "must be known to every observer in the Universe," and was also the wavelength of the first radio search of two near-by stars (ϵ Eridani and τ Ceti) conducted by Frank Drake in 1960. It was most inspiring that all three of these protagonists, Ed Purcell, Philip Morrison and Frank Drake, were all present and very actively involved in the first IAU Symposium on the Search for Extraterrestrial Life. Figure 1 is from the banquet of the Symposium and shows Purcell, Morrison and Drake together with Carl Sagan and Michael Papagiannis.

In a review paper, Jill Tarter of NASA-Ames and the University of California-Berkeley reported that from 1960 to 1984 there had been at least 46 different searches, most of them at the Hydrogen line. She also reported how the technological sophistication of the searches, as well as the international participation in this effort, have increased in an impressive manner during these past 24 years. Paul Horowitz of Harvard University reported on his Project Sentinel which, with the support of the Planetary Society, has been using the Harvard-Smithsonian 84-ft radio telescope at the Oak Ridge Observatory for an all-sky survey at the hydrogen line. This radio telescope has now become a SETI dedicated facility and has been operating on a 24 hour basis since March 1983. Robert Dixon of the Ohio State University reported on the other continuous search, the Ohio SETI Program, which is supported by NASA and has been in operation since 1973.

6. TECHNOLOGICAL PROGRESS IN RADIO SEARCHES

This Session was chaired by Frank Drake, previously of Cornell University and now of the University of California-Santa Cruz, and George Marx of Eötvös University, Hungary. The reports presented showed the great progress that is now being made both in the hardware and in the software for SETI. They also emphasised the potential uses of these new developments in several other areas of science ranging from radioastronomy to brain research.

Bernard Oliver of NASA-Ames, who is now the Director of NASA's SETI programme, and Kent Cullers, also of NASA-Ames discussed the development of sophisticated algorithms for fast data processing and signal recognition, while Alan Peterson of Standford University gave a progress report on the 8-million channel, 8 MHz Standford-NASA spectrum analyser. When completed around 1988, it will be used to cover the entire 1-10 GHz range in NASA's well planned programme of targeted and all-sky searches. Paul Horowitz of Harvard University described his new narrow-band, 8.4 million channel spectrum analyser, which in early 1985 will be added to his Project Sentinel thus expanding its frequency range by more than hundredfold to 350 kHz. H. Hirabayashi of the Tokyo Observatory described the Fourier transform spectrometres being prepared for the new 45 metre microwave radiotelescope at Nobeyama Japan, which will spend a portion of its time on a Japanese SETI programme.

7. THE FERMI PARADOX AND ALTERNATIVE SEARCH STRATEGIES

This Session was chaired by Philip Morrison of MIT and was certainly one of the liveliest of the entire Symposium. The Fermi paradox can be summarised in the following statement: If there were many other technological civilisations about other stars, they would have long ago colonised the entire Galaxy and hence our own Solar System, but then where are they? This apparent contradiction has been named after the famous Italian physicist Enrico Fermi, who supposedly was the first one to pose this question.

Franke Drake, Eric Jones of the Los Alamos National Laboratory, John Wolfe of NASA-Ames, John Ball of the Harvard Observatory, Ben Finney an anthropologist and explorer from the University of Hawaii, and others, debated the feasibility and/or the inevitability of galactic colonisation, a subject that has attracted great interest in the recent years [6, 7]. For the first time, however, a new consensus began to emerge, namely the admittance of our ignorance of how stellar civilisations far more advanced than ours are likely to behave. As a result, none of us can be very certain on whether they will choose to colonise the Galaxy, or even to reveal their presence if they happen to have space colonies in our Solar System. Michael Papagiannis summarising this point said: "We have finally entered the experimental stage in the search for extraterrestrial life. Debates are interesting and in many ways useful, but we must not let them slow down the momentum we have gained. A flexible search strategy, which in addition to several basic programmes would also encourage the experimental testing of alternative theories, seems at this stage the most prudent approach."

8. SUMMARY AND CONCLUSIONS

This was the last Session of the scientific programme, and was chaired by Harlan Smith of the University of Texas. In the beginning of the Session, George Gatewood of the Allegheny Observatory of the University of Pittsburgh, William Irvine, John Billingham, Jill Tarter, Frank Drake and Philip Morrison summarised the highlights from each one of the first six Sessions. They were followed by Paul Horowitz, Bernard Oliver, J. Mayo Greenberg, John Ball, George Marx and Michael Papagiannis who were invited commentators. At the end Harlan Smith gave a balanced summary of the entire Symposium mentioning also the opposing points of view that have been advocated in the literature by Michael Hart, Frank Tipler and others.

