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Galaxy in Ursa Major, NGC 3718. A type S0 (pec), with unusual absorption features.

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INERTIAL FUSION SYSTEMS STUDIES AND NUCLEAR PULSE PROPULSION

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Although inertial fusion systems studies have dealt primarily with commercial electric power generation, they may have broad implications for thermonuclear rocket propulsion. Recent developments in these studies, ranging from new projections of fusion energy gain to more detailed models and analyses of reactor systems, are reviewed here. Important similarities and distinctions between electric power applications and rocket propulsion applications are identified, and prospective research problems in thermonuclear pulse propulsion are discussed. It is concluded that the prospects for thermonuclear rocket propulsion are significantly affected by inertial fusion systems studies.

1. INTRODUCTION

In recent years, extensive systems studies of inertial fusion electric generating stations and fissile fuel production facilities have enhanced our understanding of the prospects for terrestrial applications of fusion microexplosions. These studies may contain broad implications for the feasibility of nuclear pulse propulsion. This paper reviews advances in inertial fusion systems studies and assesses their effect on the prospects for rocket propulsion. New developments since Project Daedalus [1] are summarised, and the present status of inertial fusion systems studies is described. Driver development, target studies, reaction chamber studies, pellet injection and tracking studies, and systems studies are reviewed. Important distinctions between electric generating station applications and nuclear pulse propulsion applications are identified, prospective propulsion application research problems are discussed, and conclusions concerning the implications of inertial fusion studies for rocket propulsion are presented. A complete historical review of nuclear pulsed propulsion and fusion microexplosion rocket concepts is presented in Ref. 2.

2. DEVELOPMENTS SINCE PROJECT DAEDALUS

Several new developments that have occurred since Project Daedalus must be considered in any assessment of the prospects for inertial fusion rocket propulsion. These developments are part of a broad-scale conceptual advance in the field of inertial fusion. Although the broad-scale effort has been motivated principally by military, commercial electric power, and fissile fuel production applications, the new developments present certain implications for inertial fusion rocket propulsion.

One of the more significant developments since the Daedalus study has been the revision of pellet performance estimates. At the time of the Montreal Quantum Electronics Conference, it was believed that the energy break-even condition could be attained with an energy as small as a kilojoule and that an electricity-producing reactor might require hundreds of kilojoules [3]. Since then, the estimates of beam energy required to achieve the break-even condition and an economic reactor have climbed steadily. Today, it is believed that the break-even condition may require 100 kilojoules to a megajoule or more and that an economic reactor may require 10 megajoules. These estimates are based on the assumption of D-T fuel cycles and maximum 30 per cent recirculating power fractions for economic power generation. For advanced fuels and low-mass rocket engine applications, where the permissible recirculating power fraction is likely to be even less, the requirements of beam energy will be even higher. This has important implications for mission performance.

A second consideration is that the revised target performance estimates place upward pressures on driver efficiency. As it becomes increasingly difficult to extract a given amount of energy from a pellet, more and more electrical energy must be supplied to the driver. Because the amount of electrical energy that must be supplied to the driver depends on the driver's electrical efficiency, a premium is placed on high-efficiency drivers. At the time of the Montreal conference and the Daedalus study, propects for the development of high-efficiency drivers were somewhat more hopeful than they are at present. This also has implications for spacecraft propulsion.

Against this somewhat pessimistic backdrop stand several promising developments in recent systems studies. We now have a better understanding of reactor cavity phenomenology and are better able to model the complex phenomena occurring in and around the exploding pellet. Because we are better able to perform conceptual designs of realistic systems, we need allow less of a margin of uncertainty and need be less conservative in our designs. The result is a more efficient, higher performing reactor that more closely approaches an optimum configuration. Since inertial fusion rocket propulsion will stretch design considerations to the limit, these improvements are particularly important in reaching an overall assessment of the feasibility of thermonuclear pulse propulsion.

In addition to an improved quantitative understanding of reactor design principles, several qualitative advances, including new first-wall protection concepts, have been achieved. Although the function of the first wall in a terrestrial reactor is to provide a pressure boundary to maintain cavity conditions against the surrounding atmosphere, an inertial fusion rocket engine will have first-wall-like structures that receive the brunt of the microexplosion. These structures are likely to be critical elements that sharply influence engine lifetime, mass, and cost. New developments in first-wall protection concepts for terrestrial reactors thus permit qualitative advances in the design of rocket reactors.

Another significant development favouring the outlook for inertial fusion rocket propulsion is a greater understanding

* *The work described herein is an independent work of the author. The views and opinions expressed here are entirely those of the author and do not necessarily reflect those of Computer Sciences Corporation or its clients.*

of pellet radiation output and shielding considerations. For this purpose, pellet burn simulations have been supplemented with multigroup calculations of neutron transport to provide realistic source spectra for neutron response and shielding calculations. For fuel cycles such as D-T, D-D, and D-He^3, where significant quantities of neutrons are produced either directly or in side reactions, the shape and magnitude of the neutron spectrum significantly influence the design of shielded structures. Work with terrestrial power generation has strengthened our understanding of pellet radiation output and contributes to our confidence in analysing the requirements of optimised shielded structures for nuclear pulse propulsion.

The advent of revised pellet performance predictions, combined with more refined and accurate methods of design and analysis, tends to complicate any assessment of the prospects for thermonuclear pulse propulsion. It is not immediately apparent to what extent more stringent driver requirements can be traded for greater flexibility and more highly optimised design. These considerations suggest that previous assessments of the prospects for inertial fusion rocket propulsion may require modification and updating to reflect these recent developments.

3. REVIEW OF INERTIAL FUSION SYSTEMS STUDIES

Preliminary to any assessment of the prospects for nuclear pulse propulsion is a thorough review of the state of the art in inertial fusion systems studies. Considered here are driver development, target studies, reaction chamber studies, pellet injection and tracking studies, and systems studies. A more extensive discussion is presented in Ref. 4.

3.1 Driver Development

The main requirements of a driver are the ability to deliver nanosecond energy pulses and to sustain high average power, operation at high electrical efficiency, and good target coupling. The principal driver classes of interest include lasers, light-ion drivers, and heavy-ion drivers.

3.1.1 Lasers

The lasers of main interest are the neodymium-glass (Nd:glass) laser, the carbon dioxide (CO_2) laser, and short-wavelength lasers such as the krypton fluoride (KrF) excimer laser. Developed early to high energy levels, the Nd:glass laser, which emits at a wavelength of 1.06 micrometres, has been most extensively developed at Lawrence Livermore National Laboratory. For single-shot laboratory experiments, the Nd:glass laser offers good pulse shape control, desirable optical characteristics, and reasonably satisfactory target coupling. The NOVETTE Nd:glass laser system has compressed DT targets to 100 times liquid density. Still higher performance is expected from the 120-kilojoule NOVA system. Experiments with frequency conversion using KDP crystals have produced 0.53- and 0.35-micrometre beams with superior target coupling. These results have partially offset the pessimism that has pervaded the laser community in recent years. With the frequency-converted NOVA laser, target compressions up to 1000 may be achieved. Unfortunately, the intense burst of optical energy from glass lasers produces distortion effects and cooling problems even with single bursts. It appears unlikely that a glass laser system could operate at a pulse repetition rate greater than 1 hertz. A more serious limitation is posed by the inherently low electrical efficiency of the glass laser: no better than 0.5 per cent. Efforts to overcome some of the disadvantages of glass lasers are being pursued through the development of crystalline lasers.

The CO_2 gas laser, unlike the Nd:glass laser, is readily cooled. Pulse repetition rates of 10 hertz or higher at high average power levels appear feasible. At Los Alamos, the large, high-power CO_2 laser ANTARES has been placed into operation. In its initial phase, ANTARES generates 40 kilojoules with two beams. Unlike the Nd:glass laser, the CO_2 laser may offer useful efficiency; estimates range to 10 per cent. Unfortunately, the 10.6-micrometre radiation emitted by this laser has produced relatively poor target coupling, which is thought to be due to the generation of superthermal electrons and the accompanying phenomenon of preheat. Although sophisticated target design may ameliorate the problem, it is not certain whether the CO_2 laser will furnish an acceptable driver.

In view of the better target coupling at shorter wavelengths, efforts are underway to develop a short-wavelength gas laser with good electrical efficiency. Foremost among the candidates is the KrF excimer laser with a 0.25-micrometre wavelength. Although experimental KrF lasers such as the AURORA 3-kilojoule laser at Los Alamos have so far operated only at relatively modest power levels, a 50-kilojoule KrF retrofit of the ANTARES facility has been proposed. One drawback of the KrF laser is the excessively long pulse. Special techniques such as angular multiplexing will be necessary to obtain the nanosecond pulses required for inertial fusion.

3.1.2 Light-Ion-Beam Drivers

The relativistic electron beam accelerator promises the ultimate in pulse power capability. Honed to a high degree of perfection for weapon effects simulation, the electron beam unfortunately suffers from poor target coupling. Theory predicts much better coupling with light ions such as lithium. By a fortunate circumstance, it became possible to convert the megajoule-class electron machine PROTO at Sandia Laboratories to operation with light ions. With electrical efficiencies approaching 50 per cent, the Particle Beam Fusion Accelerator promises to deliver cheaply large amounts of pulse power on target. The PBFA II machine will generate 3.5 megajoules and deliver approximately 900 kilojoules to the target. Although the principal drawback to the light-ion approach is difficulty in transporting the ions from the diode to the target, recent results with PBFA I have been encouraging. Because some residual atmosphere must be present to form the required beam transport channels, an ingenious scheme will be required for operation in outer space. Reactor concepts employing light ions have proven to be more complex than other concepts. Like laser drivers, light-ion drivers face a number of scientific and engineering challenges.

3.1.3 Heavy-Ion-Beam Drivers

Because ion stopping in targets is nearly classical, the target coupling of heavy ions such as mercury or uranium is better understood and is believed satisfactory for inertial fusion. Moreover, the technique of accelerating heavy ions has already been demonstrated in a number of accelerator laboratories throughout the world. Indeed, the accumulation of large quantities of particles in high-energy storage rings such as the CERN ISR facility provided much of the stimulus to heavy-ion fusion. The promise of relatively high electrical efficiency – perhaps 35 or 40 per cent – has added incentive to pursue heavy-ion beams. Two accelerator technologies are of interest: the radio-frequency (RF) linac

feeding multiple storage rings and the linear induction accelerator. Both concepts for accelerating heavy ions appear more costly than lasers at target energy levels of immediate interest. A hidden benefit of accelerators is an ability to operate initially at the higher repetition rates and average power levels needed for a reactor driver. The high "buy-in" cost of heavy-ion fusion may postpone its deployment until successful single-shot experiments have taken place with reactor-type pellets driven by lasers or light-ion beams.

3.2 Target Studies

The various types of target, the problems of target fabrication, and pellet performance are next discussed.

3.2.1 Types of Target

Two types of target have been employed in current experiments: the exploding pusher and the ablatively driven targets. In the exploding pusher target, a glass microballoon is filled with DT gas. The sudden deposition of driver energy explodes the glass and drives a shock into the fuel. Unfortunately, the shock preheats the fuel and prevents the optimum, isentropic compression. Although fairly copious quantities of neutrons are produced, significant fuel densities are not achieved by this method. To achieve significant densities, the fuel region must be protected from preheat by a separate layer. Under irradiation, this layer ablates and is driven inward by reaction forces. Using such ablative targets, compressions up to 100 times the density of liquid DT have been obtained. To improve performance, the DT gas may be replaced by a layer of DT frozen to the inside of the ablator, which increases the compression ratio. Significant progress is yet to be made as compressions of a factor of 10,000 must be reached for practical reactors.

The exploding pusher and ablatively driven targets are simple targets of the single-shell type. In double-shell targets, two layers are separated by a void. The collapse of the outer layer upon the inner layer creates a momentum exchange that accelerates the inner layer, thus allowing larger gains to be achieved.

It has hitherto been implied that the target is irradiated directly by the driver beam. In some designs, a target may be imploded by radiation from the conversion of driver energy to thermal or soft X-rays within a high atomic number radiation container. This technique may improve the symmetry of the implosion. Experiments with these and other concepts will advance our understanding of target performance.

3.2.2 Target Fabrication

It is apparent from the preceding description that reactor targets can be rather complex, multilayered objects containing cryogenic materials. The problems in manufacturing such objects uniformly and with precision in large quantities appear formidable. A limited comparison may be made between the requirements for manufacturing transistors or large-scale integrated circuits and those for inertial fusion targets. A similar precision industry must be developed if inertial fusion propulsion is to become a reality.

3.2.3 Target Performance

Predictions of target performance are obtained with large, complex computer codes that simulate detailed processes of absorption, energy exchange, and hydrodynamics. With today's rapid computing machinery, accurate calculations still require times on the order of hours. Such calculations are performed under conditions of ideal geometry and distribution of materials. In the interests of cost and time, the calculations are usually performed in one-dimensional spherical symmetry. Correlations with experiments are necessary to relate accurately calculated and measured performance. One of the most significant developments since the Daedalus study has been the revision of pellet performance estimates. It is helpful in interpreting such estimates to consider a simple energy balance in a thermonuclear reactor.

If we let the driver energy beamed on to the target be E_D, the thermonuclear energy output of the pellet is $E_D G$, where G is the target energy gain. The thermonuclear energy is deposited in the form of neutrons, gamma rays, X-rays, and plasma in the reactor energy recovery system. The slight additional gain from exoergic nuclear reactions is neglected here. If the thermal energy in the recovery system is converted to electricity at a conversion efficiency η_{th}, an electrical energy $E_D G \eta_{th}$ is produced. To achieve the electrical break-even condition, the electric energy produced must balance the electric energy supplied to the driver. If the driver electricity-to-beam conversion efficiency is η_D, the break-even requirement is

$$E_D G \eta_{th} = E_D/\eta_D \quad (1)$$

or

$$G = 1/\eta_D \eta_{th} \quad (2)$$

Suppose that η_{th} is 33 per cent. For driver electrical efficiencies of five or 25 per cent, the gain must then be 60 or 12, respectively. Consider now the recirculating power fraction F_R. F_R is defined as the electrical power fed back to resupply the driver divided by the plant gross electric power output. This quantity is a measure of the power-handling equipment required merely to supply the internal energy requirements of the system and we wish to keep it as low as possible. F_R may be written

$$F_R = (E_D/\eta_D)/(GE_D\eta_{th}) = 1/G\eta_D \eta_{th} \quad (3)$$

The gain required to achieve a given recirculating power fraction is then

$$G = 1/F_R\eta_D\eta_{th} \quad (4)$$

For a practical electric plant, F_R must not exceed about 30 per cent. Driver efficiencies of five or 25 per cent must then require a target gain of 200 or 40, respectively. These gain requirements are shown as horizontal lines in Fig. 1.

Superimposed on Fig. 1 are various gain estimates for DT pellets taken from Ref. 5. The double-shell target offers superior gain in the region of interest for practical reactors. Note that a 25-per-cent-efficient driver requires one to three megajoules of target input energy, and a five-per-cent-efficient driver requires 10 or more megajoules. The above target performance estimates represent a significant increase in driver requirements over initially postulated levels.

The above argument defined a recirculating power fraction for an electric generating station with an electric energy output $GE_D\eta_{th}$. For an inertial fusion rocket, an analogous quantity may be defined in terms of the kinetic energy of the jet $GE_D\eta_J$. Here η_J is the efficiency of converting pellet thermonuclear energy to kinetic energy of the jet. Suppose, for example, that the recirculating power fraction for a nuclear pulse rocket is five per cent. Let the efficiency of converting pellet thermonuclear energy to plasma energy be 75 per cent and let the efficiency of converting plasma energy to jet energy be 80 per cent. Then, η_J is approximately 60

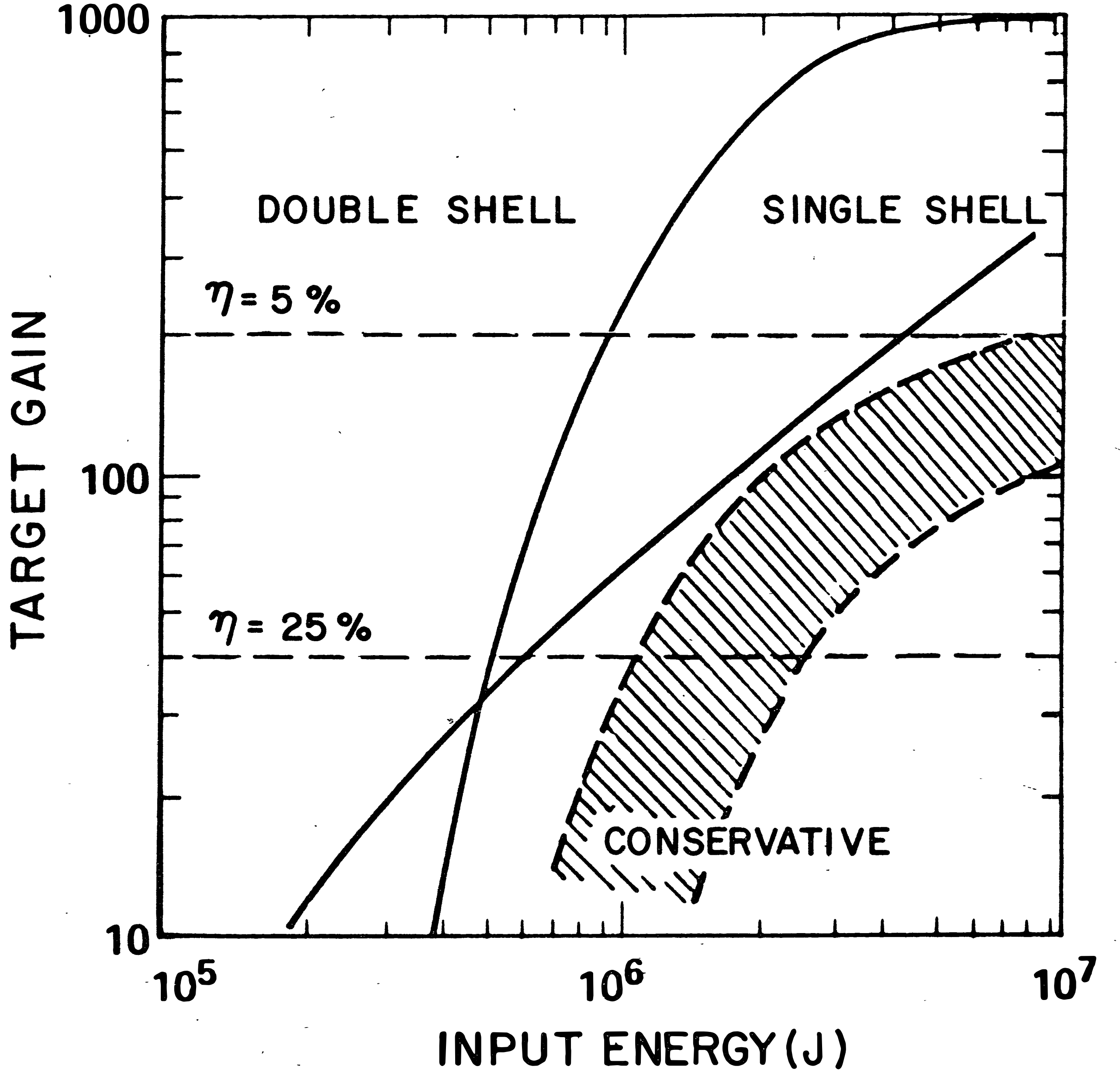

Fig. 1. DT target gain *versus* driver energy. Target gain is defined as ratio of thermonuclear energy produced by target to energy beamed on capsule. Solid lines for single- and double-shell targets correspond to ideal, one-dimensional computer simulations. Dashed band represents correction of simulations for experimental uncertainties such as implosion asymmetry. Position within band depends on ion kinetic energy and beam intensity for the case of heavy-ion-driven capsules and driver wavelength in the case of laser-driven capsules. Curves assume efficient beam-target coupling. Horizontal lines correspond to economic power generation at various driver efficiencies η. Reproduced from Ref. 5 with permission.

per cent. By analogy with Eq. (4), driver efficiencies of five or 25 per cent then require pellet gains of 700 or 135, respectively, compared to the electric power case of 200 or 40, respectively. The implications of the revised pellet performance estimates for inertial fusion rocket propulsion may thus be even more serious than they are for electric power generation.

Pellet burn codes predict radiation output characteristics as well as total thermonuclear yield. Output characteristics of interest include neutron, gamma-ray, X-ray and ion spectra. Detailed knowledge of these spectra is essential for accurate estimation of pellet radiation effects on reactor structures. Figure 2 shows a pellet multigroup neutron spectrum obtained with a discrete ordinates neutronics code. The application of pellet burn codes is discussed again below.

3.3 Reactor Chamber Studies

A number of schemes have been proposed for protecting the reactor first wall from neutrons, X-rays, and plasma from the exploding pellet [7]. For the various internal-configuration propulsion systems, in which the thermonuclear energy is completely contained within a massive combustion chamber, the requirements of electric power reactors and space propulsion reactors are qualitatively similar. For the external-configuration systems, in which the energy of the microexplosion is directed from space on to a pusher plate beneath the vehicle, the protection of the pusher plate poses similar problems. In the Daedalus concept, the magnetic field coils and structural members must be protected. Thus, the problems of wall protection for both electric power reactors

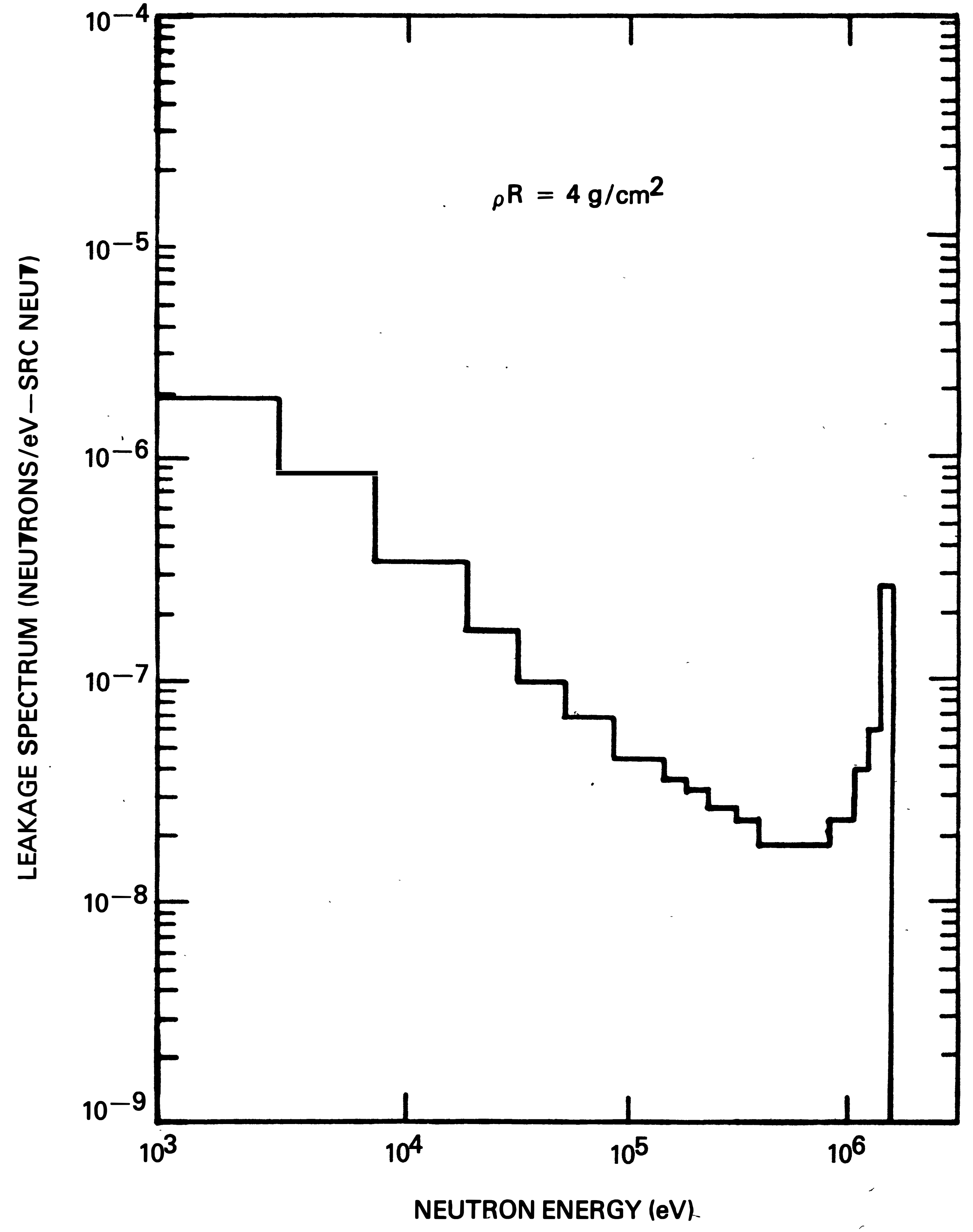

Fig. 2. Multigroup neutron spectrum from simplified reactor pellet. Pellet consists of 1-mg equimolar DT mixture uniformly compressed to density-radius product ρR of 4 g/cm^2. Spectrum calculated with the discrete ordinates neutron transport code ONETRAN-DA and using 30-group ENDF/B-IV cross sections in an S_8P_3 approximation. Note spectrum is divided into three regions, a 14.1-MeV fusion peak, a region of first- and second-collided flux, and a 1/E tail. Due to (n,2n) reactions in deuterium, slightly greater than one neutron on average is emitted from the pellet per thermonuclear source neutron. Calculation neglects motion of hot fuel ions. See Ref. 6.

and propulsion reactors are generic. The various protection schemes that have been proposed include the wetted wall and porous wall, the falling curtain, the rotating chamber, the spinning vortex, the dry wall, and the gas-protected wall. The wetted wall and the magnetically protected wall concepts are discussed here.

3.3.1 Wetted Wall Concept

The wetted wall concept may be traced to Hermann Oberth's proposal to cool the interior of liquid rocket combustion chambers with a rapidly moving film of propellant exposed to the burning gases. In the case of inertial fusion electric power reactors, the coolant is liquid lithium. This metal is chosen because it is already present in the reactor neutron blanket to regenerate tritium fuel and is a good soft X-ray absorber. The light element is also a satisfactory propellant and was in fact proposed for a magnetic fusion rocket by M. U. Clauser at the Second Geneva Conference on the Peaceful Uses of Atomic Energy. A variant of the wetted wall is the porous wall, in which hot liquid lithium seeps through porous metal into the reaction chamber.

The wetted wall is very effective in protecting surfaces from pellet X-rays and ions. However, the absorption of these radiations in the thin liquid film is accompanied by sudden ablation, and a large recoil impulse is subsequently communicated to the underlying structure. These ablation and recoil phenomena have been extensively studied at Los Alamos. One of the principal uncertainties in liquid wall concepts is the time required to evacuate the vapour- and droplet-filled cavity to a sufficiently high vacuum to permit propagation of the next driver pulse. Studies of interpulse clearing for electric power generation reactors and fissile fuel production reactors suggest a maximum pulse repetition rate of only 1 hertz. This has implications for rocket engines of the internal configuration.

3.3.2 Magnetically Protected Wall

In this concept, X-rays and neutrons interact with the first wall as in other concepts. However, hot ions and electrons are deflected by an axial magnetic field and funneled into plasma dumps at opposite ends of the cylindrical cavity. An extensive study of plasma behaviour in magnetic-wall reactors has been performed by I. Bohachevsky, J. Goldstein and D. Dickman [8]. The plasma model simulates the trajectory of hot pellet ions in the cavity background gas. The background gas is treated as a conducting fluid because calculations show that the X-ray pulse preceding the arrival of the fast burn ions completely ionises the residual gas, and the mean free path of these background ions is much smaller than the cavity dimensions. However, the mean free path of the fast burn ions is much longer than the characteristic reactor dimensions, and these ions must be modelled as single particles. The equation of motion is solved numerically for each of 5,000 to 25,000 simulation particles. This equation includes a collisional drag force exerted by the background fluid on the ion. The result of the simulation is a description of ion number density and energy as a function of position within the cavity at various times after the microexplosion. By this means it is demonstrated, for example, that a 0.1-tesla magnetic field can effectively funnel the ions from a 150-megajoule microexplosion in a suitable cavity when the background gas density is low (see Fig. 3).

3.4 Pellet Injection and Tracking Studies

Common to electric power reactors and rocket engines are the requirements of pellet injection and tracking. Because time must be allowed between microexplosions to clear the cavity of exhaust gases to permit beam propagation, the fuel pellets must be injected quite rapidly. Small deviations of the pellet trajectory from the ideal path will occur, and some tracking of the pellet will thus be necessary to determine precisely where and when to fire the driver beam. Adaptive optics may be necessary to meet this objective. The requirements of time and distance imply high injection velocities, but such high velocities generate heating effects in the gun that may degrade cryogenic pellets. Studies and analyses of these effects have been performed for representative pellets and reactor conditions, but much additional work remains to be done.

3.5 Systems Studies

By combining studies of the components of inertial fusion systems, namely the driver, target, reaction chamber, pellet injection and tracking system, and balance-of-plant, and by adopting, where necessary, arbitrary but plausible values of uncertain parameters, it is possible to model the behaviour of a complete system. The most extensive of these studies have been performed for electric generating stations and fissile fuel production reactors [9], but the principles are the same for rocket propulsion.

A computer model of a complete system is approached by constructing a line diagram connecting the major subsystems such as the driver and pellet. The projected input and output variables are listed, and mathematical relations among these variables are written down in terms of known physical processes. Typical input variables include gross plant power, number of reactors, target performance data, and assumed conversion efficiencies. Output variables include power cost and plant capital cost. To ensure completeness and consistency, the number of input variables and the number of mathematical relations must equal the number of output variables or unknowns. Some trial and error is necessary to ensure a proper balance of simplicity and information content.

When the major elements have been defined, the various subsystems are defined and the procedure is repeated. For example, if the subsystem is an RF linac/storage ring driver, the functional blocks consist of injector, accelerator, debuncher, stacking ring, storage rings, bunchers, and final transport. Although the physics content of the mathematical expression is as realistic as possible, it is usually necessary to include adjustable parameters that may be assumed to be constants within the range of operating parameters of interest. Such a parameter might be the permissible energy spread in a debuncher or the maximum number of injection turns in a storage ring.

When the complete system has been defined, trial calculations are performed by hand to confirm the reasonableness of the model and to suggest improvements in the computational procedure. Computer coding is then performed, and the results of trial runs are compared to hand calculations to validate results. At this point, parametric studies may begin and system layouts may be constructed.

Figure 4 shows the results of a parametric study of a heavy-ion reactor final-focus subsystem as a function of the distance from the front of the focus magnet to the pellet explosion. The study shows that increasing the magnet standoff distance exacts a gradually increasing mass penalty and the range of masses involved is very large for a space system.

4. DISTINCTIONS BETWEEN ELECTRIC POWER APPLICATIONS AND ROCKET PROPULSION APPLICATIONS

Although the wealth of study invested in inertial fusion electric power applications makes it attractive to draw inferences concerning rocket propulsion, it is useful to note

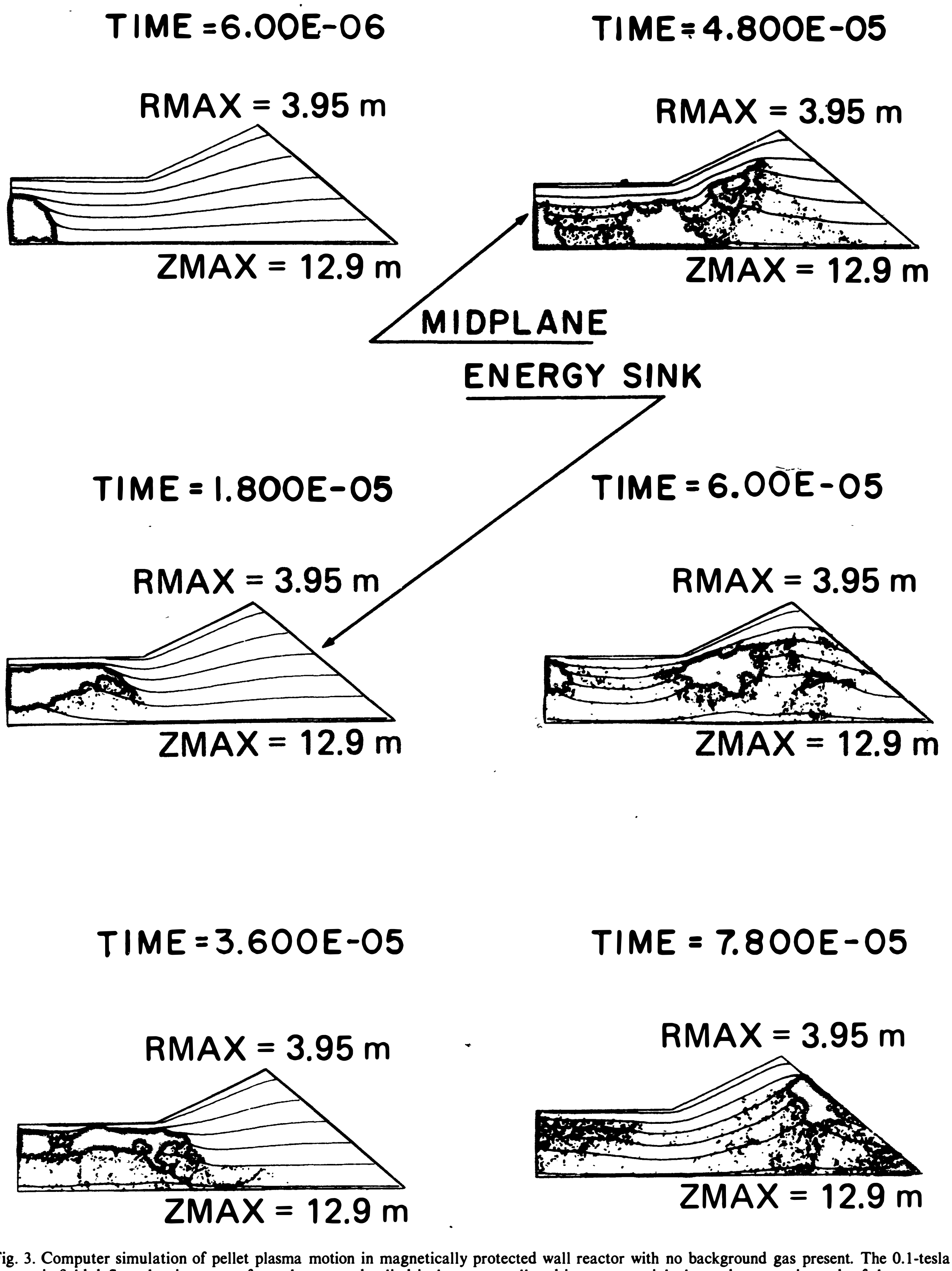

Fig. 3. Computer simulation of pellet plasma motion in magnetically protected wall reactor with no background gas present. The 0.1-tesla magnetic field deflects hot ions away from the exposed cylindrical reactor wall and into energy sinks located at opposite ends of the reactor. Reproduced with permission from Ref. 8.

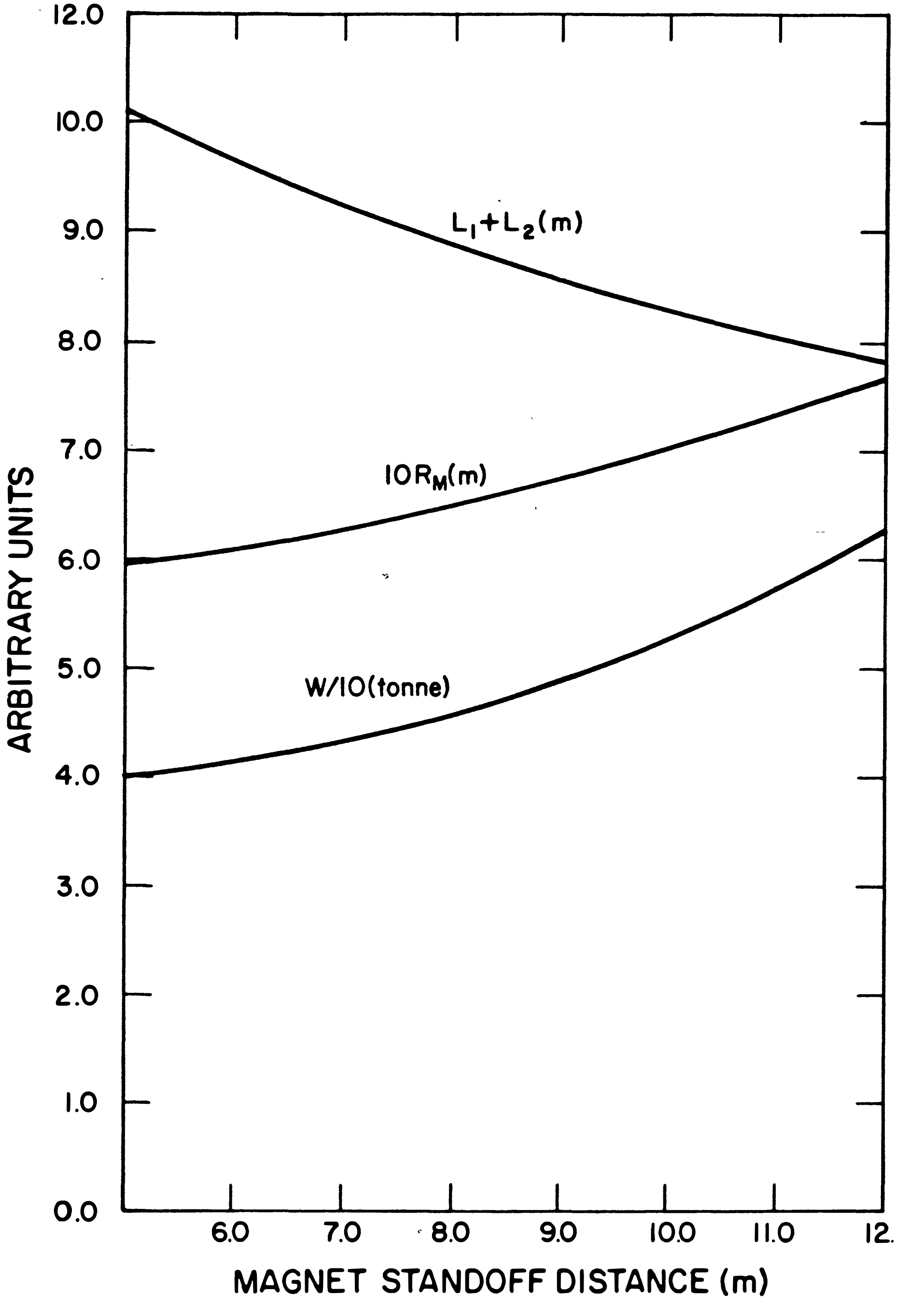

Fig. 4. Heavy-ion-driven reactor final-focus system parameters as function of magnet standoff distance from fusion target. $L_1 + L_2$ represents the length of the quadrupole magnet doublet, R_M symbolises the radius of the magnet clearance bore, and W stands for the weight of one of the 16 doublets. System shown is based on 3 MJ, 10 GeV, U^{+1} induction linac driver and 10-T/m quadrupole gradient with 60-MA/m^2 bulk superconductor current density.

several distinctions between electric power reactors and rocket reactors. One of the more significant differences is that the heat rejection system for a terrestrial inertial fusion reactor can occupy relatively large land areas and be relatively heavy without a great penalty in system performance. This is not true for inertial fusion rockets. The cost of boost from the Earth's surface is still so large that the orbital payload must be as small as possible. Moreover, the achievable acceleration and final payload of the inertial fusion vehicle itself decrease sharply with increasing radiator mass. Thus, the comparison of systems and conclusions drawn from studies of terrestrial powerplants may be misleading.

There is hope that the role of radiator mass in space systems can be reduced through innovative design. For example, A. T. Mattick and A. Hertzberg propose the use of liquid droplet radiators [10]. Such developments may offer order-of-magnitude reductions in the mass per unit of radiating surface.

Because of the heat load posed by the scattering and absorption of neutrons in engine structures, inertial fusion rockets will use advanced fuel cycles such as D-D, D-He^3, or p-B^{11}. On the other hand, terrestrial electric generating stations will at least initially use the neutron-rich D-T cycle. Because the energy split between neutrons, X-rays, and ions is markedly different, the quantitative relationships of the various subsystems in the two cases will be different. For this reason, comparisons and conclusions drawn from electric generating station system studies may have only limited validity when applied to inertial fusion propulsion.

Another source of concern in the interpretation of terrestrial power studies is the operating assumption of no more than 30 per cent recirculating power. Space propulsion systems will require significantly smaller recirculating power fractions because the recirculating power handling equipment, like the neutron shields, represent a source of dead mass. If only five- or ten-per cent recirculating power fractions are permissible for a practical fusion rocket, the results of terrestrial generating station studies will have only limited applicability.

The low importance of mass considerations in terrestrial power studies may lead to quite different conclusions regarding driver suitability. For reasons already discussed, the heavy-ion accelerator may be a promising driver for terrestrial power applications. However, the design and technology of in-place accelerators such as the Fermilab accelerator or the LAMPF accelerator strongly suggests that such equipment would be far too massive. Of particular concern is the vast contribution of magnet iron to the system mass. For a feasible spaceborne accelerator, the use of "air-core" superconducting magnets is implied. Whether such structures can be designed to satisfy all pertinent requirements is an open question.

For these reasons, fusion propulsion reactors can pose more stringent requirements than terrestrial reactors. On the other hand, the demands of propulsion systems are not always more stringent. For example, the round-trip time for interplanetary missions of interest is quite brief compared to the desired lifetime of terrestrial electric generating stations. Consequently, the neutron damage limit for terrestrial applications may be too stringent for interplanetary mission requirements.

The role of economics in terrestrial power generation may be quite different than for space propulsion. Electric power from terrestrial fusion reactors is a market product that is no different than electricity from a fossil fuel plant; both have the same end use. Consequently, the probable additional cost of electricity from inertial fusion must be justified in terms of other benefits. Contrast the economics of terrestrial power generation with the procurement of a strategic weapon system. When the benefit is not easily measured in simple economic terms, hardware may be procured almost regardless of cost. In many respects, the benefits of space missions for which the inertial fusion rocket is uniquely qualified are not easily measured in economic terms. If the benefit were perceived to be sufficiently great, a fusion rocket would not require economic justification in the same way as a terrestrial fusion plant [11].

For all of these reasons, important distinctions exist between electric generating station applications of inertial fusion and rocket propulsion applications. Conclusions from electric generating station system studies must therefore be drawn with care.

5. PROSPECTIVE ROCKET PROPULSION RESEARCH PROBLEMS

The large number of ongoing tasks that must be completed before inertial fusion becomes a practical energy source may suggest that studies of inertial fusion rocket propulsion are premature. Some argue that even electric generating station studies have attempted too great a step on the still limited and meagre knowledge we possess today. In support of this view, our grasp of pellet-beam interactions is still approximate and our confidence in pellet performance predictions is poor. Experimental neutron yields are today many orders of magnitude smaller than we will require of a practical reactor. Our knowledge of materials response to conditions in an inertial fusion reactor is derived from a very narrow base, and our estimates for conceptual designs still contain a measure of educated guesswork.

On the other hand, there can be no question that it would be shortsighted and impractical to delay consideration of reactor issues to some point in time when all of the scientific problems are solved. It is simply not possible to postpone planning and evaluation activities until the day after scientific feasibility is demonstrated. The resolution of important technology questions must begin years in advance of the time when such technology is needed. This is no less true of the inertial fusion rocket than it is of the electric power generating station.

Accordingly, some prospective rocket propulsion application research problems are considered next. The discussion focuses on problems that are a logical extension of studies already undertaken for electric power generation and that have a degree of leverage on overall progress. The list is not intended to be exhaustive but should suggest avenues of study. Doubtlessly, numerous additional areas of study are warranted and would contribute to our understanding of inertial fusion propulsion.

5.1 Fundamental Studies of Thermonuclear Burn Phenomena

Inertial fusion target studies model thermonuclear burning in highly compressed fuel. Burning occurs in a special type of detonation wave. In a detonation wave, the velocity of the burn front exceeds the velocity of sound in the unburned fuel. This is a requirement of inertial confinement. In another type of burn wave, namely the deflagration wave, the velocity of the burn front is subsonic. Deflagration occurs in a conventional chemical rocket. Although the propagation of thermonuclear deflagration waves in relatively low-density systems has been studied previously [12, 13], deflagration in highly compressed fuel apparently has not been studied in detail. In such a study, the physics methods and calculation techniques developed for inertial fusion target modelling could prove useful.

5.2 Design of Pellets with High Charged Particle Fraction

A central challenge of inertial fusion rocket propulsion is

the harnessing of advanced fuel cycles with a high output of charged particles that may be magnetically focused to produce thrust. Much of the original work in this area is cited in the review mentioned previously [2]. Additional work appears occasionally in the technical literature [14, 15].

An interesting parallel exists between electric power generation studies and rocket propulsion studies involving pellet radiation output. Most early studies of power generation applications neglected neutron moderation within the pellet, a satisfactory assumption when only rough estimates were required. It was realised in subsequent work, first with analytic approximations and later with machine calculations, that pellet moderation effects ranked with previously recognised concerns like cross-section uncertainties. At the other extreme, the Daedalus study assumed that neutron moderation in the thicker pellets used for rocket design is complete and that heating of engine structures by leakage neutrons may be neglected. This view is now questioned [15]. As in the case of electric power generation studies, increasing sophistication of techniques and methods throws into doubt assumptions once considered adequate.