The general consensus was that it was a very successful

meeting which accomplished several important objectives, including the following:

1. It established the scientific credentials of this new field, and launched in an impressive manner this new IAU Commission.

2. It brought together distinguished scientists from many different fields (astronomy, biology, chemistry, paleontology, physics, anthropology, etc.), as well as from many different countries, thus strengthening the interdisciplinary and the international base of this effort.

3. It provided accurate information for the general public through excellent reports on the Symposium by top science editors in some of the most prestigeous news media including Walter Sullivan in the *New York Times,* Robert Cooke and David Chandler in the *Boston Globe,* Robert Cowen in the *Christian Science Monitor,* etc.

4. It made it clear that by the end of this decade we will have the instruments, and possibly the first results, for an effective search for large planets around the 100 to 200 nearest stars.

5. Also, that by the end of the 1980's we will have the highly sohphisticated megachannel spectrum analysers and signal recognition algorithms to undertake the most systematic and comprehensive radio searches ever attempted. These targeted and all-sky searches over a wide frequency range, which are being carefully planned by NASA, will exceed by several orders of magnitude what has been accomplished so far and will bring us much closer to an answer on the abundance of other communicative civilisations in our Galaxy.

9. A SAD NOTE WITH A HAPPY ENDING

The only major disappointment of the Symposium was the absence of our colleagues from the USSR. The three Soviet scientists who were scheduled to participate, give papers, and chair one of the Sessions withdrew at the last minute. They did send, however, a long telegram with warm greetings to all the participants and best wishes for the success of the Symposium. The message stressed the need for international collaboration in the search for intelligent life in the Universe and added "In the complicated situation of the modern world, the search for intelligent life in the Universe helps to recognise better the unity of human culture and the need to preserve peace on Earth," It was signed by: V. A. Kotelnikov, N. S. Kardashev, L. M. Gindilis, L. M. Mukhin, V. I. Slysh, V. S. Troitsky and J. S. Shklovsky.

M. D. Papagiannis cabled back on behalf of the Organizing Committee, saying "Thank you for the warm feelings about our first IAU Symposium and the strong support for international collaboration in the search for extraterrestrial life," and read both messages at the opening Session of the Symposium. Later on, at the suggestion of Phylis and Philip Morrison, we all signed the cover of the Morrison's new book "Powers of Ten" and Carl Sagan took it with him to the COSPAR meeting in Austria and gave it to Nikolai Kardashev, Vice President of our IAU Commission 51 and also Vice President of COSPAR.

Finally in August, 1984 M. D. Papagiannis went to Moscow for the International Geological Congress as a guest of the USSR Academy of Sciences and brought to our Soviet colleagues mementoes from the Symposium (Paul Revere bowls, a symbol of Boston, inscribed IAU SYMPOSIUM 112 *JUNE 1984* BOSTON 1984, which had been give to all the Symposium participants). He also gave an invited lecture on the results of the Symposium at the Institute fo Space Research of the USSR Academy of Sciences, where many of our Soviet colleagues hold prominent positions, and invited them to send their papers for the Proceedings. The happy ending is that in spite of their initial absence, the Soviets will be present in the volume of the Proceeding of the Symposium with two contributions, one by N. S Kardashev and one by V. I. Slysh.

10. FUTURE ACTIVITIES OF IAU COMMISSION 51

The Organizing Committee of IAU Commission 51 held meeting during the Symposium in which several importan resolutions were formulated and the following day wer unanimously endorsed by all the members present. Th President of the Commission communicated these resolutions to the Executive Committee of the IAU, which ha already endorsed the following ones:

1. The next IAU Symposium of Commission 51, at the invitation of the Hungarian Academy of Sciences, will be held in Hungary in June 1987.

2. The next President of Commission 51, for the period 1985-1988, will be Frank D. Drake. He is currently one of the two Vice Presidents of the Commission, and the Dean of Natural Sciences at the University of California – Santa Cruz. He is also a member of the U.S. National Academy of Sciences.