The improved techniques in pellet design are made possible by the large computer codes mentioned previously. These codes require significant resources of money and talent to develop as well as significant resources to operate and maintain. Historically, their use has been limited to the nuclear weapons community. Partial results from these codes are sometimes disseminated to support pellet performance claims and general claims about the feasibility of inertial fusion. Unfortunately, the calculations are not easily reproducible by outside investigators, and progress is hampered. This issue is likely to influence rocket propulsion studies as well as electric power generation studies for some time to come.

5.3 Study of Magnetic Nozzles

With the study of the magnetically protected wall, an important start has been made on the design of effective magnetic nozzles for expanding microexplosion plasma. Before the existing tools can be applied to magnetic nozzles with a high degree of confidence, certain refinements in the calculational approach may be warranted. For example, the present model assumes that the background fluid is decoupled from the radiation field. In some operating ranges, this assumption may not be valid. Many calculations that have already been performed have involved geometries other than that of interest for propulsion applications. It is important to verify that a realistic distribution of currents in the field-energising coils can achieve unidirectional flow. Recent studies of plasma expansion in the Daedalus engine demonstrated successful reversal of the plasma at the chamber wall [16]. Studies of the nature and composition of the exhaust flow should be performed to verify neutralisation and impulse predictions. In addition to plasma modelling, the study of magnetic nozzles should be enlarged to include superconducting coil and magnetic structures design.

Studies of the nature and composition of the exhaust flow should be performed to verify neutralisation and impulse predictions. In addition to plasma modelling, the study of magnetic nozzles should be enlarged to include superconducting coil and magnetic structures design.

5.4 Integrated Engine Neutronics Study

Regardless of the fuel cycle adopted, a substantial flux of 14-MeV neutrons and other fast neutrons will be emitted from the microexplosion. Spacecraft structures and the crew compartment must be protected from these neutrons by a shadow shield mounted forward of the engine bay. When superconducting or cryogenic coils are used, the coils constituting the magnetic nozzle must be shielded against nuclear heat deposition to minimise cryoplant mass. Although neutronics studies for terrestrial fusion reactors have embraced the design of blankets and shields, the methods are now only beginning to be applied to spacecraft requirements. Minimisation algorithms for the design of optimal shields that were developed for the SNAP nuclear-electric power systems should be applied to the Monte Carlo and discrete ordinates calculations used in fusion reactor neutronics studies. Analyses of pellet output for electric power systems have resulted in methods for approximating the time-dependent multigroup neutron spectrum from reactor pellets. These methods should be applied to advanced fuel pellets and the results combined with magnetic nozzle analyses to produce an integrated engine neutronics study. Reference 15 provides an example of such a study.

5.5 Innovation of Low-Mass Driver Structures

Power generation studies suggest that the driver will constitute a major portion of the propulsion system mass. Mass reduction accomplished in the driver system will greatly improve vehicle performance characteristics. Although considerable thought has already been devoted to minimising driver costs, there has been little opportunity to consider driver mass reduction. It may be argued that, within certain broad ranges, the cost of materials is directly related to the mass employed and that cost-reducing techniques must also save mass. There are, however, instances where cost reduction may increase mass, as in the substitution of cheaper steel for titanium. What is more important is the innovation of new driver concepts in which minimum materials usage is a criterion at the outset.

5.6 Propulsion System Modelling

The techniques developed for computer modelling of complete electrical power reactors may effectively be applied to rocket propulsion. To date, most studies of inertial fusion rockets have been studies of point designs. By means of computer modelling, it is feasible to characterise a complete range of concepts and to identify sensitive design parameters. The parameters may then be varied systematically to achieve significant improvements in design. Such studies are not only useful in generating the most attractive designs but also identify key technology areas that pace future development.

6. CONCLUSIONS

It has been argued here that developments in systems studies for inertial fusion electric power generation present broad implications for thermonuclear rocket propulsion. Foremost among these is a downward trend in fuel pellet performance estimates. Although new results with short-wavelength drivers appear to have stopped this trend, the earlier predictions have proved to be optimistic. The effect of this movement is to increase the size of the driver and to increase the overall size of the propulsion system and vehicle. On the other hand, a better understanding of reactor phenomenology has evolved from recent system studies, and more sophisticated methods of analysis have been developed. As a result, it is possible in principle to design systems less conservatively and closer to optimal performance values. Although these new developments alter the prospects for inertial fusion

rocket propulsion in different ways, it is evident that inertial fusion systems studies significantly affect the prospects for thermonuclear pulse propulsion.

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EVOLUTIONARY APPROACH TO DEVELOPING ABIOGENESIS MODELS

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This paper discusses the evolutionary curve of the cosmic-time dependence of the atomic-complexity matter plotted under certain assumptions and with allowance for modern data. The evolution curve shown graphically has an impulse character with the ascending (comoslogical, chemical, and biological stages) and descending (postbiological stage) branches, the peak of which corresponds to the existence of humanoids. This allows us to show the main regularities of evolutionary process and to suppose some things about abiogenesis.

The situation specific (chemical, biological, and post-biological) stages of the evolution on to the impulse allows the describing of evolutionary processes occurring at these stages as autocatalytic, strongly non-equilibrium, and those that lead to dissipative structures to be formed.

The similar processes occurring at the chemical and biological stages, together with certain quantitative characteristics for a transient hypothetical material system obtained as a result of this work, make it possible to return to the nucleotide hypothesis of live matter origination. The idea was confirmed about the possible origination, in the transient period, of symbiotic material systems which are composed probably of RNA-like molecules of polynucleotide, synthesised autonomously abiogene, together with a clayish "liposome" as the base for a future protocell. Such a symbiosis could become, in the case of its experimental confirmation of efficiency, a basic mechanism of the Oparin-Haldane theory of abiogenesis. It follows that one of the main regularities of the evolution is the simplification (decreasing a number of "letters" in "alphabet") of an information code as the matter is complicated.

The impulsive shape of the evolution curve hinders the possibility of establishing a direct contact between humanoids of different impulses (if the latter are more than one in the Universe) disconnected in space and time.

1. ORIGINATION OF LIVE MATTER – THE REGULAR STAGE OF THE EVOLUTION

Many attempts have been made to substantiate live matter origination on the Earth as a regular stage of matter evolution from its simplest forms up to Homo Sapiens. In this connection the so-called anthropic principle [1, 2], the evolution continuity principle [3] and so on, have been formulated.

This implies that live matter origination is a regular consequence of the continuous transformation of the matter in the Universe, whose main stages are traced on the cosmic time scale beginning from the Big Bang ($\sim$ 20 x 10^9 years ago [4-6]).

Below we will attempt to represent graphically the dependence of the matter complexity evolution in the Universe, beginning from the first atoms origination, as a function of cosmic time up to the present time and, then, to the future.

The evolution curve, shown in Fig. 1, allowed some parameters to be specified that are necessary for developing the models of the physical-chemical stage of the "live" matter origin on the Earth [7, 8]. Such models, as is known [7, 8], are rather critical to physical and geochemical conditions on the primitive Earth. As to conditions in this period of time there are many significant uncertainties in our knowledge about them that leads to the necessary studies of various ways of evolution and, therefore, to the development of many models for this stage. The use of this evolution curve may permit decreasing a number of uncertainties and developing a more reliable model of abiogenesis.

In the graphical representation of the evolution the interval of time we are interested in, which is associated with the time of live matter origin on the Earth, becomes inner interpolation interval of the evolution curve. Therefore, with the information available about the matter status at the previous and following stages of evolution one can attempt to obtain more precise data about the matter status in the intermediate moment of time of our interest (4 x 10^9 years ago), i.e., about the structure of that material system which was tentatively the start of self-organising the "non-living" matter to the alive one (abiogenesis).

2. PRINCIPLE FOR PLOTTING THE EVOLUTION CURVE

Figure 1 shows the dependences (1) to (3), which have been plotted under the assumption that on the way from the "non-living" to live matter the open evolving material systems discretely complicated in time successively:... – atom – molecule-solid-state particle (cluster) – macromolecule system – protocell – one-celled microorganism (m/o)-multicellular organism – mammals (human beings) –... [3, 9] have been formed.

These systems are the elementary carriers of the quality of the various levels of the matter organisation. They are evolving due to those factors determining the selection of Darwinian type as the individual and the collective instabilities [9]. Figure 1 demonstrates (in log-log-coordinates) the dependence (1) of the atomic complexity (a number of atoms of the above mentioned material systems *versus* cosmic time (in seconds) which is used as a base for our further discussion. The appropriate data were taken from Ref. 4.

We assumed the ten-atom complexity (conventionally) for moleculae. It is known [10] that in the interstellar medium only the 13-atom moleculae, i.e. moleculae of the largest complexity, have been detected up to the present. According to Ref. 4 the time of the first appearance of atoms in the Universe is assumed to be $t_a \sim 10^6$ years; the first appearance of molecules, $t_m \sim 4 \times 10^9$ years which we have identified coincident with the appearance of the first stars in the Universe.

The next point on the curve (1) corresponds to the time when a one-celled microorganism (m/o) appeared on the Earth, $t_{m/o} \sim 17 \times 10^9$ years [4]. For a m/o and for the class of biological objects as a whole (including human beings)

we suggested the atomic complexity (a number of atoms) of a genome as a measure of the complexity (and intelligence) of an appropriate organism. Such a choice was ascertained by the hypothesis proposed in Ref. 11 that a genome dimension is a measure of the evolutionary complexity (and intelligence) of an organism.

Note that the attempts to represent graphically the matter evolution have been already made (Teijard de Chairden, A. I. Oparin, C. Sagan, *et al*) but on somewhat another base [12-14]. The biological stage of the evolution alone was also graphically represented elsewhere [14, 15]. However, it was insufficient for describing abiogenesis and understanding the conditions for the "non-living"-to-alive matter transfer.

It is seen from Fig. 1 that the ascending branch of the evolution curve (1) consists of two almost-linear parts; the initial part of the physical ("cosmological") evolution characterised by the comparatively slow rising of the matter complexity and the portions of the chemical and biological ("Earth") evolution with the much more rapid rising of the complexity. Our task involved the interpolational conjugation of these two parts. As a conjugate point we assumed (conventionally) the point lying on the extended "Earth" branch the date of which is $t_c \sim 12.8 \times 10^9$ years. This point can evidently be considered as the first appearance in the Universe of the condensed state of matter, a solid-state cluster containing $\sim 10^2$ atoms.

The special-purpose experiments [16] have revealed that a minimal number of atoms (e.g. of metal), for which all the bulk properties characteristic of the metal (heat conductivity, etc.) begin to manifest themselves, is typical for clusters concerned with the $\sim 10^2$-atom complexity (approximately). Such clusters that form a solid-state surface are also effective catalysts, even in moisture-free conditions [16].

In this connection one can suggest that the further run of the matter evolution related with the processes of self-organisation and selection (synergetic) can be stipulated to a certain extent by the occurrence of the solid states and the autocatalysis on to them [17, 18]. The latter could probably be responsible for the chemical evolution beginning in the Universe.

Generally speaking, a solid body, along with liquid water and carbon, is, according to the modern conceptions [19] one of the three components necessary for live matter origination. The more rapid evolution of matter along the "Earth" branch was due to the primary autocatalysis occurring on solids which can lead to the matter self-organisation processes being almost very non-equilibrated. In accordance with Eigen's point of view [20] we will suggest metabolism, replication, mutability, and natural selection of Darwinian type as the necessary attiributes of the matter self-organisation on the ascending branch of the impulse.

The later period of time, up to $t_s \sim 15.2 \times 10^9$ years, could tentatively be used for further complication of the matter up to forming complex molecules [21] which could become a part of carbonaceous chondrite meteorite composition, i.e. the substance that is the most primitive substance in the Solar System, as believed elsewhere [22], and then fall on to the primitive Earth together with them. Other possible ways have also been proposed for transportation of complex organic compounds from space to the Earth (e.g. together with interstellar particles, etc. [21]).

Figure 1 also shows two auxiliary curves (2) and (3). The curve (2) is the variation of temperatures (in degress Kelvin) under which the material systems exist with the growth of their atomic complexity. This dependence has two branches corresponding to the maximum and the minimum of variations of these temperatures.

It is seen from Fig. 1 if the atomic complexity decreases the temperature range ("corridor") of the system existence broadens, and *vice versa*. So, for a human being (as a biological species) the range of the allowable internal temperature is only several degrees [36.6 (+5, -1 to 2)°C] but for a microorganism this temperature "corridor" of life is already wider ($\sim$ 450°C) and corresponds to the range where the free intracellular water exists in a liquid state [23, 24]. Here the upper boundary of this "corridor" is determined by the critical temperature, T_c for water ($T_{c_{H2O}} \sim 646$ K [25]) and its lower boundary is assumed equal to $T_{min} \sim 213$K (-60°C), the temperature under which a living microorganism has been found in Antarctic ices [26].

For a solid-state cluster the upper boundary is assumed to be the melting point, T_m, of the most refractory chemical element, carbon ($T_m \sim 4 \times 10^3$K [25]); for a molecule this is the temperature corresponding to binding energy of chemical compounds, $E_{M_{max}} \sim 12$ eV ($T_{M_{max}} \sim 1.2 \times 10^5$K [27]); for an atom this is the temperature of nuclear reaction $T_{a_{max}} \sim 10^8$K [25].

As far as the lower boundary of the temperature "corridor" is concerned, it is evidently decreasing sharply towards temperatures close to absolute zero starting from a dust-particle to an atom.

The curve (3) represents the dependence of the system lifetime on its atomic complexity and is characterised by the minimum corresponding to microorganisms with the lifetime from days to hours (assumed that $\tau_{m/o} \sim 10^5$s) or to human beings with the lifetime growing to $\sim 10^2$ years. The atom lifetime is assumed to be $\tau_a \sim 10^{39}$s as estimated by the proton lifetime, the solid-state cluster lifetime, $\tau_c \sim 10^9$ years that is close to that of a graphite dust-particle [28].

3. BEGINNING OF THE LIVE MATTER SELF-ORGANISATION ON THE EARTH

Now we will try using the dependences (1) to (3) to obtain additional data about the hypothetical material system X from which the processes of self-organisation of the non-living matter into a protocell might probably have been started. To this end, let us consider the material system X which existed in the time interval $t_X \sim 16 \times 10^9$ years ($\sim 4 \times 10^9$ years ago) on the Earth surface. This was the time when the Earth has recently formed as a planet and its crust had hardly finished forming [29]. It should be noted that the parameters of the system X can also be obtained by analysing only the biological stage of the evolution, interpolating its biological branch backward up to the time of our interest. However, such an approach could not result in a needed generalisation we succeeded in making in this paper.

It follows from the curve (1) that the initial system X was evidently characterised by the atomic complexity, $N_X \sim 6 \times 10^6$ atoms (Fig. 1). If this system was assumed to be spherical its approximate linear size should be equal to $a_m \sim 10^6$ cm. This system could exist at temperatures $T_{x_{max}} \sim 750$K to $T_{x_{min}} \sim 160$K and its average lifetime would be $\tau_x \sim 10^6$ s (i.e. shorter than a year). Then, the minimal energy of binding in this system was $\Delta H_x \sim 1.5$ Kcal.mol^{-1} that corresponds to forces [30] acting in the colloid-chemical system.

The upper boundary of the above temperature range allows a preliminary conclusion that this system should evidently have been composed mainly from inorganic matter with some amount of organic one. The proposed concept does not contradict the suggestion that complicated organic compounds of the "yellow stuff" type can also be used in the abiogenesis processes occurring on the Earth. Such compounds could form on interstellar dust-particles and then be transported to the primitive Earth when the Solar System was passing through the interstellar medium [21].

It is also significant that our results are in good correlation with those obtained analytically in Ref. 31 based on other assumptions. Moreover, these results can supplement each

other. So, we can believe that all the estimates made in Ref. 31 can be valid, not only for polypeptides but also for polynucleotides. Then, a characteristic size of our system X will be $a_m \sim 10^{-6}$ cm which allows the system to include an available polynucleotide with $a_m \sim 10^{-7}$ cm taken from Ref. 31.

The further advance to understanding the processes occurring at the physicochemical stages of the live matter origination if the results obtained are used, can be achieved only based on different models of autocatalysis. As an example, we can indicate the models (scenarios) where clays are used as a basis for the beginning of the self-organisation of the non-living (inorganic) matter to the living one occurring on the Earth [32] or other models (see, hypercycle as in [33]).

If, in the types of "life" (chemical, biological etc.) existing in the impulse shown on Fig. 1, the electromagnetic interactions dominate, then, apparently, one cannot exclude the possibility of the existence of similar impulses of matter self-organisation in which are also dominating strong nuclear, weak nuclear and gravitational interactions [57]. Moreover, the assymptotical state similar to Hoyle's "Black Cloud" may already present itself the evolutionary meaningful element of the gravitational "life" of the future.

Man, as the biological species, does not disappear for a long time when evolution moves along the descending branch of the self-organisation impulse on electromagentic interactions, as on the Earth many species did not disappear which existed before man's appearance.

Eventually, he "will gradually disappear and his psychosocial component will gradually "move" into machines with artificial intelligence" [59]. The natural selection of Darwinian type for ideas, of which we got used to, will be absent there. However, the interaction between machine and man civilisation will put an imprint on the behaviour of the latter. The possible expansion of mankind's development due to the exponential growth of many of its parameters will, apparently, obey the slower laws of development.

In this sense, the successes of computerisation may cancel out much of the pessimistic forecasts of the Club of Rome.

4. EXAMPLES OF SELF-ORGANISATION AND SELECTION OF THE NON-LIVING MATTER AT THE CHEMICAL EVOLUTION STAGE

We can site several examples of the non-living matter self-organisation and selection processes being at the chemical evolution stage. So, Ref. 34 postulates the processes of matter self-organisation and selection of the Darwinian kind occurring suppositionally on interstellar dust-particles. A microporus interstellar dust-particle itself as the authors of Ref. 35 believed, is an effective catalyst.

It has been shown experimentally [36] that the basic features of these processes are also manifested on smectite clays during their interaction with liquid water. So, the main manifestations of self-organisation, namely metabolism, replication (type of DNA-replication) and "mutation," were observed in the course of 32 generations of one of clays. Cairns-Smith [8] gave in his papers examples of the possible selection of self-organisation in the case of a wider class of clayish materials. Note that inorganic molecules are the structural base of clays, whose atomic complexity was much lower than that of DNA.

As a whole, the chemical stage of the evolution associated with autocatalysis was evidently similar with the biological stages in a sense that it was characterised by occurrence of so-called dissipative structures. The existence of these structures in states far from equilibrium was maintained by their energy and substance exchange with the environment. On the comsological branch these states were evidently much closer to equilibrium. It follows from the above that there is no difference (barrier) between the non-living and live matter which cannot be insurmountable in principle [58].

If this is the case, one can assume that the symbiosis between the inorganic and organic matter would be possible on the Earth at the period of the "live matter" origination. By the way, the symbiosis theory being applied to the biological evolution stage is widely spread, and as is mentioned in Ref. 37 the symbiosis is the main mechanism of the evolution.

All the above mentioned allows us to return to the idea about the nucleotide hypothesis of live matter origination [8, 38, 39], but based on the new concept namely, as a result of symbiosis between clayish "liposome" and primitive nucleotide (RNA-type molecule) synthesised independently in the environment by a abiogenous way. This idea is strengthened by observations of some enzyme-mimick properties in clays [40] and enhancement of transfection by clays [56].

According to the evolution curve (Fig. 1) to the time of about 4 x 10^9 years ago primitive nucleotides (atomic complexity of $\sim 10^6$ atoms) could have already existed on Earth [3, 38]. However, to meet the requirement $T_{x_{max}} \sim$ 750K ($\Delta H \sim 1.5$ Kcal.mol^{-1}) (curve 2, Fig. 1) one should suppose the possibility that they can penetrate inside a clayish "liposome" and they can function there self-dependently, i.e. their symbiosis with the following substitution of the hemodynamic mechanism of the clayish "liposome" on the virus RNA-type basis ("genetic metamorphism" following Cairns-Smith [8]). At present this hypothesis can be verified experimentally in laboratory and if it turns out to be valid this mechanism can become the basic in the Oparin-Haldane abiogenesis theory [41].

5. INFORMATION CODE IS SIMPLIFIED ALONG WITH THE EVOLUTION CURVE

Above we singled out on the evolution curve (1) (Fig. 1) two branches: the "cosmological" (a) and the "earth" one, the latter composed from the chemical (b) and biological (c) stages. It is clearly seen from Fig. 1 that the rates of the system's atomic complexity increase are different for the "cosmological" and "earth" branches. The drastically higher rate of evolution is a characteristic feature of self-organisation processes far from equilibrium. We tried to explain the difference in the evolution rates (except for autocatalysis) using the terms of information theory, i.e. namely by the change of the number of "letters" in the "alphabet" of an information code [42]. At the biological stage of the evolution, which reflects generally the structure of bipolymers carrying genetic information, this "alphabet" consists of four "letters" corresponding to the number of nucleotides in information macromolecules DNA and RNA [43]. On the part of the cosmological branch shown on Fig. 1 (from atom to molecule) the number of "letters" in the "alphabet" can be taken equal to about $\sim 10^2$ which evidently corresponds to the number of elementary particles [25, 53, 61].

The higher rate of the evolution when passing from one branch to another may be associated with the beginning of the chemical stage of evolution and with the dissipative processes in states far from equilibrium. It is here due to autocatalysis that the conditions for origination of informational macromolecules became favourable. The abiogenetic production at first of inorganic and the of organic polymer molecules during the chemical evolution preceeded evidently the appearance of DNA and RNA.

Using the scaling presentation [44] we will try to determine the number of "letters" in the "alphabet" of a polymer molecule formed at the chemical evolution stage, as a predecessor of DNA.

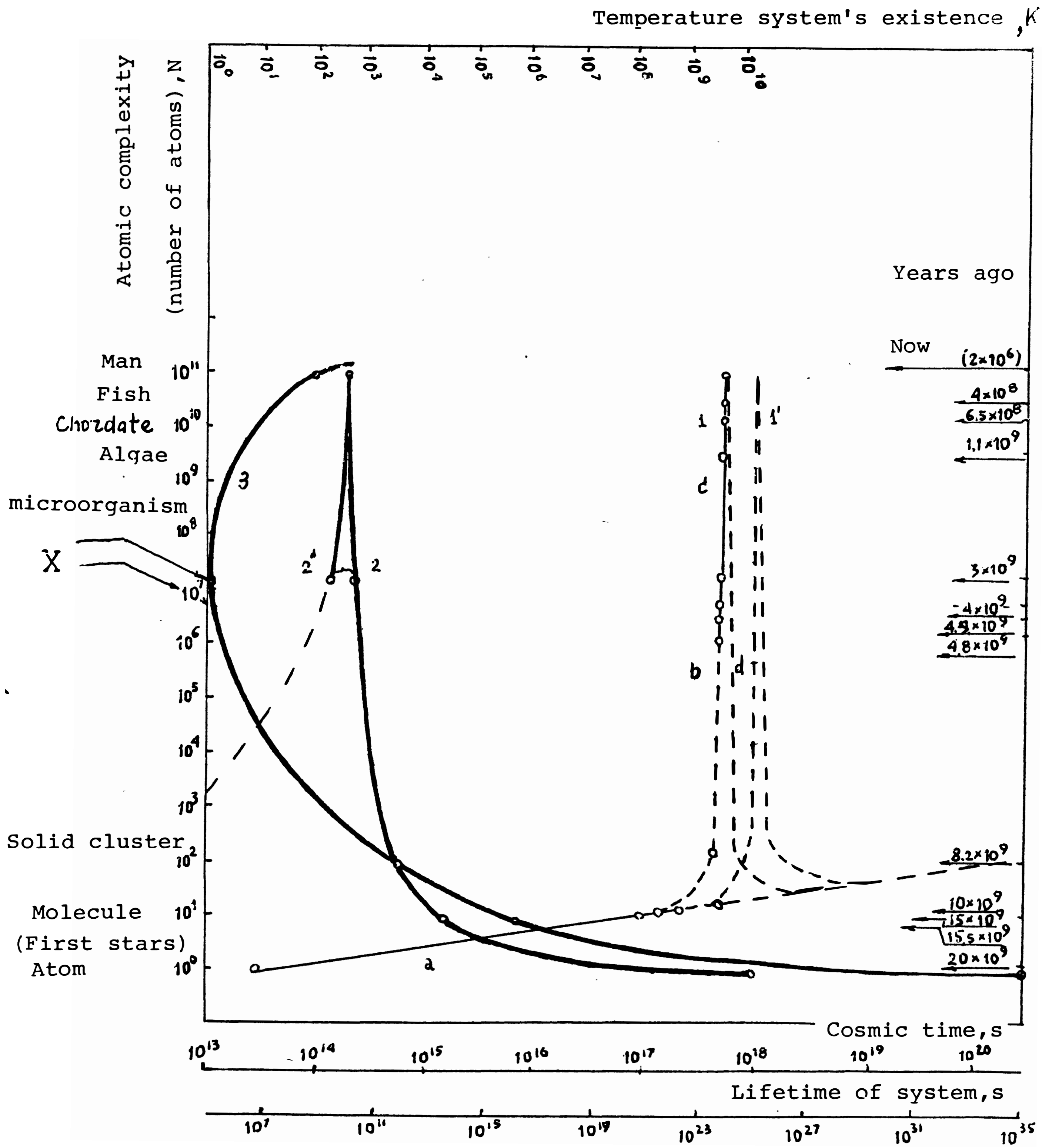

Fig. 1. Evolution dependences (1) to (3) used for refining several parameters of the initial material system X which initiated the self-organisation of non-organic matter to evolving biological systems.

(1) – Dependence of the atomic complexity of the system (number of atoms – number of atoms in a genome) *versus* cosmic time (seconds) (beginning from the first atom appearance in the Universe).

(2) – Dependence of the temperature range of the system existence *versus* the system complexity: (2') – upper temperature boundary (in K); (2") – lower temperature boundary (in K).

(3) – Dependence of the system lifetime (3) (seconds) *Versus* its atomic complexity.

(1') – Graphical illustration of possible contacts between the impulses originated in various times.

One of the ways to simulate the statistical states of flexible polymeric chain is to present it as the trajectories of random walk over a periodic grate [44]. The informational entropy of an ideal chain, Sm, permitting self-crossings during a walk over the grate can be estimated [44] as follows:

$$S_m \sim \ell n Z^N = N.\ell n Z \quad (1)$$

where N is the number of links, and Z is the number of neighbours of a grate node.

For the simple cubic grate Z = 6. This is the least neighbours for the grate in space. The structure of this equation is so that Z is taken as the number of "letters" in the effective "alphabet" similar to the four-letter DNA "alphabet."

However, the presentation of a real-polymeric chain in solution to a greater extent corresponds to its description as trajectories of random walk without self-crossing [45]. In such a case the entropy has a value of order [45]:

$$S_m \sim \ell n (\tilde{Z}^N.N^{\gamma-1}) = N.\ell n\tilde{Z} + (\gamma-1)\,\ell nN \quad (2)$$

The first term in Eq. (2) is similar to that in Eq. (1), however, $\tilde{Z}$ is somewhat smaller than Z. For the simple cubic grate the numerical calculations of possible trajectories results in Z = 4.68 [45]. The value of γ depends on the space dimensionality and in the case of the three-dimensional space it is equal to γ = 7.6 [45].

If the number of chain links is great (N>10) Eq. (2) can be written as follows:

$$S_m \sim N.\ell n\tilde{Z} \quad (3)$$

Here $\tilde{Z}$ means the informational code of a polymeric molecule which became larger than in molecules DNA and RNA.

Note that from our viewpoint during the evolution the number of "letters" in the "alphabet" decreases (the cosmological branch $\sim 10^2$, the chemical evolution stage on the "earth" branch – a polymeric molecule – 4.68, the biological stage of the "earth" branch – DNA-4).

Protein molecules possess the "twenty-letter alphabet" following the number of aminoacids which form them. Therefore, for their self-organisation in the living matter the recording needs transcription when one aminoacid reside corresponds to three nucleotides (codon) [43]. Then, the effective informational entropy of such a structure becomes equal to

$$S_{m_p} \sim \ell n\ 20^{N/3} = N\ell n \sqrt[3]{20} \quad (4)$$

Hence, the effective number of "letters" in the "alphabet" of a protein molecule amounts to $Z_{eff} = (20)^{1/3} \simeq 2.72$. This can mean that in terms of the evolution, from our viewpoint, proteins are the derivatives of nucleic acids and are the younger systems than DNA, but not conversely [43].

The decrease of the number of "letters" in the "alphabet" of structural elements determining the atomic complexity of the system is formulated by us as the most significant regularities without which the self-organisation of matter and its faster evolution are impossible.

6. POST-BIOLOGICAL EVOLUTION

Based on the works of Tziolkovskii [46], Dyson [47], Shklovskii [48] and others, we have tried to present graphically the evolution curve behaviour in the future as in the nearest ($\sim 10^9$ years) and as in the more distant for the open Universe model. In so doing, we conserved the basic regularities observed at the previous evolution stages, i.e. the faster rate of evolution in time and the lower number of "letters" in the "alphabet" of the evolving material systems.

The temperature "corridor" of the life for a human being (Fig. 1) is already close to zero at the present time, and the most part of energy and information, extracted from the environment, is spent on maintaining homeostasis [42]. Hence, already now we can speak about the crisis of the structural complexity of live matter.

The further run of evolution in the near future, following Ref. 48, can be assumed to be: "...man (natural intelligence (living beings) – artificial "intelligence" (non-living beings) –..." [59].

Such a continuation of evolution leads to, as was shown in Ref. 48, that "the era of natural living beings could be comparatively short-time, the transient stage in the matter evolution in the Universe." This evolution will evidently be substituted by the era of machine evolution, the foundations of which are already laid. Such "artificial intelligence" living beings (machines) could be very small and compact [48]; that is, in accordance with the modern tendency toward microminiaturisation of the elemental base of computers during their evolution. So, for example, it is indicated in Ref. 49 that in the next 20 years (i.e. to the beginning of the 21st century) the bulk density of elements will be $\sim 10^9$ per crystal, and the atomic complexity of these elements will evidently decrease up to a molecule.

Such machines will possess the two-letter alphabet (bit) that will lead to the further acceleration of evolution. They will undoubtedly be much more capable for faster adaptation to the environmental effects and conditions in space than the modern live matter [48]. Hypothetical machines of the future will also be capable of the functional self-organisation similar to that of live systems [50, 51, 52].

Here we deliberately do not speak about the stage of the possible improvement of modern live matter by methods of genetic engineering because it should be rather short and should not lead to essential evolutionary results. Though we can imagine other scenarios of the evolution in the future (e.g. not saw-shaped impulse but stepwise, rectangular impulses or anothers) we prefer to present it as a peaky impulse in order to make the impulsive (fluctuational) character of the matter evolution more distinct, at the stage just preceding the appearance of the "alive" matter on the Earth.

As far as the perspective of the evolution to the far distant future, the self-organisation of the artificial intelligence from the viewpoint of several scientists will be connected with simple cooperative structures. So, for example, in Dyson's model of the open Universe [47] they are charged micron dust grains, in Tziolkovskii's [46] they are photons and so on.

Note also that the matter evolution in the future is to some degree due to the energy and information of man's activity. Man has already been on the eve of the post-biological stage of evolution and its activity stipulates the passing to the two-letter code.

Following the above mentioned, evolution in the future is imagined graphically as a descending branch (d) in Fig. 1, which is inclined to a veryical axis less steep than the biological branch and is characterised by the lower atomic complexity of material systems.

As a whole, the ascending branch of the evolution curve includes cosmological (a), chemical (b) and biological (c) evolution stages and the descending one – the post-biological branch (d) with their asymptotic exit to the continuation of the cosmological branch. These do compose an impulse, as seen in Fig. 1, of the atomic and information complexity of the matter with a characteristic time of (1.2 to 2).10^{16}s.

The impulse area under the curve in Fig. 1 shows the

information volume accumulated by the matter during its self-organisation and extracted from the "back-ground" information of the Universe. We believe that this curve of the evolution is typical in the Universe. The self-organisation can be also considered as a giant large-scale fluctuation (in time) of the matter complexity in the fluctuating Universe (in the sense of a numerical value of fundamental constants) [53]. It is known that fluctuations are the exceptional aspect of the evolution of macroscopic systems obeying a nonlinear kinetics, being far from equilibrium [54]. In turn, each point of the curve is the beginning of small-scale (not shown in Fig. 1) fluctuations so that the curve has actually the form of a saw-shaped impulse. Since the fluctuation stage of the evolution comes sooner or later to an end and the new stationary (or pseudo-stationary) state is reached this can serve as one more argument in favour of an impulse shape of the evolution curve shown in Fig. 1.

7. POSSIBILITIES OF CONTACTS

The impulse shape of the evolution curve reveals the possibilities for contacts between the evolving impulses in the Universe. The suggestion that a similar "impulse" occurs somewhat later than our impulse is indicated by the curve (1') (Fig. 1). It is seen from Fig. 1 that peaks of these impulses corresponding to the stages of humanoids do not coincide in time. In this case it is possible that the ascending branch of the later impulse intersects with the descending branch of the earlier impulse. Here, the matter self-organisation levels of these impulses will be essentially different.

We can assume that impulses occurred simultaeously in different regions of the Universe. Then, the possible contacts between humanoids will depend on the technological level of the civilisations development which they have reached at that time.

In any case the stages of humanoids will be separated in space and time. Therefore, the civilisations of humanoids should send radiosignals or should leave other traces of their activity in the Universe. The problem lies in the sufficient number of these traces left in the Universe that is necessary for their detection by another civilisation of humanoids.

That is why we conceive as reasonable and timely the activity of Sagan (see [55]) which was encouraged by more than 100 well-known scientists from different countries (including Soviet scientists).

8. CONCLUSIONS

The above discussion yields the following basic conclusions:

(1) The origin of live matter on the Earth is a regular rather than accidental stage of the matter evolution in the Universe, which began from the Big Bang ($\sim 20 \times 10^9$ years ago).

(2) A prolonged stage ($\sim 8.10^9$ years) of extraterrestrial' chemical evolution (interstellar medium, solar nebula, comets, asteroids, etc.) followed by a cosmological stage in the Universe preceded the stage of biological evolution on the Earth.

(3) Obviously all 'advances' of the chemical extraterrestrial evolution, that is, fairly complex organic and inorganic chemical compounds, had been to some extent used in the abiogenesis on the Earth.

(4) The evolutionary curve in Fig. 1 clearly reveals an impulse (fluctuation) nature of matter evolution, especially at certain stages (chemical, biological, and postbiological). Therefore it follows that evolutionary processes at the chemical and biological stages did not differ much; they were strongly non-equilibrium, autocatalytic processes of self-organising open material systems. The latter also means that in terms of evolution there are no fundamental and insurmountable differences between live and "non-living" matter. They differ only in the quantity and quality of the information they carry.

(5) The transfer from one evolutionary stage to another should not be smooth but abrupt ("informational shock") by change of one open system for another with two probable consequential periods (the parasitic ("virus like") and the symbiotic one).

(6) Systems of "clay"-"liquid water" type and some other may be examples of such self-organising systems at the stage of chemical evolution of matter ("non-living" matter).

(7) Some quantitative characteristics of a hypothetical transitional system which are derived from the evolutionary curve make it possible, assuming a symbiotic mechanism of evolution as fundamental, to regard again the possibility of the formation of a symbiotic transitional system (polynucleotide (RNA-like molecule) – clayish "liposome") being the basis of protocell formation. Today the above assumption may be verified in the laboratory and be regarded, if confirmed, as a basic working mechanism of the Oparin-Haldane abiogenesis theory.

(8) The theory of hypercyclic (Eugen, Kuhn, etc.) origin of live matter also agrees with the data obtained.

(9) Matter evolution at a postbiological stage must also (under certain assumptions) proceed *via* strongly nonequilibrium processes of matter self-organisation, though less complex as to their atomic composition and with simpler information codes of the systems involved. The latter, as a specific character of the transfer from one stage of evolution to another, is a prevailing evolutionary trend.

(10) The electromagnetic interactions dominate in all types of material system self-organising through giant impulse (fluctuation) shown on Fig. 1. One can also suppose an existence in the Universe of other types of impulses of self-organisation started from the very beginning of the Big Bang in the material system, of which strong nuclear, weak nuclear and gravitational interactions could dominate.

(11) The impulsive nature of evolution suggests that humanoid stages of various impulses in the Universe's evolution should always be spread apart in space and time and direct contacts between them are, in effect, very difficult.

Note Added in Proof

Characteristic time of the impulse existence, measured in nuclear units [53] and estimated over an impulse area, represents the large Dirac number – $(0,2 \text{ to } 0.4).10^{40}$. Hence

characteristic linear dimension of the impulse is (1 to 2).10^2 Mps which coincides with the cell non-uniformity of the distribution of galaxies and proved to be much less than the Hubble radius. This means the possibility of similar impulses existing in the different Universe regions.

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EXTRA-SOLAR PLANETARY SYSTEMS: A MICROCOMPUTER SIMULATION

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Knowledge of the physical and chemical processes which occur within the circum-stellar nebula of a newly formed star is still uncertain and permits a number of distinct theories to account for the formation of planets. In order to gain a greater insight into the complexities of planetary formation, researchers have concentrated on 'realistic' simulations of clearly defined and limited aspects of the problem of the formation of the Solar System. Attempts to describe the nature of planetary systems of other stars have been left largely to popular speculation.

The microcomputer model presented here produces a wide range of data for possible planetary systems with primary stars in the mass range 0.6-1.3M⊙. A synthesis of current theory, research and speculation, the purpose of the model is not to add to our understanding of the processes that form planets, but to give an integrated view of the possible nature of extra-solar planetary systems and to investigate the possibility of a systematic variation in planetary characteristics with primary mass.

1. INTRODUCTION

It is considered that planetary systems are common in the Galaxy and that their origin is related to the stellar formation process. Evidence for the existence of extra-solar planets is tenuous. Measurements of the apparent perturbations of Barnard's star, made by van der Kamp [1] have been shown by Gatewood [2] to have been within the error band of the measurement technique used and hence cannot be taken to prove the presence of invisible companions. The recent discovery by IRAS of shells of dusty detritus surrounding nearby luminous stars; the identification of a ~ 10 Jovian mass substellar companion to the red dwarf VB8B [3]; and the identification by Smith and Terrile of a disc shaped mass of dust and gas orbiting the young star Beta Pictoris are significant. The latter observation is of particular interest as the most widely accepted modern theories envisage planetary formation occurring within a disc shaped nebula.

On the assumption that the formation of planets is a consequence of star formation itself, the only time a star will possess a nebula from which planets could form would be when the star is still embedded in its 'placental' cloud. Thus, models of star formation are also crucial to an understanding of the origin of planets. Modelling of this process has developed in step with the increasing power of the computers available to perform the calculations. Stars form by gravitational collapse of concentrations of interstellar gas and important work on spherically symmetric collapse was performed by Larson [4, 5]. More recent work, including axisymmetric and asymmetric collapse has been reviewed by Boddenheimer and Black [6] and Boss [7]. Their work leads them to suggest that commonly a rapidly rotating cloud fragments to form a multiple star system. However a slow rotating cloud does not fragment and the central condensation forms a single star, having previously transferred excess angular momentum to the outer regions of the cloud by gravitational interactions. The results of these theoretical studies, and the models built upon them, further restrict capture and tidal origin models for the origin of the Solar System.

The precise process by which the planets of our Solar System, and presumably extra-solar planets, formed is still unknown. Cameron [8, 9, 10] has done much work in developing the 'Protoplanet Hypothesis' in which giant gaseous protoplanets form by gravitational collapse of the solar nebula on a time scale as short as ~ 10^4 years. The inner terrestrial planets are assumed to have their initial massive, distended, atmospheres removed by solar tides. Difficulties encountered by this hypothesis include the requirement for a very massive nebula and the lack of agreement between the predictions of the theory and the measured isotopic abundancies of various noble gas isotopes present on Earth, Venus and Mars. The 'Planetesimal Hypothesis' proposes that planets form by the aggregation of dust grains into planetesimals which accrete by collision to form planets, over a much longer time scale of ~ 10^8 years. Although this hypothesis appears to account satisfactorily for many features of the terrestrial planets, a number of 'leaps of faith' are necessary to reach planetary masses observed in the Solar System. Goldreich and Ward [11] modelled the formation of ~ 2 km planetesimals from dust grains. Greenberg *et al* [12] have performed a computer simulation of the growth of planets from a swarm of 1 km planetesimals. However by the time the simulation had formed a number of ~ 1000 km bodies, no further growth occurred as the planetesimal orbits had evolved to a near circular and isolated state. Further evolution from such a state might take place through perturbation of planetesimal orbits by a massive planet close to the outer limit of the planetesimal zone. In the Solar System this could indicate that Jupiter may have formed on a short time scale, possibly by a Cameron gravitational instability. Heppenheimer [13] has concluded a mathematical analysis that does not conform with this proposal in that it suggests that perturbations on planetesimal orbits from a body not much greater in mass than Jupiter will prevent planetary growth as colliding planetesimals will fragment rather than coalescing. Further work is necessary to resolve this issue. Cox and Lewis [14] and Wetherill [15] have modelled the formation of terrestrial planets from a system of 100 planetesimals of.02m⊕. Planets similar in number and mass to those of the inner solar system are produced so long as the initial eccentricity of the bodies is fairly high ~ 0.15. Greenberg *et al* [16] have extended their work to simulating the accretion of Uranus and Neptune from icy planetesimals. Thus, at the present time there is no generally accepted physical theory of planetary formation, and this situation is likely to persist for some time into the future. Any attempt to predict the probable nature of extra-solar planetary systems must be made on the basis of a simplification and synthesis of the most compatible hypotheses currently available. This is the aim of the current paper.

2. THE MICROCOMPUTER MODEL

The computer simulation that is the subject of this paper (assigned the identifier 'Silicon Creation') runs on a BBC microcomputer with 6502 second processor. The code is ~ 31K long and written in BBC BASIC, several K extra are also used on top of this for 37 arrays of data storage. One planetary system run takes approximately 70 seconds which includes a graphic display of the results.

The purpose of the model is to create physically possible planetary systems accompanying stars of between 0.6-1.3M⊙. A multiplicity of data is produced, the output is calculated from procedures in the program derived from current and generally accepted hypotheses on the formation and chemical composition of the planets. For certain aspects, where present knowledge or theory is incomplete, then empirical approximations based on Solar System data or informed speculation are used.

The results derived for each planet within a system are as follows.

DYNAMIC CHARACTERISTICS: Semi-major axis; sidereal period; orbital eccentricity; inclination of rotational axis; rate of rotation and presence of full or partial synchronicity.

PHYSICAL/CHEMICAL CHARACTERISTICS: Radius; density; mass; surface gravity; surface temperature; albedo; surface pressure and probable composition of atmosphere; extent of hydrosphere; size of polar ice caps; boiling point of water (where applicable); the possible existence of life.

A number of factors are taken into account during generation that do not appear in the program output, including: the effect of orbital eccentricity on spin locking; tidal forces; U.V. light; volatile inventory and atmospheric outgassing; runaway greenhouse and runaway glaciation effects.

This kind of data, in the context of extra-solar planets, has formerly been confined to generalised discussions e.g. Dole [17], Asimov [18] and Pollard [19]. The output of 'Silicon Creation' has the advantage of being more detailed and specific, on a random basis, and not subject to human bias during calculation. Totally unique systems are generated each run which, superficially at least, appear plausible alternatives to our own Solar System. We shall now examine the physico-chemical basis and the assumptions contained within the model, followed by some examples of the output.

3. CHARACTERISTICS OF THE PRIMARY STAR

Although stable orbits within binary star systems are possible (Harrington [20]), it is not clear that planets would be able to form in such systems. Thus all the stars discussed herein are assumed to be single.

'Silicon Creation' will generate hypothetical planetary systems over a range of primary stellar masses. However most of the program algorithms have been derived and extrapolated from research on 1M⊙ stars and so the results must become increasingly unreliable with high or low values of M/M⊙. Thus the range chosen for this paper is 0.6-1.3M⊙, spectral class K5-F5. The value chosen for the upper mass limit coincides with the observed discontinuity in rotational behaviour of early F type stars (Kraft [21]).

The luminosity of a star depends on its mass. It is convenient however to approximate the luminosity of a star in solar units by a power law:

$$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^n \qquad (1)$$

TABLE 1: Range of Stellar Characteristics for the Computer Model.

Mass (M⊙)	Luminosity (L⊙)	Ecospheric Radius (A.U.)
0.6	0.12	0.34
0.7	0.21	0.46
0.8	0.36	0.60
0.85	0.47	0.69
0.9	0.61	0.78
0.95	0.78	0.88
1.0	1.00	1.00
1.05	1.27	1.13
1.1	1.59	1.26
1.15	1.96	1.40
1.2	2.40	1.55
1/3	3.48	1.86

The mass/luminosity power function 'n' is not a fixed quantity and approaches a maximum of ~ 5 at 1M⊙. n is assumed to vary as:

$$\frac{M}{M_\odot} < 1: n = 1.75\left(\frac{M}{M_\odot} - 0.1\right) + 3.325 \qquad (2)$$

for

$$\frac{M}{M_\odot} >= 1: n = 0.5\left(2 - \frac{M}{M_\odot}\right) + 4.4 \qquad (3)$$

The age of the central star, and therefore the age of the system is an important factor, having a bearing on the rotational and chemical evolution of planets. Stellar luminosity is also thought to vary with age, although the exact nature and scale of this change remains uncertian; the extra complexity of including this factor has militated against including this within the model. Following Pollard [19], a maximum age of 6 x 10^9 years (6 Byr) has been assumed for a Population I star with sufficient heavy elements to form a planetary system chemically similar to that of the Sun. This limit may be conservative when one considers the 'Big Bang' theory of Reeves [22] where solar type stars are envisaged as being born 'amidst a fireworks of supernovae'! The main sequence lifetime of a star in Byr is taken as:

$$t_{ms} \sim 10\left(\frac{M}{M_\odot}\right)/\left(\frac{L}{L_\odot}\right) \qquad (4)$$

Stars with $t_{ms} >= 6$ Byr have ages randomised between 1-6 Byr. Stars with $t_{ms} < 6$ Byr have ages randomised between 1-t_{ms} Byr.