3. The next Vice President of our Commission will be George Marx of Eötvös University, Budapest, Hungary and a member of the Hungarian Academy of Sciences.

4. The 10 member Organizing Committee of IAU Commission 51 will consist of the following: R. D. Brown (Australia), P. Connes (France), G. D. Gatewood (USA), J. Jugaku (Japan), P. Feldman (Canada), J. Mayo-Greenberg (Holland), N. S. Kardashev (USSR), P. Morrison (USA), M. D. Papagiannis (USA), and V. S. Troitsky (USSR).

5. Eight prominent scientists from other fields, who had been serving as Consultants of Commission 51, have, at the recommendation of our Commission, been elected full members of the IAU. They are:

   John Billingham, Chief, Extraterrestrial Research Division, NASA-Ames Research Center, Co-chairman, IAF/IAA CETI Committee.
   Donald Devincenzi, Chief, Research and Development Life Sciences, NASA Headquarters, Secretary of ISSOL. Chairman, Sub-Commission F-3 of COSPAR.
   Paul Horowitz, Professor of Physics, Harvard University, Director, Project Sentinel.
   Anthony R. Martin, Physicist, UKAEA Culham Laboratory, England. Editor, *JBIS* Interstellar Studies.
   Bernard M. Oliver, Director of NASA's SETI Program, NASA-Ames Research Center.
   Rudolf Pesek, Member, Czechoslovak Academy

of Sciences. Co-Chairman, IAF/IAA CETI Committee.
Cyril Ponnamperuma, Professor of Chemistry, University of Maryland. President of ISSOL.
Edward M. Purcell, Professor of Physics, Harvard University, Nobel Laureate in Physics. Co-discoverer of the 21 cm radio line of Hydrogen.

11. PUBLICATIONS

The next issue of "Bioastronomy News," the news bulletin of IAU Commission 51, will be mailed to the more than 250 members of our Commission in the beginning of 1985. We regret that because of limited funds and help we cannot satisfy the many requests we have received from individuals, organisations and libraries to put them on the mailing list of IAU Commission 51 to receive our bulletin. Our inability to respond is contrary to our wishes, because we do indeed want to communicate our activities and every progress that is being made in this new field. For this purpose we publish periodically a summary of the activities of IAU Commision 51 in professional journals, which can be found in most libraries, and thus we make all this information available to our many friends who want to know about our work.

The Proceedings of our Symposium, for which many people have also asked us, are scheduled to be published early in 1985 by the D. Reidel Publishing Co. (P.O. Box 17, 3300 AA Dordrecht, The Netherlands) in their Series of IAU Symposia. The volume will contain about 50 contributions from many well known scientists from several fields and countries, as well as commentaries and introductions by the Editor of this volume, Michael D. Papagiannis [8].

12. CONCLUDING REMARKS

Following this most successful IAU Symposium, the general feeling has been that this new field, for which the participants unanimously endorsed the name BIOASTRONOMY, has finally gained the scientific acceptance it deserves. It tries to answer a very profound and highly intriguing question that has occupied the minds of people for thousands of years: Is there any other life, primitive or advanced, anywhere else in the Universe? On this Carl Sagan said at the banquet: "Provided we play, we win" because, he explained, even if after an extensive search we were to find nothing, "this would still teach us a valuable lesson about our place in the Universe, and would also tell us we should be very careful with the sole living planet in the Cosmos."

At the closing of the Symposium, Michael Papagiannis thanked all the participants for their contributions, and concluded by saying: "We stand at a historic threshold because we finally have the technology to open the windows of our tiny planet and seek experimentally the answers to fundamental, old questions about the Universe and the plurality of life in it. Let us take full advantage of this unique opportunity."

ACKNOWLEDGEMENTS

We want to thank The British Interplanetary Society and especially Dr. Anthony R. Martin, the Editor of Interstellar Studies of the *JBIS* for the kind hospitality they have offered to IAU Commission 51, allowing us to communicate through the pages of *JBIS* with the many people who have an interest in this new, interdisciplinary branch of Astronomy.

I want to personally thank my colleagues Tom Bania and Robert Stefanik of Boston University and Eugene Mallove of the Lincoln Laboratories for their invaluable help with all the logistics and the organisational details of the Symposium. I also want to thank the many participants who wrote warm letters congratulating us for the successful organisation of our first Symposium. Their good words were a much appreciated reward.