The luminosity of the primary determines the position of the ecosphere, or 'habitable zone' in which an Earthlike planet may exist. The relationship for the mean ecopsheric radius in A.U. is:

$$r_{ecos} = \left(\frac{L}{L_\odot}\right)^{1/2} \qquad (5)$$

The range of stellar characteristics assumed for the model is displayed in Table 1.

The inner and outer boundaries are not so easy to deter-

mine. In the last century it was thought that both Venus and Mars might be habitable, which would give $r_{inner} = 0.72$ and $r_{outer} = 1.52$ A.U. Dole [17] performed calculations on Earthlike planets with optically thin atmospheres. It was assumed that they were habitable if at least 10% of the surface had average yearly temperatures between 0-30°C with highest mean daily temperatures not above 40°C and lowest not below -10°C. He obtained the values for $r_{inner} = 0.725$ and r_{outer} 1.24 A.U. Rasool and de Bergh [23] calculated the evolution of a young planet with an outgassed CO_2/H_2O atmosphere taking into account the greenhouse effect on surface temperature and condensation of volatiles. They found that beyond a value for r_{inner} between 0.93-0.95 A.U. planets automatically underwent a runaway greenhouse effect to become Venusian in character. Hart [24] with his well known computer simulation of the evolution of the Earth's atmosphere obtained the values for $r_{inner} = 0.95$ and $r_{outer} = 1.01$ A.U. His model is very sensitive to initial conditions and balance between runaway greenhouse effect and runaway glaciation is critical. Recently, Sawyer [25] has demonstrated that to a large degree this sensitivity is linked to Hart's assumption of a reducing atmosphere early in the Earth's history. For the purposes of 'Silcon Creation,' an optimistic value for r_{inner} is taken:

$$r_{inner} = r_{ecos} \times 0.93 \tag{6}$$

r_{outer} is not derived as an exact radius within the model, but is determined individually for each planet, using a simplified Hart cloud/ice climatic feedback model (discussed later). Since 'Silicon Creation' is not a dynamic evolutionary model r_{outer} is less sensitive than Hart indicates, massive Earthlike planets with dense atmospheres and extensive low albedo oceans remain stable out to ~ 1.1 A.U.

4. PLANETARY MASS DISTRIBUTION

For the generation of hypothetical planetary systems, a method of obtaining the number of planets, and their individual values for semi-major axis, orbital eccentricity, and mass, is crucial.

As outlined in the introduction, within the framework of the hypotheses concerned, limited aspects of the puzzle of star/planet formation are partially understood, but the picture is still incomplete. None of the computer models mentioned terminate with 'complete' planetary systems, and many of them would be unsuitable for a microcomputer. The computer model of Dole [26, 27], 'ACRETE,' does simulate the process of planetary formation from start to finish. Commencing with an idealised spherical nebula of gas and an exoconic disc of dust surrounding a star of 1M⊙, randomly injected accretion nuclei are allowed to grow iteratively by sweeping up dust particles through collision and gravitational capture. Depending on the local temperature in the nebula and the mass of the nucleus, gas can be swept up as well to form giant planets. When all the dust has been removed, the residual gas is deemed to have been expelled from the system by a T-Tauri stellar wind. When run with certain 'ideal' values for the input parameters Dole found that 'ACRETE' produced planetary systems with characteristic mass distribution similar to the Solar System. Orbital spacings were reminiscent of a Bode style 'law.' Isaacman and Sagan [28] experimented further with 'ACRETE' and found that, by varying the input parameters, anything from multiple star systems to systems containing terrestrial planets only could be created.

Dole's model has received criticsm from Wetherill [29], as over simplified and physically unrealistic in ignoring dynamical perturbations and gas drag. However, Bond and Martin [30] in attempts to determine a value for the possible number of 'habitable' planets in the Galaxy, used their own modified version of 'ACRETE' as part of their calculation procedure. Response to citicism caused Bond and Martin [31] to modify their calculations slightly but not to abandon the Dole model as an integral part. The capability of 'ACRETE' to generate planetary systems not dissimilar to the Solar System remains impressive, at least from the standpoint of the 'Principle of Mediocrity.' The present author has found that Dole's algorithm can be reconstructed from the published work, condensed into ~ 2K of BASIC and run on a microcomputer, and has obtained similar results with various values of initial parameters as Dole and Isaacman and Sagan. The Dole algorithm forms a procedure within 'Silicon Creation,' the initial parameters fixed at the 'ideal' values.

This path leads to considerable difficulties. The virtual entirety of research into the subject of planetary formation assumes a central star of 1M⊙ and there is no generally accepted hypothesis that describes a systematic difference in the properties of planetary systems of stars of varying mass. The minimum assumption model of Taylor [32] suggests that the orbital radii of maximum mass condensation zones within a pre-planetary nebula can be directly linked to stellar luminosity, and the mass of the resulting planets to the local gravitational field and escape velocity. This leads to the formation of massive planets close to low mass stars, and to low mass, gas poor, planets remote from high mass stars. This model has been computerised by Fogg [33] and, while an attractive hypothesis, a number of inconsistencies remain to be worked out.

Is it possible to modify the Dole algorithm to accommodate a wider stellar mass range? Isaacman and Sagan [28] showed how sensitive the output of 'ACRETE' is to alterations, so an effort has been made to make any changes subtle and justifiable. The value of m_{crit}, the mass at which a nucleus starts to collect gas is determined by the local temperature at a given radius from the central star. Thus Dole's formula is modified to take into account stellar luminosity:

$$m_{crit} = B\left(Rp\left(\frac{L_\odot}{L}\right)^{1/2}\right)^{-3/4} \tag{7}$$

where $B = 1.2 \times 10^{-5}$ M⊙ A.U.$^{3/4}$ and Rp = radius of perihelion in A.U.

One obvious way to scale the mass of the nebula might be to vary Dole's central density parameter, 'A,' directly with stellar mass. However Larson's [5] work on stellar formation indicates that the cores of massive stars form and evolve faster than the infall time of the surrounding gaseous envelope, whilst for low mass stars the core takes longer to form, and the infall of the envelope that is denser to start with becomes complete. Once a protostar reaches the main sequence, radiation pressure would be expected to hinder further infall of gas and dust from external regions of the nebula; thus more massive stars associated with a nebula of high initial mass may not have all that mass available for planetary formation. The Jeans density for a collapsing cloud, $\rho \propto (M/M_\odot)^{-2}$ and the magnetic field strength at the centre $\propto \rho^{1/2}$. If magnetic braking is a process involved in transferring angular momentum from the central star to a planetary system, then lower mass stars might be expected to be more efficient at this because of a denser cloud and stronger magnetic field. On this basis it was decided to vary the parameter for central density as:

$$A \propto \left(\frac{M}{M_\odot}\right)^{1/2} \tag{8}$$

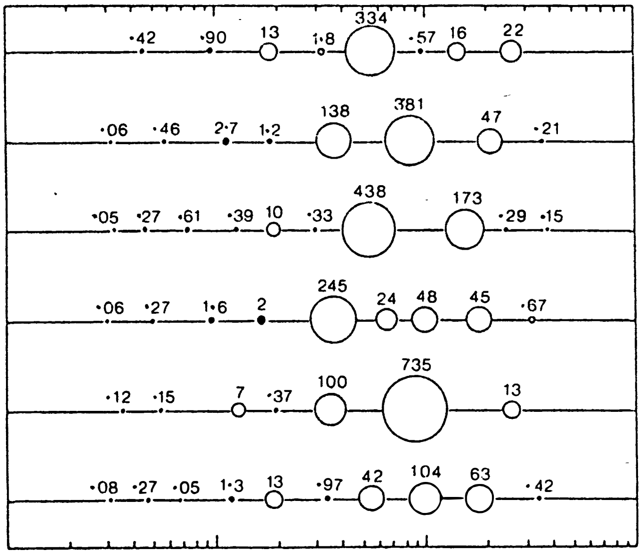

Fig. 1. Planetary system mass distribution, generated by 'Silicon Creation' for a primary of 1M⊙. The horizontal scale represents orbital distance in A.U. Planetary mass is in units of M⊕. Solid circles represent 'terrestrial' planets that have accreted dust only from the nebula, open circles represent 'giant' planets that have accreted gas as well as dust.

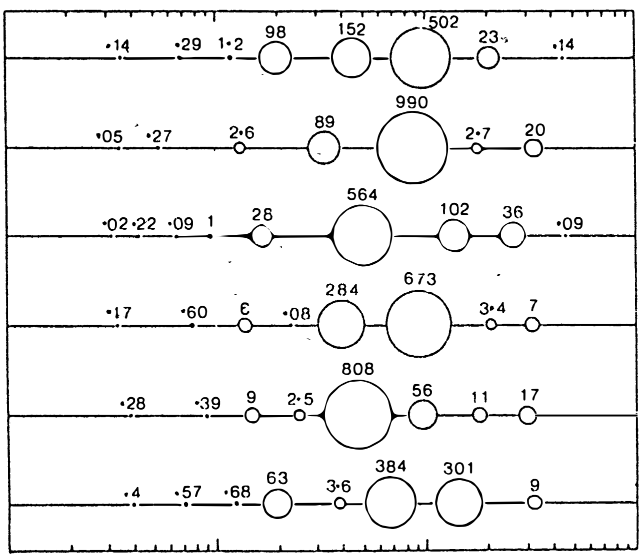

Fig. 3. Planetary system mass distribution – primary 0.6M⊙.

Varying the maximum mass condensation radius with Dole's algorithm leads to very bizarre results. Condensation of volatiles such as H_2O, NH_3 and CH_4 would depend ultimately on the luminosity of the central star. However H_2 and He remain gaseous throughout the nebula and a systematic variation in the radial density gradient of gas in a preplanetary nebula for stars of differing mass is difficult to predict. Since the total stellar mass range discussed in this paper is only 0.7M⊙ and because of difficulties with the Dole algorithm in 'Silicon Creation' Dole's value for the maximum mass condensation radius, ~ 5.8 A.U., is not altered. Huang [34] does describe a possible scenario in which the scale of planetary systems is insensitive to the

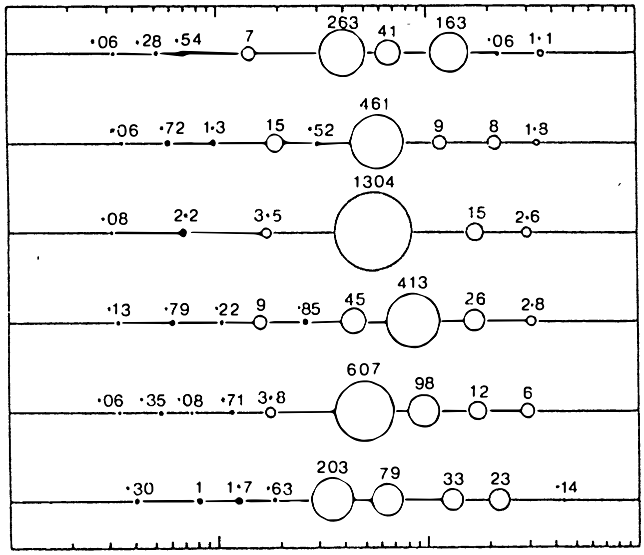

Fig. 2. Planetary system mass distribution – primary 1M⊙.

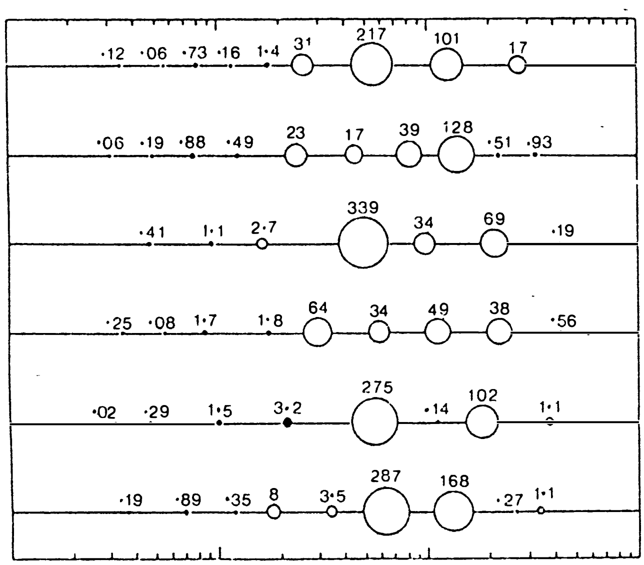

Fig. 4. Planetary system mass distribution – primary 1.2M⊙.

mass of the central star and the modification of Eq. (7) does lead to the greater accumulation of volatiles on inner terrestrial planets hypothesised by Cameron [9].

Figures 1-4 display mass distributions for planetary systems generated by 'Silicon Creation.' It is noticeable that there is a rise in the average mass of a planetary system with decreasing stellar mass, even though Eq. (8) has the effect of decreasing 'A,' the central density of the nebula. It is the modification to Eq. (7) that strongly counteracts the sensitivity to 'A' demonstrated by Isaacman and Sagan [28]. Lower temperatures around less luminous stars allow a greatly increased accumulation of gas relative to the density of that gas adjacent to an accreting nucleus. Planets of ~ 2-3 Jovian masses are common in such systems. The converse is true for the higher mass stars within the chosen range; higher temperatures reduce the amount of gaseous accretion from a denser medium and the largest planet to

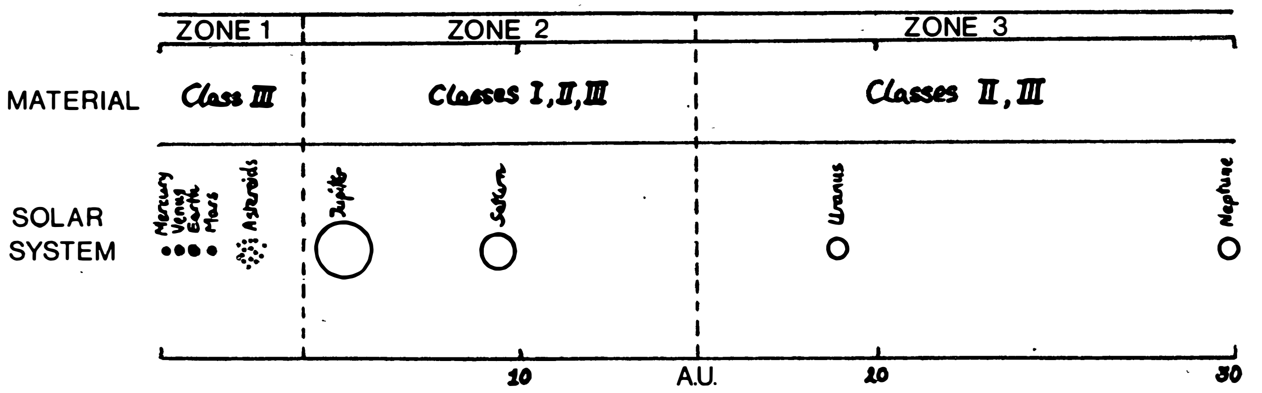

Fig. 5. The Solar System and planetary formation zones in a solar nebula for a 1M⊙ star.

form is typically less than 1 Jovian mass. Apart from raising the value of M_{crit}, Eq. (7) does not play a part in determining the final mass of a terrestrial planet, as accumulation of refractory dust is assumed not to be affected by temperature. The masses of terrestrial planets are as sensitive to the value of 'A' as Isaacman and Sagan indicate; thus there is a tendency for 'Silicon Creation' to produce low mass terrestrial planets around low mass stars and more massive terrestrial planets in systems of high mass stars, a trend opposite to that of the giant planets.

These conclusions are drawn from a limited modification of the Dole algorithm. Further study is necessary to determine whether this systematic variation in planetary mass with the mass of the primary star is to be expected.

5. PLANETARY CHARACTERISTICS

Once the masses and semi-major axes of planets within a system have been determined, the computer calculates the likely characteristics of each planet.

Figure 5, after Pollard [19], shows the hypothetical chemical segregation of material within a pre-planetary nebula around a 1M⊙ star such as the Sun. Class I material consists of H_2 and He which both remain gaseous throughout the nebula. Class II material represents volatile 'ices' containing the elements CHO and Class III material represents refractory materials. As the figure shows, in 'Zone 1' out to a distance of ~ 4 A.U. the chemical composition is mostly Class III, from which the Earth and inner planets and asteroids have formed. 'Zone 2' is between ~ 4 A.U. and 14-16 A.U. the nebula is hydrogen rich and approximates to solar composition; the most massive planets form in this region. Beyond this, in 'Zone 3' the escape velocity from the nebula becomes low enough for an increasing loss of H_2 and He and a relative enrichment of any giant planets formed with CHO compounds. It would be expected that the distribution of Class II material particularly would be sensitive to the luminosity and thus the mass of the central star. The variation in the maximum condensation radius of this material $\propto (L/L_\odot)^{1/2}$. This process of early chemical segregation in the nebula is what determines the future properties of planets.

5.1 Density and Radius

Kothari [35] derived a relationship between the 'radius' of a 'cold' planetary body and its mass:

$$r = \frac{\frac{2\beta}{a_1} \frac{1}{(2A)^{1/3}} M_\odot^{1/3}}{1 + \frac{a_2}{a_1} \frac{A^{4/3}}{Z^2} M_\odot^{2/3} (\frac{M}{M_\odot})^{2/3}} (\frac{M}{M_\odot}) \quad (9)$$

where M is the mass of the body, a_1, a_2, and β are constants and A and Z relate to chemical composition, being the averaged atomic weights and atomic numbers respectively of the elements comprising the body.

For bodies below a certain critical mass (about 1-6 times the mass of Jupiter), planetary radius increases with mass. Above this mass however, gravitational forces dominate over electrostatic forces and the radius shrinks with increasing mass. Equation 10 is very sensitive to chemical composition and it was found to be far simpler, for the purposes of computation, to determine the relationship between mass and density for a terrestrial planet ($m < m_{crit}$) by the following empirical formulae:

$$\rho = (\frac{m}{m_\oplus})^{1/8} (\frac{r_{ecos}}{R})^{1/4} \times 5.5 \quad (10)$$

where r_{ecos} is determined from Eq. (5) and R is the semi-major axis in A.U. This formula gives values of density to within +- 10% to the values of all the terrestrial planets and Titan and Pluto and is designed not only to reflect gravitational compression of massive terrestrial planets but also a systematic increase in incorporated lightweight Class II material with increasing distance from the central star.

5.2 Rotation and Tidal Force

The origin of planetary rotation is still obscure, but is generally considered to be a by-product of the process of the formation of the planets, in which tangential impacts of planetesimals from interior and exterior orbits a quantity of angular momentum to the planet and contribute to its spin. Axial inclination is also thought to result from the impact angles of the last few large bodies to collide with the young planet. Harris [36] has arrived at an analytical theory of planetary rotation rates; however incorporation of this work into 'Silicon Creation' is hampered by the lack of detailed knowledge of planetesimal encounter velocities.

Dole [17] made use of an empirical relationship that suggests that rotational energy per unit mass of a planet is directly proportional to the planet's mass:

$$\frac{k_2}{2} \omega^2 r^2 = jm \quad (11)$$

where ω is the angular velocity j is a constant 1.46×10^{-19} cm^2/sec^2 g and k_2 is related to central condensation. ~ 0.33 for a terrestrial planet, ~ 0.24 for a giant planet.

Thus:

$$\omega = \left(\frac{jm}{\frac{k_2}{2} r^2}\right)^{1/2} \qquad (12)$$

This gives good approximations to the angular velocities of the non-tidally decelerated planets in the Solar System, depending on the exact value of k_2. Equation 12 is used in 'Silicon Creation' to determine the initial rotation rates for the generated planets. A value for planetary axial inclination is determined randomly from an empirical relation derived from the observed axial inclination values of the Solar System planets.

Planets close to the central star are subjected to tidal forces that decelerate the spin of the planet. (As satellites are not catered for in the model, tidal forces from nearby massive moons do not come into play.) A detailed analysis of the properties of tidal forces is presented by Goldreich and Soter [37]. The magnitude of the stellar tidal force is proportional to the cube of the distance from the central star and the magnitude of the tidal counter torque is proportional to the square of the tidal force. The ratio of deceleration of a planet to that for Earth is:

$$\frac{\dot{\omega}}{\dot{\omega}_S} = \left(\frac{\beta_\oplus}{\beta}\right)\left(\frac{r}{r_\oplus}\right)\left(\frac{m_\oplus}{m}\right)\left(\frac{M}{M_\odot}\right)^2\left(\frac{1}{R}\right)^6 \qquad (13)$$

where $\omega_s = -1.3 \times 10^{-6}$ rad/sec/10^9 year and β is the matter/mass distribution.

For habitability (in human terms) a planet would have to maintain the angular velocity above about 2×10^{-5} rad/sec (~ 87 hour rotation rate). Beyond this limit, excessive diurnal temperature fluctuations and permanent gale force winds generated by thermal tides within the atmosphere, would probably render the planet inhospitable to higher forms of life. Table 2 shows how rotation rates might alter after 4 Byr and 4.6 Byr (the age of the Solar System). The planet is assumed to be $1m_\oplus$, with an initial rotation rate of 15 hours, and slowed rotation rates are calculated for positions at r_{inner} and r_{ecos}. If, as seems likely, planets take ~ 4 Byr to generate oxygen rich atmospheres and become habitable, then there are unlikely to be many habitable planets accompanying stars of less than $0.8M_\odot^+$.

It is not certain exactly what effect synchronous rotation would have upon a planetary atmosphere. Venus rotates, relative to the Sun, very slowly in 122 days, but heat transfer to its dark side is carried out very effectively by a four day circulation of its atmosphere. Possibly the atmosphere of a planet with one permanently illuminated hemisphere would behave like this; however, if the planet had become tidally despun early in its history when its atmosphere was less dense, the likely outcome would be a freezing out of all volatiles on the dark side of the planet. It is this latter scenario that is always assumed by the model.

Before 1962 it used to be thought that solar tidal forces had rendered the rotation of Mercury synchronous, the planet's rotation period equalling its orbital period of 88 days. However, the high orbital eccentricity of Mercury, 'e' = 0.205, has prevented true synchronous rotation, resulting instead in a 2/3 resonant/synchronous spin-lock period of 58.65 days. This arises because of the marked variation in the magnitude of tidal breaking between perihelion and aphelion; for Mercury this ratio is ~ 3.5. If, for a spin lock to come into existance, we assume a minimum value for the tidal ratio of 2, then this occurs for an orbital eccentricity of 0.115. The spin resonance period can be derived from the relation:

TABLE 2. Change in Rotation Rates for an Earth-Mass Planet.

Primary Mass $M_\odot$	Rotation rate at 4Byr r_{inner}	r_{ecos}	Rotation rate at 4.6Byr r_{inner}	r_{ecos}
0.75	-SYNCHRONOUS-		-SYNCHRONOUS-	
0.80	303.5	39.0	SYNC	51.3
0.85	28.1	21.5	32.2	23.0
0.90	20.0	17.9	21.1	18.5
0.95	17.4	16.5	17.8	16.7
1.00	16.2	15.8	16.3	15.9
1.05	15.6	15.4	15.7	15.5

$$(1 - e) / (1 + e) \qquad (14)$$

for Mercury this gives (1-0.2)/(1 + 0.2) = 2/3.

In 'Silicon Creation' the computer calculates a resonant spin lock period for any planet that is tidally despun and for which 'e' > 0.1. Since such a planet receives illumination to all parts of its surface, it is assumed (subject to its mass) to be capable of retention of an atmosphere.

5.3 Atmospheres and Climate

Although for a terrestrial planet, the mass of its atmosphere is only a tiny fraction of its total mass, the presence of that atmosphere and its chemical composition has a profound effect on surface conditions. Since atmospheric processes are so complex and to a certain degree still uncertain, extrapolation to extra-solar planets has had to be handled using Solar System examples from which to construct a very generalised empirical model.

The following factors are taken into account by 'Silicon Creation' in determining the chemical constituents of an atmosphere:

(a) Primordial gas retained after planetary formation;

(b) Volatiles released from the interior of the young planet;

(c) The escape velocity of the planet.

(These first three factors are themselves related to the mass of the planet;)

(d) The exospheric temperature of the planet;

(e) The surface temperature of the planet;

(f) The intensity of U.V. radiation received from the central star over time;

(g) The presence of life.

Whether or not a planet can retain a gas depends on its escape velocity and the root mean square velocity of the gas atoms or molecules.

The escape velocity of a planet is:

$$V_e = \sqrt{2gr} \qquad (15)$$

where g is the acceleration due to gravity at the escape altitude.

The RMS velocity of an atom or molecule is:

$$V_o = \sqrt{\frac{2kT}{m_a}} \qquad (16)$$

where k is Bolzmann's constant, m_a is the atomic or molecular mass and T is the exospheric temperature $\sim$ 1000°C. A simple assumption is made that exospheric temperature varies inversely with the square root of perihelion distance. If the ratio V_e/V_o is five or greater than the fraction of gas atoms or molecules moving faster than escape velocity is so low that the retention of the gas becomes essentially permanent.

For $m > m_{crit}$ (Eq. (7)), a planet becomes capable of retaining hydrogen and therefore sweeping up large quantities of gas from the nebula. These planets therefore become 'giants' possessing promordial H_2 and He rich atmospheres. According to some theories, smaller, terrestrial planets lose their primordial atmospheres rapidly, and essentially begin their lives 'airless." A secondary atmosphere slowly builds up from within by an outgassing process. Possibly the original dust grains within the nebula might have contained 0.01% volatile material, which vents to a planetary surface during thermal differentiation of the interior. Depending on the escape velocity, exospheric temperature and surface temperature of the planet, some or all of these components may be lost to space or frozen on the surface. If so, the end result is a body like the Moon, Mercury or Ganymede. It is the amount and chemical evolution of the remaining constituents over time that determine the characteristics of the atmosphere of a terrestrial planet.

The planets Venus and Earth are of similar mass but the atmosphere of Venus is 90 times more massive than that of the Earth. Yet it is clear that both planets have outgassed a similar amount of carbon and nitrogen compounds; because of the runaway greenhouse on Venus these compounds remain in the atmosphere whereas on the Earth they have been largely re-deposited into surface reservoirs. If all the carbon and nitrogen containing rocks in the Earth's crust were to be decomposed, the Earth would possess an atmosphere similar in mass and composition to that of Venus. Venus does appear to have much less water than the Earth, but one explanation for this is that, over the lifetime of Venus, most of the water vapour resident in the atmosphere has been photodissociated by solar U.V. radiation, the hydrogen that is released escapes to space and the oxygen combines with surface rocks.

Examination of the surface of Mars shows sinuous channels apparently caused by flowing water. These could only have formed when the atmosphere was considerably denser than it is at present; estimates for the total amounts of volatiles outgassed on Mars give a partial pressure range between 1500-15000 mb of H_2O and from 37-370 mb of CO_2 (Levine [38]). It is believed that much of the water and CO_2 originally vented to the exterior has been absorbed back into the planet's crust. Some models (Sagan [39]) place Mars in an 'Ice age' that occurs twice each equinoctal precession $\sim 5 \times 10^4$ Years. During intermediate periods vapourisation of surface CO_2 could raise atmospheric pressure and surface temperature by > 30K.

Given the limited data available and the lack of detailed knowledge of volatile outgassing, we assume that the initial volatile inventory can be taken as directly proportional to planetary mass. Cameron [9] has pointed out that planets of low mass stars will accumulate greater masses of volatiles due to lower temperatures of formation, the volatile inventory is also assumed to be inversely porportional to the mass of the central star. Incorporating a random variation we get:

$$V_{inv} = q\left(\frac{m}{m_\oplus}\right)\left(\frac{M}{M_\odot}\right)^{-1} \pm 20\% \qquad (17)$$

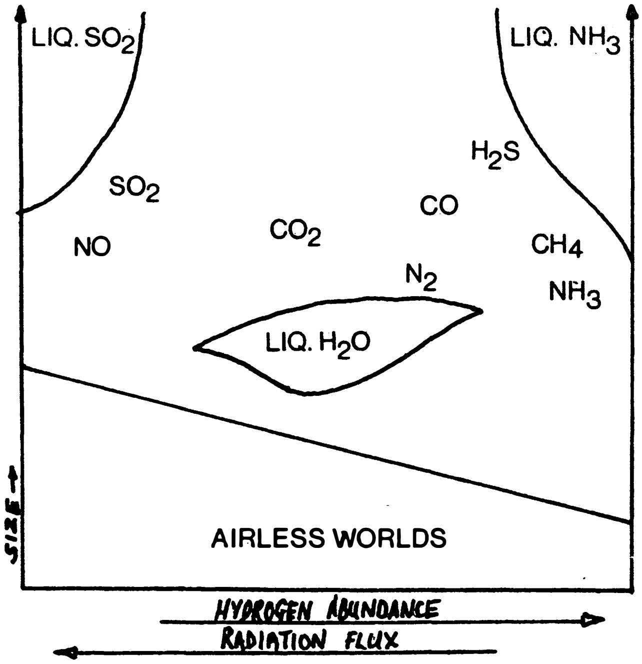

Fig. 6. Possible major atmospheric gases for terrestrial planets, from oxidising to reducing composition.

where q is a constant of proportionality normalised to Earth (q = 100000) for planets in 'Zone 1,' normalised to Titan (q = 75000) for planets in 'Zone 2,' and normalised to a hypothetical residual Helium and sublimated CH_4/N_2 atmosphere (q = 250) for planets in 'Zone 3.' In 'Zone 1' planets do not undergo a runaway greenhouse effect ($R >= r_{inner}$) are assumed to depoit 99% of their volatiles to surface reservoirs, ($V_{inv} = V_{inv}/100$).

The surface pressure of this atmosphere in mb would be:

$$\rho_{surf} \sim V_{inv} \left(\frac{r}{r_\oplus}\right)^{-2} \times g \qquad (18)$$

Given the mass and semi-major axis of an extra-solar terrestrial planet, it is just as difficult to construct an exact model of its atmosphere as it was for planets in the Solar System before the use of space probes. Models proposed for the atmosphere of Venus included such exotic features as oceans of oil and clouds of perpetually whirling dust. Some astronomers took seriously the concept that Mars had a breathable atmosphere and was inhabited; an alternative model suggested that the Martian atmosphere was toxic and enriched with nitrogen oxides. Before the Voyager missions it had been generally concluded that Titan possessed only a thin atmosphere of methane. It is now known that the Solar System planets are very different, and in many respects more strange, than previously imagined, many of these models were and are not inherently impossible and might apply under slightly different conditions on planets elsewhere in the Universe.

The continuum of gaseous composition for possible terrestrial planet atmospheres, from highly reducing to strongly oxidising, is illustrated in Fig. 6. Planetary mass determines what gases can be retained. Incident U.V. flux has an important effect on the evolution of an atmosphere as ultraviolet radiation photodissociates many hydrogen bearing compounds and loss of hydrogen to space will result in a more oxidising gaseous composition with age. The temperature and pressure of the atmosphere determines which

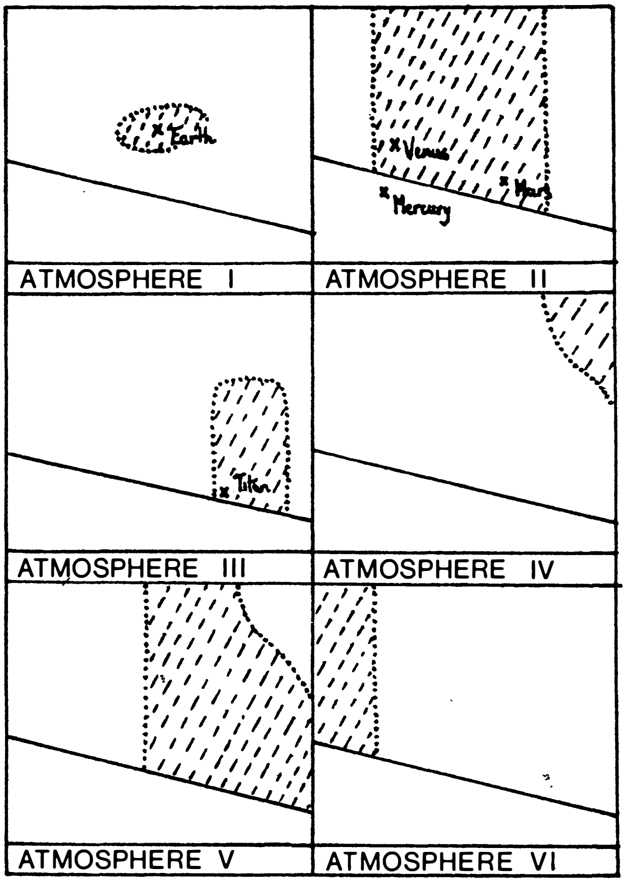

Fig. 7. Six types of atmosphere into which the continuum of composition is divided.

compounds can remain gaseous and which are deposited to the surface as a liquid or solid.

It was necessary to divide this continuum of composition into seven 'slices,' as the number of decision gates and the amount of code the computer has to run through to make the most likely choice is large and requires a lot of memory. Thus 'Silicon Creation' assigns one of seven types of atmosphere to a terrestrial planet, subject to physical conditions and age. Figure 7 displays six of these atmospheres in the context of Fig. 6. There would be a considerable variation in composition within each type. The seven atmospheres are here briefly described.

Atmosphere I – A nitrogen/oxygen atmosphere, always in this model associated with liquid water and the presence of life. Percentage of oxygen is linked with age and with the land/sea ratio as suggested by Dole [17]. This is representative of the Earth's present atmosphere.

Atmosphere II – Predominantly carbon dioxide with N_2 and H_2O and many other trace constituents. Distinction is made by the computer as to whether the origin of this atmosphere is the result of a runaway greenhouse effect, which occurs automatically for planets with semi major axes less than r_{inner}. Both the atmosphere of Venus and Mars fall into this wide category, as does the Haldane model for the Earth's primordial atmosphere and the initial composition of the Earth's atmosphere in Hart's model [24].

Atmosphere III – Nitrogen and hydrocarbons. Titan and planets situated in 'Zone 2' that do not retain H_2 but can retain N_2 are in this category.

TABLE 3. Assumed Planetary Albedo Values.

	ALBEDO
Gas Giant	0.4
Airless rocky body	0.07
Airless icy body	0.4-0.7
Atmosphere II (Venusian)	0.7
Atmosphere III	0.2
Atmosphere IV	0.3
Atmosphere VI	0.6
Atmosphere VII	0.4-0.7
Atmospheres I, II, V	
Clouds	0.52
Rocks	0.15
Oceans	0.04
Ice	0.7

Atmosphere IV – A hypothetical methane atmosphere with quantities of N_2 and NH_3. If surface temperature and pressure is suitable, liquid ammonia can exist and an ammono organic chemistry scheme like that envisaged by Firsoff [40] might occur. This type of atmosphere, even if possible, would not be stable over long periods of time unless there is a low U.V. flux from the central star. 'Silicon Creation' only chooses this option for planets in a certain temperature band around young late K class stars.

Atmosphere V – An atmosphere of reduced carbon compounds, with quantities of N_2, CO_2, water vapour and NH_3. Similar to the primitive atmosphere of the Earth proposed by Oparin and the Hart model's intermediate phase of atmospheric evolution ($\sim$ 3.5-2.5 million years before present).

Atmosphere VI – A fully oxidised atmosphere resulting from total loss of hydrogen by photodissociation of water. Sulphur and nitrogen oxides are present. If a planet has received double the intensity of U.V. radiation of the correct energy over time as Venus, then the computer chooses this atmosphere.

Atmosphere VII – An atmosphere of helium and sublimated 'ices,' for terrestrial planets in 'Zone 3.'

The surface temperature of a planet depends on its albedo and the greenhouse effect of the atmosphere. In 'Silicon Creation,' planets orbiting between r_{inner} and 4 x r_{ecos} are subjected to an albedo/surface temperature climatic feedback procedure; other planets have a fixed value for albedo. Table 3 lists these assumed albedo values.

Taking the Earth's albedo as 0.3 and using parameters already derived, the effective temperature of a rapidly rotating planet is:

$$T_{eff} = \left(\frac{r_{ecos}}{R}\right)^{1/2} \left(\frac{1 - A}{0.7}\right)^{1/4} \times T_{eff\oplus} \qquad (19)$$

where A is the albedo and $T_{eff\oplus}$ = 255 K.

The rise in average surface temperature (T_{surf}) due to the greenhouse effect is taken as (Hart [24]):

$$(\Delta T)_{green} = [(1 + \tfrac{3}{4}\tau)^{1/4} - 1]\ T_{eff}\ F_{conv} \qquad (20)$$

where τ is the optical depth of the atmosphere and F_{conv} is a 'convection factor' = 0.43. τ is the sum of the optical depths of the component greenhouse gases within a particular atmosphere such as CO_2, H_2O, CH_4 and NH_3. The optical depth of a gas is proportional to the square root of its quantity.

A planet that undergoes a climatic feedback procedure has its albedo and composition and greenhouse effect of the atmosphere recalculated iteratively. When the variation in T_{surf} is less than 1 °C between interactions, the planet is assumed to have reached a stable condition. The albedo of such a planet depends on cloud cover, ice cover and the land/sea ratio (see Table 3).

So long as T_{surf} is less than the boiling point of water then liquid water can exist on the surface of the planet. The boiling point of water approximates to:

$$bp = \left(\frac{\ln (P_{surf}/1000)}{-5050.5} + \frac{1}{373}\right)^{-1} - 273 \qquad (21)$$

The fraction of the planetary surface covered with water (the hydrosphere) is taken as:

$$F_{hyd} = \frac{0.75\ V_{inv}}{1000} \left(\frac{r}{r_{\oplus}}\right)^{-2} \qquad (22)$$

Cloud cover is proportional to the amount of water vapour in the atmosphere. From Hart [24] we have:

$$Q_{water\ vapour} = Q_1 \exp [Q_2 (T_{surf} - 288)] \qquad (23)$$

where Q_1 and Q_2 are constants.

The area covered by ice caps is (Hart [24]):

$$F_{ice} = \left(\frac{328 - T_{surf}}{70}\right)^5 \qquad (24)$$

In 'Silicon Creation' F_{ice} cannot exceed 1.5 x F_{hyd}.

From the calculations performed by 'Silicon Creation,' it appears that the position r_{outer}, beyond which planets become permanently frozen, is not as close to r_{ecos} as Hart suggests and is sensitive to individual planetary characteristics. Ocean covered planets with dense but cool atmospheres have a low albedo and are stable out to ~ 1.1 x r_{ecos}. With relatively small decreases in T_{surf}, runaway glaciation is prevented by a reduction in cloud cover and a lowering of albedo. However, below ~ 5°C the albedo rises rapidly due to surface ice and runaway glaciation occurs. These results are of course dependent on acceptance of the sort of albedo feedback model envisaged by Hart, applied to a system over a restricted period of time.

5.4 Life and Habitability

When asking the question if life may exist on other planets, we are hampered by only having the Earth's biosystem for comparison. Mars, the planet that once held so much hope for harbouring extra-terrestrial life forms, appears to be a sterile desert. Sagan's [41] fanciful speculations concerning aerial life forms in the atmosphere of Jupiter, and the investigation of Reynolds *et al* [42] into the possibility of life existing in the liquid water mantle of Europa are both unlikely to be confirmed of disproved for many decades. The idea that an alternative biochemistry might be possible based on an element other than carbon (Firsoff [4]) is difficult to sustain in view of the specific chemical properties and wide abundance of carbon.

Virtually all known organisms, from viruses to man have in common a genome of nucleic acid. The genetic information in the genome specifies the structure of proteins and controls the growth and maintainance of a living cell. A minor exception to this is the 'Prion' (Prusiner [43]); enigmatic and primitive organisms, it seems that a Prion possesses no nucleic acid and is little more than a protein capable of replicating itself within a host cell. Whether a protein could serve as the genome for more advanced organisms is questionable.

To confine speculation just within the bounds of science we concluded, for the purposes of the model, that life will occur on extra-solar planets in conditions similar to those on the Earth. Amino-acids and nucleic acids have been successfully synthesised by subjecting 'primitive Earth' atmospheric mixtures to electric discharge and U.V. radiation, so it is also assumed that life will appear and evolve wherever conditions permit. The conditions required by the model for the genesis of life are given in Table 4. Most factors are linked to the requirement for liquid water to be a permanent feature on the planet's surface.

Habitability is meant to imply a planet colonisable by man without artificial modification of climate, atmosphere or biosphere. The conditions required for habitability are also given in Table 4. The less obvious of these conditions are briefly explained.

In the case of a planet with an axial inclination of 55°, the insolation ratio between summer and winter hemispheres ~ 10; thus planets with a higher axial tilt or an orbital eccentricity more than 0.2 are considered to have too extreme a seasonal variation to be habitable.

A significant quantity of free oxygen in an atmosphere is usually considered to be a by-product of biological processes, if this is correct it follows that a habitable planet will possess indigenous life forms. The sudden proliferation of more complex organisms on Earth 600 Myr ago, often termed the 'Cambrian Explosion' has been attributed to a rise in oxygen percentage of the atmosphere which permitted more efficient metabolic processes and to the formation of an ozone layer dense enough to shield the surface from U.V. radiation. The Earth is ~ 4.6 Byr old and, assuming evolution follows a similar course on other planets, a world will need to be ⊲4 Byr old to be habitable. Partial pressure of O_2 must be between to 70 mb to 526 mb, and partial pressure of N_2 must not be more than 3066 mb.

It is possible that indigenous life forms on an extra-solar planet might be toxic or indigestible to organisms from Earth, which would render colonisation very difficult. Cox [44] has pointed out that as a biological synthesis of amino acids produced equal quantities of L and D forms, it might be pure chance that L-amino acids predominated early in the Earth's history, with the complete exclusion of D-amino acids from biological processes. If there is an equal chance of D forms predominating, then a mirror image biochemistry is possible that would produce a biosystem totally incompatible with any Earth organisms. In the absence of more complete knowledge of the origin of life, a probability of 0.5 is assumed for the existence of a biosystem that is non-toxic to Earth organisms.

6. THE OUTPUT

'Silicon Creation' has the potential to produce a wide variety of planetary characteristics, and each run, initiated with a new random number seed, will generate a unique system. Because of the large quantity of data in the output, it is only possible to present the results of one run here. Studies of a large number of generated systems is necessary for an adequate appreciation of the capabilities of the model.

The planetary system presented here has a primary of $1 M_{\odot}$, which facilitates easy comparison with the Solar System. Planet 3 appears to be potentially habitable. As

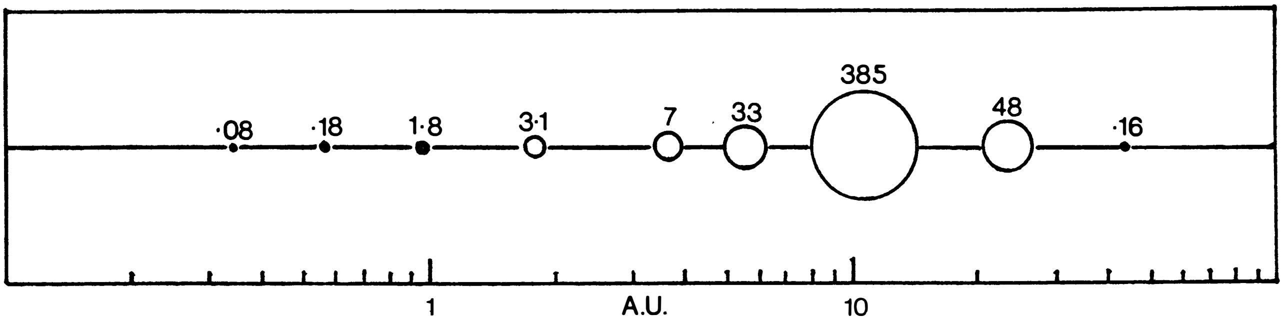

Fig. 8. Mass distribution of planets in the demonstration system.

TABLE 4. Model Conditions Necessary for Life and Habitability.

	Conditions necessary for: Life	Habitability
Semi-major axis	> = r_{inner}	> = r_{inner}
Orbital eccentricity	< = 0.27	< = 0.2
Axial inclination	< = 80°	< = 55°
Rotation rate	< = 87 hr	< = 87 hr
Surface temperature	> -15°C	> -15°C
Surface pressure	> = 10 mb	breathable and non toxic partial pressure of O_2 and N_2
Hydrosphere %	> 0%	> 0% < 100%
Age	> = 1 x 10^9 yr	> = 4 x 10^9 yr
Life		L-amino acid based proteins

```
SYSTEM JBIS

SEED NUMBER : -561100

SPECTRAL TYPE OF PRIMARY G

MASS:1 M⊙ LUMINOSITY:1 L⊙
ECOSPHERIC RADIUS:1 AU

SINGLE SYSTEM

SYSTEM AGE 5.746 BILLION YEARS

TIME LEFT ON MAIN SEQUENCE
4.254 BILLION YEARS

PLANETS OF STAR 1
PLANETS PRESENT AT THE FOLLOWING
DISTANCES

 1      0.34    AU.
 2      0.584   AU.
3      0.965   AU.
 4      1.917   AU.
 5      3.705   AU.
 6      5.748   AU.
 7      10.342  AU.
 8      22.804  AU.
 9      43.543  AU.
```

Fig. 9. Computer generated characterstics of the central star and semi-major axes of the planets in the demonstration system.

planets fulfilling the conditions set out in Table 4 for habitability do not occur often in the output, the system is slightly unusual. Below is a brief discussion of points of interest from the data, with emphasis on the inner system planets.