In closing, we want to express our deep appreciation to the IAU, to NASA and to Boston University for their financial and moral support, which made possible the first IAU Symposium of IAU Commission 51.

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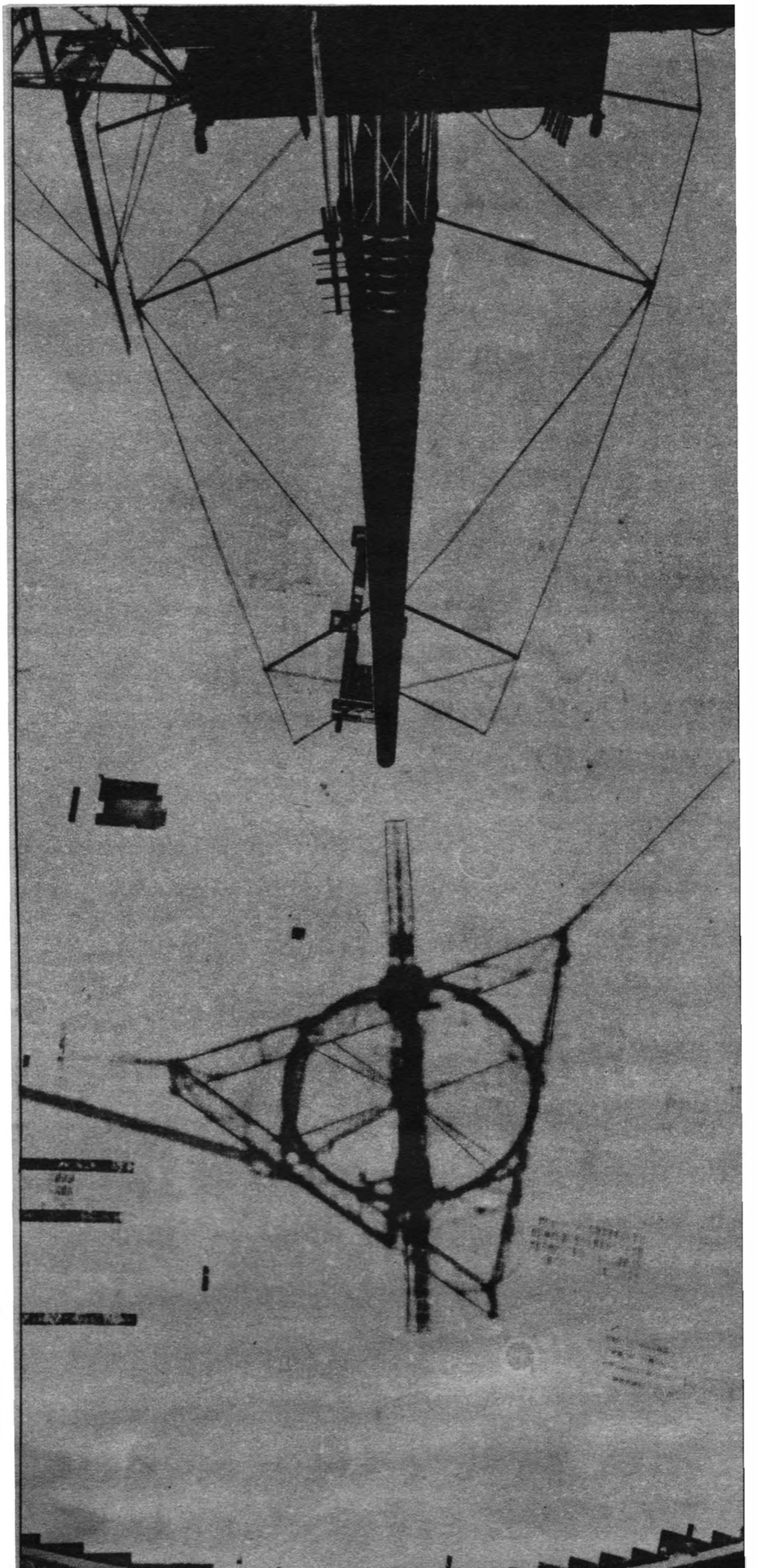

The Arecibo Observatory's longest antenna for receiving radio signals from space stretches 29 m from base to tip and weighs almost five tonnes. Hanging from the very bottom of the triangular support structure, the antenna points to the platform's shadow on the shiny aluminium surface of the reflector – hundreds of feet below the tip of the antenna.