Figure 8 is the planetary mass distribution diagram for the demonstration system. The total planetary mass is only 7% greater than the combined masses of the Solar System planets. 80% of this mass (~ 1.2 Jupiter masses) is contained within the seventh planet. The system differs principally from the Solar System in that the most massive planet is situated twice as far from its primary as Jupiter, ~ 10 A.U., and that three low mass gas giants orbit closer to the central star. The planets exhibit a regular logarithmic spacing, as might be expected from a Bode type 'law.'

Figure 9 gives the characteristics of the primary and the semi-major axes of the planets. The system is ~ 1.15Byr older than the Solar System. The third planet has a semi-major axis of 0.965 A.U., closer to the primary than the Earth, but well within the boundaries of the ecosphere.

Figure 10 sets out the data given by the computer for Planets 1 and 2. Both planets are similar to Mercury in that they are hot airless worlds and have had their rotation rates slowed by tides from the central star. In these two cases rotation has become synchronous and, neglecting minor libration effects, one hemisphere is permanently illuminated and the other in permanent darkness. The value given for average surface temperature assumes a rapidly rotating body; in fact temperatures on the illuminated side would be several hundred °C higher and temperatures on the dark side would be close to absolute zero. Planet 2 is slightly more massive than Mars and would have outgassed a substantial atmosphere; the remaining volatiles not previously lost to space would be present as a layer of frozen 'ices' on the surface of the dark hemisphere.

The data in Fig. 11 is particularly interesting. Planet 3 is a 1.8m⊕ planet within the ecopshere. Its radius is ~ 1.2r⊕ and the planet has an average density 8% greater than the Earth. Human colonists could most probably adapt to the 1.27 g surface gravity without too many difficulties. The atmosphere is more massive than that of the Earth, with a higher oxygen percentage; this produces a surface atmospheric pressure 50% greater, and an inspired oxygen partial pressure 85% greater than at Earth sea levels: a non toxic gas mixture. Surface temperatures average 5°C higher than on the Earth and the consequences of this is that ice caps on Planet 3 are relatively smaller. Surface temperatures would be even higher if it was not for the slightly raised albedo of Planet 3 from a greater percentage of cloud cover. A very large quantity of H_2O has been outgassed and oceans cover 90% of the surface; however because of the greater surface area of Planet 3, there is 51% less dry land area present than on the Earth. The high orbital eccentricity of 0.14 brings the planet at perihelion to within 0.87 A.U. from

```
PLANET: 1
DISTANCE FROM STAR:          0.34      AU
ORBITAL ECCENTRICITY:        1E-2
YEAR:                        72        days

AXIAL INCLINATION:           0
EQUATORIAL RADIUS:           2810      km
DENSITY:                     5.26      g cc
MASS:                        4.9E23    kg
GRAVITY:                     0.42      G
ROTATION RATE:               SYNCHRONOUS

ALBEDO:                      7E-2
AVERAGE TEMPERATURE:         196.23     C
HYDROSPHERE:                 0         %

ATMOSPHERIC PRESSURE:        0         mb

BULK COMPOSITION             IRON/SILICATE

LIFE: NO LIFE FORMS

SUMMARY OF PLANET: 1

PLANET TYPE: TERRESTRIAL(Mercurian)
HIGH DENSITY PLANET
NO ATMOSPHERE
INTOLERABLE TEMPERATURES
LOW GRAVITY
NO SEASONS
```

```
PLANET: 2
DISTANCE FROM STAR:          0.58      AU
ORBITAL ECCENTRICITY:        5E-2
YEAR:                        162       days

AXIAL INCLINATION:           0
EQUATORIAL RADIUS:           3704      km
DENSITY:                     5.08      g cc
MASS:                        1.08E24   kg
GRAVITY:                     0.53      G
ROTATION RATE:               SYNCHRONOUS

ALBEDO:                      7E-2
AVERAGE TEMPERATURE:         85.38      C
HYDROSPHERE:                 0         %

ATMOSPHERIC PRESSURE:        0         mb

BULK COMPOSITION             IRON/SILICATE

LIFE: NO LIFE FORMS

SUMMARY OF PLANET: 2

PLANET TYPE: TERRESTRIAL(Mercurian)
HIGH DENSITY PLANET
NO ATMOSPHERE
BARELY TOLERABLE TEMPERATURES
MODERATE GRAVITY
NO SEASONS
```

Fig. 10. Computer generated characteristics of Planets 1 and 2.

the primary and at aphelion it recedes to a distance of 1.1 A.U. A strong seasonal variation would therefore be imposed on surface conditions, mollified somewhat by cloud cover/albedo feedback. The equatorial region would probably be too hot to be habitable during the summer season and high latitudes would be bitterly cold in the winter. Mid latitudes should be habitable all year round and would suit our species best. The indigenous life forms of Planet 3 would have adapted to cope with the regularly fluctuating weather conditions. The computer has designated Planet 3 as being habitable. While it fulfils the criteria in Table 4, this planet would not be as comfortable for man as his own planet Earth.

Figures 12, 13 and 14 give the data for the outer planets of the system, five gas giants of varying masses and one remote, low mass, icy planet. Temperature given for giant planets are effective temperatures (Eq. (19)) as no solid surface is present and a great deal of heat is generated internally. Only two of these planets require further comment.

Planet 4 is noteworthy as its mass is only just above m_{crit}. The planet swept up a quantity of gas during formation giving it a H_2/He atmosphere, but since then a substantial amount of hydrogen has been lost by leakage of H atoms to space. A planet like this is at the lower mass limit of the 'giant' planet range.

Planet 9 is a low density icy body, similar to the mass of Mars and orbiting further from its primary than Pluto from the Sun. The surface temperature is a bitter 32°K, most major atmospheric gases freeze well above this. Although the escape velocity of this planet is too low to retain hydrogen, a tenuous atmosphere of Helium with trace amounts of sublimated CH_4 and N_2 remains.

7. CONCLUSION

The main value of the 'Silicon Creation' model is for statistical research into the characteristics of planetary systems,

```
PLANET: 3
DISTANCE FROM STAR:          0.96      AU
ORBITAL ECCENTRICITY:        0.14
YEAR:                        345       days

AXIAL INCLINATION:           1
EQUATORIAL RADIUS:           7568      km
DENSITY:                     5.98      g cc
MASS:                        1.09E25   kg
GRAVITY:                     1.27      G
ROTATION RATE:               14.81     hours

ALBEDO:                      0.35
AVERAGE TEMPERATURE:         20.12      C
HYDROSPHERE:                 90        %
FROZEN COVER:                3.1       %
WATER BOILS AT :             112.58     C
CLOUD COVER :                62        %

ATMOSPHERIC PRESSURE:        1555      mb

ATMOSPHERIC CONSTITUENTS
MAJOR GASES                  ~ 75% N2
                             ~ 25% O2
Trace gases :                Ar CO2 H2O He

BULK COMPOSITION             IRON/SILICATE

LIFE: COMPLEX LIFE FORMS(DNA Based)
PROTEIN BASE : L-amino acids

SUMMARY OF PLANET: 3

PLANET TYPE: TERRESTRIAL(Terran)
OCEAN PLANET
HIGH DENSITY PLANET
STANDARD PRESSURE ATMOSPHERE
BREATHABLE GAS MIXTURE
TOLERABLE TEMPERATURES
HIGH GRAVITY
PRONOUNCED SEASONS
HABITABLE FOR MAN
```

Fig. 11. Computer generated characteristics of Planet 3.

PLANET: 4

DISTANCE FROM STAR:	1.92	AU
ORBITAL ECCENTRICITY:	3E-2	
YEAR:	967	days
AXIAL INCLINATION:	2	
EQUATORIAL RADIUS:	12949	km
DENSITY:	2.02	g cc
MASS:	1.83E25	kg
GRAVITY:	0.73	G
ROTATION RATE:	15.13	hours
ALBEDO:	0.4	
AVERAGE TEMPERATURE:	-95.8	C
HYDROSPHERE:	0	%

GAS GIANT ATMOSPHERE
HYDROGEN DEPLETED

LIFE: NO LIFE FORMS

SUMMARY OF PLANET: 4

PLANET TYPE: MINI GAS GIANT
MEDIUM DENSITY PLANET
SUPER DENSE ATMOSPHERE
NON BREATHABLE GAS MIXTURE
INTOLERABLE TEMPERATURES
MODERATE GRAVITY
NO SEASONS

PLANET: 5

DISTANCE FROM STAR:	3.7	AU
ORBITAL ECCENTRICITY:	5E-2	
YEAR:	2598	days
AXIAL INCLINATION:	15	
EQUATORIAL RADIUS:	18682	km
DENSITY:	1.44	g cc
MASS:	3.92E25	kg
GRAVITY:	0.75	G
ROTATION RATE:	14.92	hours
ALBEDO:	0.4	
AVERAGE TEMPERATURE:	-145.53	C
HYDROSPHERE:	0	%

GAS GIANT ATMOSPHERE

LIFE: NO LIFE FORMS

SUMMARY OF PLANET: 5

PLANET TYPE: MINI GAS GIANT
LOW DENSITY PLANET
SUPER DENSE ATMOSPHERE
NON BREATHABLE GAS MIXTURE
INTOLERABLE TEMPERATURES
MODERATE GRAVITY
MODERATE SEASONS

Fig. 12. Computer generated characteristics of Planets 4 and 5.

PLANET: 6

DISTANCE FROM STAR:	5.75	AU
ORBITAL ECCENTRICITY:	5E-2	
YEAR:	5022	days
AXIAL INCLINATION:	60	
EQUATORIAL RADIUS:	33937	km
DENSITY:	1.21	g cc
MASS:	1.98E26	kg
GRAVITY:	1.15	G
ROTATION RATE:	12.08	hours
ALBEDO:	0.4	
AVERAGE TEMPERATURE:	-170.66	C
HYDROSPHERE:	0	%

GAS GIANT ATMOSPHERE

LIFE: NO LIFE FORMS

SUMMARY OF PLANET: 6

PLANET TYPE: SMALL GAS GIANT
LOW DENSITY PLANET
SUPER DENSE ATMOSPHERE
NON BREATHABLE GAS MIXTURE
INTOLERABLE TEMPERATURES
STANDARD GRAVITY
EXTREME SEASONS

PLANET: 7

DISTANCE FROM STAR:	10.34	AU
ORBITAL ECCENTRICITY:	2E-2	
YEAR:	12112	days
AXIAL INCLINATION:	15	
EQUATORIAL RADIUS:	72400	km
DENSITY:	1.45	g cc
MASS:	2.31E27	kg
GRAVITY:	2.95	G
ROTATION RATE:	7.54	hours
ALBEDO:	0.4	
AVERAGE TEMPERATURE:	-196.7	C
HYDROSPHERE:	0	%

GAS GIANT ATMOSPHERE

LIFE: NO LIFE FORMS

SUMMARY OF PLANET: 7

PLANET TYPE: LARGE GAS GIANT
LOW DENSITY PLANET
SUPER DENSE ATMOSPHERE
NON BREATHABLE GAS MIXTURE
INTOLERABLE TEMPERATURES
HIGH GRAVITY
MODERATE SEASONS

Fig. 13. Computer generated characteristics of Planets 6 and 7.

especially the occurrence of Earthlike planets and the relevance of these planets to SETI.

Many authors interested in these subjects use the Drake equation as a crude method to break the problem down into more easily defined units. However, the Drake equation so oversimplifies the numerous factors involved that the results become largely a matter of personal choice: estimates for the number of technical civilisations in the Galaxy range over seven orders of magnitude. More detailed 'manual' analyses have been performed by Dole [17], Asimov [18] and Pollard [19], and Bond and Martin [30, 31] used a computer to carry out some of the calculations necessary in their estimate. 'Silicon Creation' is a detailed fully computerised model that is cheap to run and can be used to generate

PLANET: 8			PLANET: 9		
DISTANCE FROM STAR:	22.8	AU	DISTANCE FROM STAR:	43.54	AU
ORBITAL ECCENTRICITY:	0.14		ORBITAL ECCENTRICITY:	2E-2	
YEAR:	39682	days	YEAR:	104706	days
AXIAL INCLINATION:	40		AXIAL INCLINATION:	8	
EQUATORIAL RADIUS:	43843	km	EQUATORIAL RADIUS:	5130	km
DENSITY:	0.82	g cc	DENSITY:	1.7	g cc
MASS:	2.9E26	kg	MASS:	9.63E23	kg
GRAVITY:	1.01	G	GRAVITY:	0.25	G
ROTATION RATE:	12.87	hours	ROTATION RATE:	31.13	hours
ALBEDO:	0.4		ALBEDO:	0.7	
AVERAGE TEMPERATURE:	-221.62	C	AVERAGE TEMPERATURE:	-240.98	C
HYDROSPHERE:	0	%	HYDROSPHERE:	100	%
				PERMANENTLY FROZEN	
GAS GIANT ATMOSPHERE			ATMOSPHERIC PRESSURE:	16	mb
METHANE ENRICHED					
LIFE: NO LIFE FORMS			ATMOSPHERE: MOSTLY FROZEN ON SURFACE		
			A LITTLE He AND SUBLIMATED N2 & CH4		
SUMMARY OF PLANET: 8			STILL GASEOUS		
PLANET TYPE: SMALL GAS GIANT			BULK COMPOSITION	ICE	
LOW DENSITY PLANET					
SUPER DENSE ATMOSPHERE			LIFE: NO LIFE FORMS		
NON BREATHABLE GAS MIXTURE					
INTOLERABLE TEMPERATURES			SUMMARY OF PLANET: 9		
STANDARD GRAVITY					
PRONOUNCED SEASONS			PLANET TYPE: TERRESTRIAL(Plutonian)		
			LOW DENSITY PLANET		
			VERY THIN ATMOSPHERE		
			NON BREATHABLE GAS MIXTURE		
			INTOLERABLE TEMPERATURES		
			LOW GRAVITY		
			NO SEASONS		

Fig. 14. Computer generated characteristics of Planets 8 and 9.

a very large data base. A statistical analysis of 7500 systems generated by 'Silicon Creation' is currently being undertaken to contribute to the habitable planet/SETI debate.

This debate is likely to stimulate people many generations into the future, for only after interstellar travel becomes a reality will most of our questions be answered.

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THE IMPROBABILITY OF BEHAVIOURAL CONVERGENCE IN ALIENS - BEHAVIOURAL IMPLICATIONS OF MORPHOLOGY

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1. INTRODUCTION

The possible existence of extraterrestrial aliens is a subject of enormous fascination. Within the past 25 years the consensus of scientific opinion has become that extraterrestrial intelligence is highly probable. Consequently, more elaborate searches, with more sensitive equipment, are being planned. After all, is it not merely a matter of observation to determine whether this view is justified?

All is not well, however, as a profound and unresolved conflict persists in the two principal aspects of this topic: the physical, and the biological. These are the natural physical and chemical laws the Universe (including living creatures) is subject to; and, the biological character of a creature, respectively. Indeed, Tipler [1], following the evolutionary biologist Simpson [2], has recognised that contemporary advocates for the existence of extraterrestrial aliens are primarily physicists and astronomers, whereas evolutionary biologists deny its likelihood.

The Fermi paradox asks: if aliens are so prevalent, then where are they? It's a puzzle that still remains. Whatever our beliefs on this subject, we find ourselves greeted only by a 'Great Silence' [3]. It is true, of course, that absence of evidence is not evidence of absence, yet the existence of a profund conflict between the physical and evolutionary behooves us to re-examine the assumptions underlying this topic. In this way, perhaps, the puzzle may be resolved.

2. THE IMPROBABILITY OF 'HUMANOID' ALIENS

It has often been argued that the likely bodily form, and sensory organs, for an intelligent extraterrestrial would be 'human-like': the 'humanoid' alien [4,5,6]. Such a view, however, conflicts with what is known about the evolutionary process. Essentially, evolution is an ecological process, involving an interaction between creatures and their environment, hence feedback upon their genetic material. This feedback operates not upon the individual organism, but upon populations through successive generations. It is only the more adaptive genetic messages, hence favourable biological traits, thus the 'fittest' individuals, which tend to spread throughout the population during the course of successive generations. This interaction between creature and environment is 'nautral selection.'

The way in which a population will evolve involves two principal factors [7]:

(1) the character of the ancestral creatures, which serve as the 'raw material' upon which natural selection operates;

(2) the sequence of environmental conditions which cause the ancestral stock to evolve along a particular pathway to a descendant group.

Evolution can only occur if there are changes in the genetic material in the course of generations. The basic processes whereby this happens are recombination (rearrangement of the genetic material), and mutation (introduced changes in the genetic material) [8]. They produce a natural variation in the biological traits of the individual members of a species. The diversity of variations that they generate is *random,* in contrast to the actual diversity observed in nature, with a limited number of morphologies, physiologies and behaviours occupying a limited number of ecological niches [9]. Neither recombination nor mutation actually 'fits,' or 'adapts,' a creature to its environment, nor permits survival, or further evolution. Natural selection does that by acting upon the raw material - the natural variations - they produce. Because natural selection adapts creatures to their environment it is not in itself a random process.

From this it is apparent that if the sequence of environmental conditions were different, the descendants of the ancestral stock would correspondingly be different. Extrapolating this further, the way in which a given group of organisms can evolve depends critically upon *all* those attributes - genetic, physiological, morphological and behavioural - which characterised all their predecessors all the way back to the very origin of life itself. Even slight changes in their environmental conditions would have had a profound cumulative effect on all descendant organisms. Humankind is no exception: if the sequence of events had been different we simply would not exist.

The evolutionary process is opportunistic: it can only work with the materials already available to it. Mutation can only occur in ways dependent on the existing nature of the genetic material. Recombination can only recombine that genetic material which actually exists in given organisms. Selection can only operate upon the natural variations actually present in a population.

From such considerations as these evolutionary biologists conclude that the course of terrestrial evolution is not repeatable. Since natural selection acts in a non-random fashion upon the raw material present, by adapting creatures to their environments, the course of evolution consists of long chains of non-repetitive circumstances. This means that repetition of these events would be virtually impossible. Since recombination and mutation are random processes, repetition would entail the duplication of accidents. This non-repeatability of evolution means that the emergence elsewhere of humanlike creatures ('humanoids') is improbable [2,10,11].

3. THE PUTATIVE ALIEN

The principal advocates for SETI accept the improbability of 'humanoid' aliens [12]. Sagan [13] quotes approvingly from Eiseley [14], 'Of men elsewhere, and beyond, there will be none for ever.' Sagan argues, 'It is clear that the

evolution of intelligence and manipulative ability has resulted from the product of a large number of individually unlikely events. If the history of the Earth were started again, it is highly improbable that the same sequence of events would recur and that intelligence would evolve in the identical manner. On the other hand, the adaptive value of intelligence and manipulative ability is so great - at least until technical civilisations are developed - that, if it is genetically feasible, natural selection is very likely to bring it forth' [15].

Because the adaptive value of intelligence and technology is so enormous Sagan asks, 'Even though the development of humans - or their rough extraterrestrial equivalents, humanoids - is unlikely, might not the development of their intellectual equivalents be a persuasive evolutionary event?' [13].

Palaeontologist Russell suggests [16], on the assumption that encephalisation increases with time, that environmental conditions affect the rate of encephalisation (here equated with 'intelligence'). Planetary conditions which most effectively promote the development of 'humanoid intelligence' from primitive metazoans (the Earth probably not being an ideal nursery for intelligence) include the continuance of sufficiently abundant inorganic nutrients. This was to sustain apparently high encephalisation rates in the oceans after the establishment of terrestrial ecosystems. Russell speculated that, under such conditions, 'it would not be surprising if octopoid creatures... with humanoid levels of encephalisation and the capacity to manipulate objects' derived from metazoans within 500 Myr. The octopoid would be expected to have a relatively high metabolic rate, low reproductive rate, long life span, and prolonged caring for the young.

In summary, the putative alien is conceived to possess two distinctive attributes: a 'non-humanoid' body form combined with a 'humanoid' intelligence (hence, by implication, 'humanoid' behaviour). Russell's speculation, of an octopoid with humanoid encephalisation and manipulative ability, is the type of model that would be expected from this 'design' of the putative alien.

4. THE PROBABILITY ARGUMENT

The typical response of the physical scientist to the evolutionary argument against the existence of aliens, is summed up by the reaction of the astronomer Newcomb [17] to the evolutionist Wallace, the co-discoverer of natural selection, in 1905. He believed 'no sound reason can be shown why under certain conditions, which are frequent in the Universe, intelligent beings should not acquire the highest development.' He resorted to the mathematical theory of probabilities: 'A fundamental tenet of this theory is that no matter how improbable a result may be on a single trial, supposing it is at all possible, it is sure to occur after a sufficient number of trials, - and over and over again if the trials are repeated often enough.'

The physical scientist, as in the CETI, SETI and CYCLOPS reports [18,19,20], argues that the probability of a sequence of events is the product of their individual probabilities. If these probabilities are small compared to unity their concatenated probability will rapidly approach zero. Applied to ourselves this means we each have an infinitesimal chance of existing. For a different set of ancestors none of 'us' would exist, being replaced instead by a statistically indistinguishable generation.

In this view, it is not considered important whether the particular sequence of events leading to terrestrial intelligence can be repeated elsewhere, only that some other sequence of events may occur that leads to a similar end result. In other words, though a given evolutionary pathway may consist of individually improbable events this does not imply a low combined probability for all possible events similar to them. Support for this view is adduced from the biological phenomenon of convergence.

5. THE CONVERGENCE ARGUMENT

Convergence is that biological phenomenon whereby different creatures, under similar conditions, give rise to descendants with similar bodily forms, or sensory organs. Morrison gives the example of convergence of a fish (tuna), an extinct reptile (ichthyosaur), and a mammal (dolphin) [18,21]. To evolve a torpedo-like aquatic predator, feeding on small fast-swimming fish, did not seem easy. The phylogentic relationship of these three species, he supposed, had little to do with each other, their histories being separated, for each step, by 100 Myr. From this, he concluded that there are many evolutionary pathways to the same ecological position. A common supposition has been that if such convergence occurs the process producing it must be almost an inevitable one.

The other principal example given is the insect, cephalopod, and vertebrate eye. The SETI report describes them as having 'totally different, independent evolutionary histories' but resulting in convergence to essentially the same result, without being completely identical. The corresponding neural networks are described as being very similar. It concludes that any creature evolving in an environment in which visibile light is important might develop a light-sensor organ with similar nerve structure.

6. 'HUMANOIDS'

An important distinction can be drawn between the use of the term 'humanoid' by the physical scientist Sagan and the evolutionary biologist Simpson. For Simpson, it is a 'natural, living organism with intelligence comparable to Man's in quantity and quality, hence with the possibility of rational communication with us. Its anatomy and indeed its means of communication are not defined as identical with ours' [2]. It is thus an intellectual analogue of humans. For Sagan, in contrast, it is purely an anatomical analogue [13].