National Astronomy & Ionosphere Center.

CORRESPONDENCE

Solar Windmills

Sir, Referring to Guarav Rajen's letter in *JBIS*, **37**,September 1984, Rajen makes the elementary but all too common error of thinking that solar sails use the solar wind.

A solar sail is propelled by the pressure of light, and not to any significant extent by the solar "wind" (of protons and electrons). The relative magnitudes of the forces arising from these two sources that act on a solar sail are readily compared: The solar "wind" at the distance of the Earth from the Sun (i.e. at I.A.U.) has a density of 5 x 10^6 protons per cubic metre, and a typical velocity of 3 x 10^5 metres per second.

The mechanical pressure exerted by wind normal to a flat surface is given by (density x velocity squared): the mass of a proton is approximately 1.67 x 10^{-27} kg, and hence the pressure exerted on a sail by "wind" is given by

$$P = 9 \times 10^{10} \times 5 \times 10^6 \times 1.67 \times 10^{-27}\ N/m^2$$
$$= 7.5 \times 10^{-10}\ N/M^2$$

By comparison, the mechanical pressure exerted by light against a normal reflecting surface is given by 2I/C, where I is the electromagnetic energy intensity, and C is the speed of light. The intensity of sunlight in near-Earth space (the solar constant) is approximately 9.3 x 10^{-6} N/m^2. Thus the light pressure is more than 10,000 times greater than the pressure of the solar wind which can therefore be ignored as far as propulsion or windmilling is concerned.

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Dancing in Our Lenses

Sir, Regarding the article "Dancing in Our Lenses: Why There Are Not More Technological Civilisations," (*JBIS* November 1984). I was rather interested to find that, when it came down to it, I couldn't 'think 'alien", and this led me to thinking about the demonstrable difficulty of humans in understanding points of view they do not hold – it takes an effort to see things from the other side of the table, so to speak – especially if that viewpoint ties in with a very different culture. If to offend a politician on the other side of the table can lead to war, DARE we contact alien *species* with their alien needs and ways?

I believe there is a strategy we can employ to make things easier; (and safer). The obvious answer is to have an ambassador familiar with both cultures. Failing that, we can ánalyse the social and mental 'worlds' of the creatures on Earth; store, in exchangeable form, data relating to the instincts, reflexes and types of 'reason' used by the creatures to deal with their environment. Is it so that we have at our fingertips a biogrammar 'phrase-book?' Well, any alien being may possess parts of the reflexes of earthly beings, but also reflexes adapted to their totally alien environment, so that it seems like tackling a New Guinea tribesman with a French phrase-book. But the real resource we will have after analysing dolphins, ants, wolves, etc., is not the phase book in itself but our familiarity with the theory of reflex and instinct the 'philosophical' experience in taking cultures apart (metaphorically).

Now, our ambassador is a *method* of computing. We can employ machines as intermediaries, because a computer can be programmed to use one set of rules or another – Human; Bee; Trout; Alien; SSE; etc.

From there we can, as we meet aliens, communicate and learn still more about ways of looking at life. BUT would an alien viewpoint MEAN anything to us? We might have a chance of understanding if we had practise in using other creatures' senses – if they had senses relatable to ours. What I mean is that we might transpose the bees visual spectrum into the human range; record some of the spider's tactile 'map' and 'map' it on to the human body; but the real answer is – unless they have a similarity to human life then we wouldn't understand them, even *via* a computerised ambassador.

Is there a need to be alien, though, when we need only programme our ambassadors to select the data and experience that we need and deal with aliens on a basis of trading what CAN be traded, and sharing what CAN be shared – and letting them live in their alien way while we live in ours. Unless they were human their environmental needs would be different and if they are the dominant species on their world they would have done very well without us; and I suggest we use worlds where they don't live – after all why go down with some exotic species of bug when all the raw materials we need, to continue to be human (in O'Neill type 'worlds'), are on airless and barren, or frozen and useable, worlds with suns pouring out lots of free energy.

Why *should* we fill up the Galaxy with the human race – till we can use it sensibly, and learn to share our world with the creatures that inhabit it, as they may be sharing our 'world.' After all, regarding the article 'Dancing in Our Lenses' all they need do is arrive, they don't need to have what WE would call intelligence. Why need they mimic us?

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New Tendencies in CETI-SETI

Sir, CETI-SETI - problem, as we understand them now, can be successfully investigated after solving two fundamental questions:

(a) origin and existence of planets around the stars,

(b) origin and evolution of life on these planets.

Initial broad interest in ETI (Extra-Terrestrial Intelligence) after the publication of the well-known paper by Cocconi and Morrison (1959) in *Nature* has now less publicity but also more scientific approach to the CETI-SETI problems. We understand now that these problems can be solved only experimentally:

(1) by sending signals or looking for the electromagnetic signals from ETI by very sophisticated receivers and analysis. Spectral analysis and signal processing allows us to increase the search space and rate of coverage (e.g. multichannel spectrum analyser (MCSA) filtering a wide-band signal into many narrower bands; MCSA provides simultaneous output bandwidths of approximately 1 Hz, 32 Hz, 1024 Kz and 74 kHz over a spectrum about 8 MHz wide). This increase in the rate of coverage of search space can be many orders of magnitude larger than former searches

and at reasonable cost. Over the past 20 years 46 searches were performed without success. These searches covered a small fraction of the total search space. In the search of signals from ETI are possible the "serendipitous" and "archival" approaches, connecting SETI with the standard radio astronomy research. SETI is limited through financial reasons and the electro-magnetic "pollution" of the environment around the Earth,

(2) performing very intensive investigations in molecular biology and in biology looking for metabolism in the biological structures and their development during evolution to the level of homo sapiens. There should be determined very exactly all the possible factors designating the rate and direction of the evolution.

Contemporary knowledge in biology, physics, chemistry, planetary sciences and astronomy support the conclusion that life may be wide-spread in the Universe. This was the reason why the Soviet Academy of Sciences and NASA developed research and development programmes of SETI-CETI. But we understand now much better than in the time of the realisation of the OZMA programme by Drake (1959-60) the complexity of the conditions of the origin of life, its evolution to the level of sending signals to, or receiving from, other ETI's. Preferable in SETI is the microwave region of the electro-magnetic spectrum (water hole: 1.4 to 1.7 GHz), but also millimetre- and infrared regions are taken into account. The question of the existence of advanced extraterrestrial life can be solved only by receiving intelligent signals. Interstellar travel seems to be more and more distant, if even impossible.

The situation in CETI-SETI can be drastically changed after the possible discovery of extrasolar planets when space telescope, satellite Hipparcos or infrared satellites will be used. The astronomy and scientific communities will get useful byproducts from SETI searches. A SETI programme should be realised quickly because of growing radio frequency interference by transmission of terrestrial sources of the electromagnetic radiation (satellite television, solar power station, etc.). There are proposals to realise SETI-CETI by use of space telescopes in satellite orbits or on the far-side of the Moon (M. Subotowicz, 1976).

When realising an active CETI (sending signals from the Earth or space orbit in the Solar System) we should take into account the following dimensions unkown to both civilisations: distance, direction, polarisation, signalling rate, bandwidth, modulation, all inter-related, and frequency. When planning CETI-SETI, we should minimise the extent of these dimensions by applying ideas (Dixon, 1973, 1977) of *anticryptography* (..."beacons should be designed and operated in such a way as to maximise their probability of discovery, both by intentional searches and by accidental observation"), and *mediocrity* (..."we are just average among the inhabitants of the universe"). There was proposed (M. Subotowicz, 1979) a third idea of *partnership* (..."every civilization realizes active and passive CETI if only it can do it"). From the last idea (partnership) it follows that we should not only search for signals of ETI (passive CETI and SETI), but also send our signals (active CETI). If the terrestrial civilisation does not send signals to ETI, why we expect that ETI will send signals (beacons) elsewhere, also to us?

We can say that SETI-CETI can be the most ambitious adventure of our civilisation. There is planned very careful scanning of the sky to look for beacons from ETIs around the nearest stars (up to 10,000 light years). If we do not receive the artificial signals (beacons) from outer space we could formulate the OLBERS-like paradox in CETI-SETI, ("Our CETI-CETI sky is dark at night and day," similarly to fermi's "Where are They?") that there do not exist the scientific-technical civilisations capable of sending artificial signals containing some message and information in the distance from 1,000 to about 10,000 light years.

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