However, Simpson, like Sagan, admits 'manlike intelligence' is a marvellous adaptation, having survival value in a wide variety of environmental conditions, such that 'if it became possible at all, might be favoured by natural selection under conditions different from those on Earth.' Yet, because of the non-repetitive character of evolution, he concludes, since nothing similar to humankind is a likely occurrence, it is 'extremely unlikely that anything enough like us for real communication of thought exists anywhere in our accessible Universe.'

A question automatically arises, however, if human intelligence, like human morphology, is itself an evolved attribute, as would be expected from an evolutionary perspective. If so, the unlikelihood of the individual evolutionary steps producing a given creature should apply equally well to one evolved attribute (intelligence) as to another evolved trait (body form). Is there any evidence for this? Does intelligence (hence behaviour) also evolve?

7. BEHAVIOURAL STRATEGIES

The existence of inheritable behaviour patterns indicates that, like morphology and physiology, they are also subject to natural selection, and evolve. According to the modern Darwinian interpretation (a) evolution consists in changes in the frequency of appearance of different genes in populations, and (b) the frequency of appearance of a particular gene only increases if the 'Darwinian fitness' (the expected

TABLE 1. Payoffs for the Hawk-Dove Game.

	H	D
H	½(V-C)	V
D	O	V/2

(From Smith [23]).

number of offspring surviving) of its possessors increases [22].

Adult appeasement signals ('head flagging') in fighting gulls involves turning the head sharply away from an opponent. Young gulls, in contrast, when threatened, run for cover. One gull species, the kittiwake, is an exception to this rule. Its chicks do employ the head-flagging display when threatened. Apparently, a gene favouring head-flagging in chicks appeared in a population originally with a gene for adult head-flagging only. There is an especially strong reason why this behaviour was selected naturally in this particular gull but not in the others. This was that gulls live on beaches whereas the kittiwake nests on small ledges where there is no cover to which the chicks can run. Natural selection favoured the evolution of this anomalous behaviour pattern because it contributed to the survival of the kittiwake.

The application of a modified form of game theory to evolution [23] has had an important bearing upon understanding the 'behavioural strategies' creatures employ. Imagine two animals are contesting a resource of benefit V, that is, the Darwinian fitness of the individual obtaining that resource would be increased by V. The individual failing to gain that resource need not have zero fitness. The change in its fitness would be zero. Imagine the resource is a territory in a favourable habitat, but that there is available space in a less favourable habitat where the losers can breed.

Assume individuals may employ one of two tactics: 'hawk' (which escalates the fighting until it has won or is seriously injured); and 'dove' (which never escalates the fighting, and runs away if its opponent escalates). Injury reduces fitness by a cost C. In hawk versus hawk, each contestant has a 50% chance of winning, and a 50% chance of being injured. It's payoff is (V-C)/2. In hawk versus dove, the hawk wins the resource (V) for no cost. Dove versus hawk never wins (change in fitness zero), and dove against dove share the resource equally (V/2). Table 1 shows the payoffs for this contest.

It is possible to show that, under certain conditions, there exists an evolutionary stable strategy (ESS) for a given game. An ESS is a strategy with the characteristic that if most of the members adopt it no other mutant strategy can invade the population. That is, a strategy is evolutionarily stable if no mutant strategy gives a higher Darwinian fitness to the individuals adopting it. For this game, it is playing dove, and hawk, with a probability of 1/2.

Imagine a population of H and D strategists in which an individual appears with a mutant behavioural strategy - the 'Bourgeois' strategy - in which if it's the owner of the resource in question it adopts the hawk tactic, if the interloper it adopts the dove tactic. Could this newly arisen strategy be an ESS? The corresponding payoff matrix involves the additional facts: the bourgeois strategist employs H and D with equal frequency (1/2), being owner and interloper each half of the time: in contests between two bourgeois strategists, if one acts H the other acts D. Table 2 shows the payoff matrix.

If V = 2, and C = 4, the payoff matrix becomes that shown in Table 3. For V > C, the only ESS is H, it is worth risking injury to gain the resource, but when V < C the only ESS is bourgeois, with ownership settling the contest without escalation. In the situation given, the new mutant strategy will proliferate, becoming an ESS. In such a way as this it can be seen how a newly arisen behavioural strategy may spread by differential reproduction.

TABLE 2. Payoffs for the Hawk-Dove-Bourgeois Game.

	H	D	B
H	½(V-C)	V	¾ V-¼ C
D	O	V/2	V/4
B	¼(V-C)	¾V	V/2

(From Smith [23]).

TABLE 3. The Hawk-Dove-Bourgeois Game, for V = 2, and C = 4.

	H	D	B
H	-1	2	½
D	O	1	½
B	-½	3/2	1

(From Smith [23]).

8. BEHAVIOUR AND MORPHOLOGY

From an evolutionary point of view a given creature's morphology, physiology and behaviour has been moulded by natural selection as an adaptation to their environment. This approach attempts to explain particular anatomical features by demonstrating that they are well suited to their function. In living creatures, observation of their behaviour reveals the trait and its mode of operation. In extinct creatures, both the trait and its function must be reconstructed.

What is revealed by the examination between a creature's bodily form (or morphology) and its behaviour. An excellent example is the pterosaur *Pteranodon* [24,25,26] (Fig. 1).

Pteranodon's morphology can be summarised as a box-like rigid body, large swept-forward wings, a crested beak and hollow bones. Essentially a glider, it was probably capable of brief periods of powered flight. It seems to have soared on air currents over warm Cretaceous seas, spending much of its life aloft, feeding on fish, which it caught possibly by trailing its long beak in the water. The crest may have functioned to keep the beak facing in the direction of the wind, like a weather-vane.

Clearly, interpretations of the behaviour of *Pteranodon* are closly linked to interpretations of the biological and evolutionary functions the constituents of its bodily form served. Understanding a creature's behaviour cannot be divorced from the character of its bodily form.

9. SOCIAL BEHAVIOURS

The relation between a creature's bodily form and behaviour is intuitively obvious. It informs us as to the actual bodily movements which that type of morphology can physically perform. Yet such deductions from body form are clearly not exhaustive. The exact sequences of movements performed in social behaviours, in particular, are not evident, though some might be implicated. The antlers of deers, the long horn of the narwhal, the thickened skulls of rams and innumerable other examples, used in contests between males over mating rights with the females, are a case in point.

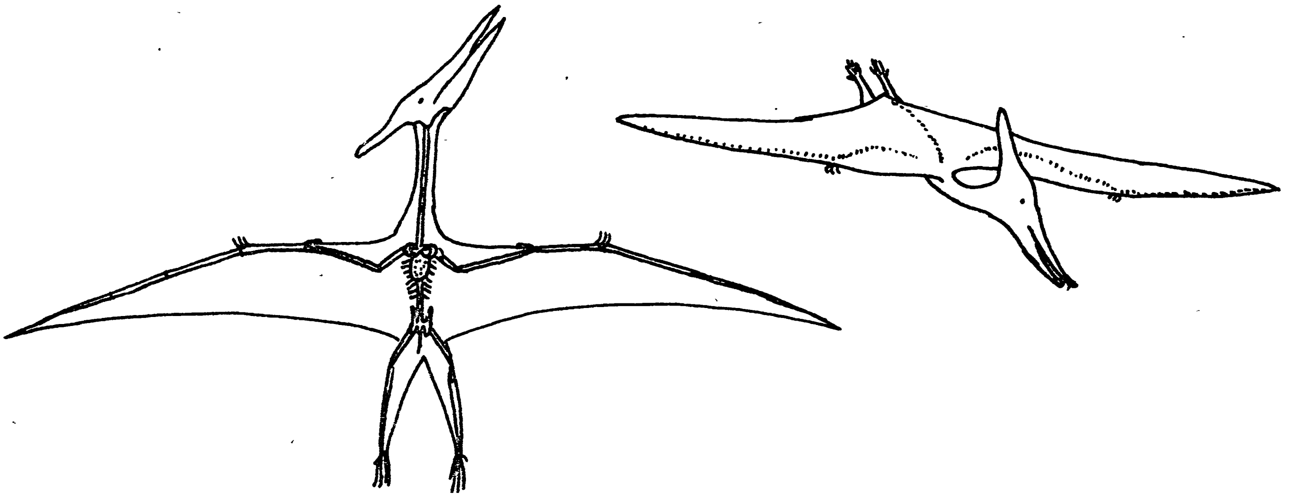

Fig. 1. The Pterosaur *Pteranodon* (from Langston, [24]). The intimate relationship between a creature's bodily form and its behaviour can be clearly seen in this example.

For a given creature, one cannot, in advance, predict the character its social behaviours would take. The appeasement signal of gulls, though not excluded from the range of their physically possible behaviours, would not be expected by a naive observer unfamiliar with them. Neither could a naive observer predict that, except for the kittiwake, young gulls would not give this signal but run away instead. What they could determine is that the particular behaviour performed by young gulls was related to the environment in which they lived. If the nesting sites of hadrosaurs (duck-billed dinosaurs) had not been discovered no deductions could have been made about the corresponding social behaviours [27].

It is quite clear that, in principle, given *only* the bodily form of a creature, one can make no reliable predictions as to the actual manifestation of *any* of its social or communicative behaviours, the very behaviours we are most interested in vis-a-vis the putative alien. Game-theoretic models of behaviour would not help either. They only provide clues as to the types of 'behavioural strategies' creatures might employ, not the ones they actually do perform. All sorts of anomalous strategies might be involved. Indeed, one spider, in a contest over a resource, does not use either 'hawk' or 'bourgeois' tactics but 'if owner, play dove; if interloper, play hawk' [23].

Ethology, the study of animal behaviour, reveals a close evolutionary relation between a creature's physically possible behaviours and its social or communicative behaviours. As we have seen, behaviour, like morphology, can evolve. New behaviours do not, however, come out of nowhere. Indeed, communicative behaviours can be demonstrated to derive from non-communicative behaviours. This happens by the re-adaptation of an existing activity for a new function [28]. In this way, a straightforward practical activity can serve a new role. In due course, an action might be performed purely for its communication effect.

In morphologically similar species, such as gulls, behaviours derived from a common ancestor can be subject to modification, loss, even addition. The kittiwake is an excellent example. It is clear, however, that the bodily movements employed in communicative or social behaviours cannot be divorced from the character of that creature's body. Furthermore, they are clearly related to its behavioural strategy and this, in turn, related to the ecological niche it inhabits. One important conclusion can be drawn: attributing *hypothetical* behaviours to *hypothetical* creatures with *hypothetical* bodily characteristics is fraught with profound theoretical difficulties.

10. PROBLEMS WITH THE 'CONVERGENCE ARGUMENT'

The putative alien is a prime example of a *hypothetical* creature. The case for it depends upon the 'probability argument,' with the phenomenon of 'convergence' adduced in its favour. Consider Morrison's instance of bodily convergence in tuna, ichthyosaur and dolphin.

Morrison supposed that their evolutionary histories and phylogenetic relationships are essentially independent of each other. If so, it would have represented an example of a 'forced' or inevitable process. This would thereby imply that there were many alternative evolutionary pathways to the same ecological position. It would thus be prime support for 'probability argument.'

However, the anthropologist le gros Clark, to the contrary, has pointed out that covergence in physical traits among creatures from separate phyletic groups could not be treated as signifying complete genetic independence [29]. Instead, such resemblances due to convergence actually indicated 'some degree of relationship,' insofar as they are an expression of a well-known evolutionary principle that the same results tend to appear independently in descendants of the same ancestors. The descendants must be endowed with rather similar inherited potentialities for evolution and therefore they will tend to react in the same way under the influence of similar environmental conditions.'

Tuna, ichthyosaur and dolphin do bear a close phylogenetic relationship: they are all *vertebrates*. Furthermore, the skeletons of ichthyosaur and dolphin are *homologous*. Convergence would thus not be unexpected in members of the same phylum. The forelimb of land vertebrates, from which dolphin and ichthyosaur derive, initially five-toed and adapted for walking, has been re-adapted for many new functions: one-toed, tip-toe running limb; flipper; arm and hand; webbed paddle and wing. These limbs remain homologous: the bones of each corresponding to each other. Convergence to the same type of adaptation - like the wing of pterosaur, bird and bat - derives from homologous limbs but in different ways.

Use of the fish, reptile and mammal example is extremely misleading. It does not support any conclusion that what is involved is a physically-forced process. Would a better example to use be, say, convergence in the humming bird and humming moth? From a distance they are often confused with each other. They are members of different phyla. Homology cannot be readily identified in them. Their wings

are structures whose functions are merely *analogous*. They seem to be completely independently evolved. They are adapted for feeding on the nectar produced by flowering plants, employing hovering stable flight, produced *via* rapid wing beat, which provides a stable platform for their elongated tongue, and proboscis, respectively, to reach it.

All is not well with use of this example either. This can be seen by reconsidering the tuna, ichthyosaur, dolphin example. It embodies aspects which seem to have eluded Morrison and other SETI supporters. They argue in favour of behavioural convergence between creatures with evolutionarily unrelated and distinctly different bodily form. Yet the example of morphological convergence given implies this: that there exists a close link between morphological convergence *and* behavioural convergence. This recalls the close link established previously between morphology and behaviour.

The humming bird and humming moth example goes even further. This also implies that, *at some level,* morphological convergence implies behavioural convergence. It is in *feeding behaviour* that this occurs. Not in other behaviours. Moth and bird are members of different phyla: arthropod, and vertebrate, respectively. It is in their other behaviours they differ radically, sharing behaviours characteristic of the different groups they respectively belong to. The overall differences may be summarised as *stereotyped* (in the moth) and relatively *flexible* (in the bird).

Though morphological convergence implies behavioural convergence, this only occurs at some level. It does not imply *full* convergence in behaviour in the creatures concerned. Thus, arguments based on morphological convergence, purporting to favour the existence of the putative alien, with 'non-humanoid' morphology and 'humanoid' behaviour, actually contradict the latter 'design.' Indeed, such arguments would better support the discredited argument for 'humanoid' aliens.

11. CONVERGENCE *VIA* DIVERGENCE

A basic tenet of evolutionary theory is that evolution is opportunistic. The possibilities for a given creature's further evolution depend upon the available materials, not on what is the *hypothetical* best. The available opportunities are never unlimited. The possible life-styles of creatures are restricted in two ways: an opportunity must be provided by the environment; and there must exist a group of creatures with the possibility to respond to that opportunity.

The evolutionary changes which can occur in a population, in response to a new opportunity, depend upon the genetic material available to it. That is, the variations which exist in the population; the nature of the variations preserved by natural selection (dependent on the surrounding environmental conditions, in addition to the surrounding creatures with which they come into competition); and the possibility for changes in the heredity of the given group [30].

The genes already present in the population need to change in their proportions within it (by recombination and mutation), including possible elimination of some, and others once rare becoming common. It means not all possible opportunities are responded to, and many will remain unexploited for long intervals. This is all the more so once it is realised that the variations produced bear no relationship to the environmental opportunities confronting a given creature. Where a creature begins to exploit an environmental opportunity the resulting changes in them is *adaptation.*

Since evolution depends on the available material, which is different in different creatures, it would be expected that similar opportunities would be exploited in different ways. There should be multiple solutions to the problems involved in performing particular functions. A good example is the great differences in morphology, despite exploitation of the same opportunities, in the marsupial kangaroos (of Australia) and the hoofed placental herbivores (of the New and Old World). In convergence itself, there is the same type of opportunistic development of a similar life-style (or adaptation) but one in which groups originally with different adaptations and genetic material converge in functional morphological (or structural) characteristics.

Indeed, the evolutionary biologist Simpson [31] argues that convergence is the product of evolutionary divergence (the divergence of creatures from a common ancestor). This *apparent* paradox is due to the opportunistic character of evolution. Divergence within a group of creatures from a common ancestor involves the exploitation of various different evolutionary opportunities. The same would be true of another group. Another such group may diverge in a way involving some of the same evolutionary opportunities. Thus, members of the two groups, diverging in ways which involve the same evolutionary opportunities, can *converge* to a similar result (Fig. 2).

12. THE IMPROBABILITY OF ALIEN BEHAVIOURAL CONVERGENCE

From an evolutionary perspective, the important features attributed to the putative alien are as follows:

1. it shares no common ancestor, or common environment, with terrestrial creatures [19] and;

2. due to the improbability of recurrence of the same evolutionary steps as characterised human evolution, it possesses an independently evolved, genetically unrelated and morphologically distinct bodily form to humans, though it is posited to have a similar intelligence (hence similar behaviour) to ourselves [13,14].

This approach utlises an 'alien design' argument [32]. That is, the specification of certain attributes an imaginary creature supposedly has. In this instance, a *hypothetical* creature with *non-humanoid* morphology and a *humanoid* intelligence. It is not based upon any physical evidence for the existence of such a creature. It is not, in any way whatsoever, an *evolutionary* model. To be so, one would require knowledge of its ancestor, and the environmental conditions which caused that ancestor to evolve to a particular descendant. It is one thing to provide a design for a *hypothetical* creature, another to assume evolution must necessarily bring it forth.

The putative alien is presumed to have originated on another planet. Consequently, it shares no common ancestor with us (neither genetically, morphologically or physiologically). Neither could it, by definition, share a common environment. It would therefore not be possible for it to respond to a common evolutionary opportunity. Due to the intimate relation between bodily form and behaviour, and with social behaviour, convergence to a similar intelligence (thus behavioural convergence) in a totally different type of bodily form is improbable. Convergence is actually the product of evolutionary divergence from a common ancestor in response to similar evolutionary opportunities.

From an evolutionary perspective, a creature's behaviour (and intelligence) cannot be exempted from evolutionary selective pressures any more than its morphology can. Without 'convergence' to prop up the SETI argument the conclusion is inevitable: the improbability of the individual steps characterising human evolution implies the unlikelihood of its repetition elsewhere. Hence, a 'humanoid' alien morphology is improbable. Similarly, for the same reason,

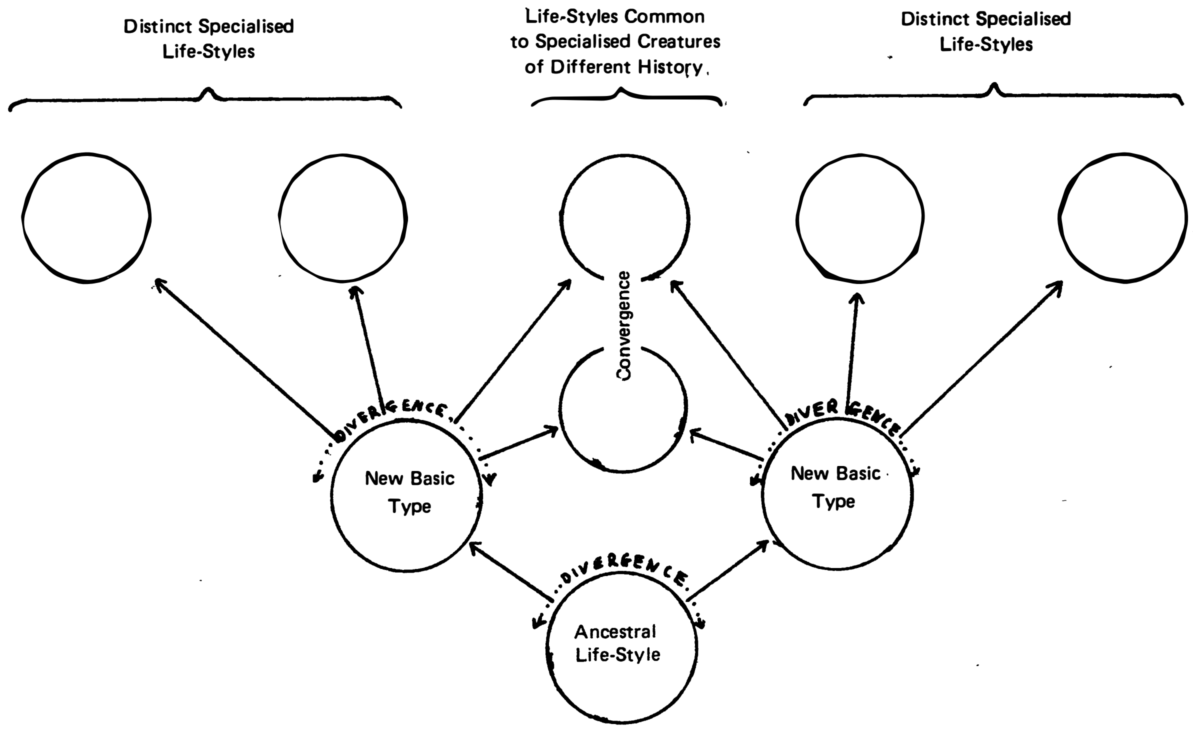

Fig. 2. Convergence is the product of divergence from a common ancestor under similar environmental conditions. (From Simpson [31]).

'humanoid' alien behaviour (and intelligence) is unlikely.

The arbitrary mix of a 'non-humanoid' morphology with a 'humanoid' behaviour (and intelligence) does not seem a viable option. The 'probability argument,' favoured by SETI proponents, because of the inadequacy of their 'convergence argument,' can be given no support by the available biological and evolutionary evidence. Behavioural convergence in a putative alien remains implausible.

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EXTRATERRESTRIAL INTELLIGENCE CONTACT TREATY?

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An encounter with extraterrestrial intelligence or with (relatively) developed life would have a great meaning. It could be an emergency case as well and possible negative effects must be avoided. The case for extraterrestrial intelligence should be a case for peaceful cooperation on the Earth. Thus a corresponding international agreement is proposed in this paper, making use of relevant Space Law instruments. Besides discussing legal issues, some proposals on cooperation are made.

1. INTRODUCTION - ENCOUNTERING EXTRATERRESTRIALS

Setting up the International Astronomical Union (IAU) Commission No. 51, promoting the Search for Extraterrestrial Intelligence (SETI), represents a major step forwards for mankind and it is a new defeat of geocentrism. This research raises many problems however.

A relevant question is "How to behave when encountering extraterrestrial life or intelligence?" It can be assumed that national space agencies have considered this question and that some directives have been formulated. Scientists and Science Fiction authors have worked out valuable answers.

Besides its great meaning for mankind, an encounter with extraterrestrials could consitute a danger. Extraterrestrial intelligence might manifest hostility and in any case, it should not get a chance to act on the Earth according to the principle "divide et impera." Mankind should stay united when such a contact is reported. A united, or at least cooperating mankind should investigate the encountered extraterrestrial intelligence.

The author feels that it is not too early, and that it would be practical, to develop some guidelines for the case of an encounter with extraterrestrials. These guidelines could be stated in the form of an international agreement. Space Law has been developed during the past decade and some acts contain relevant instruments, even if no explicit mention of extraterrestrial intelligence has been made. An early statement of principles about an encounter of this kind could enable mankind to avoid a possible late emergency.

2. RELEVANT SPACE LAW INSTRUMENTS

This section will discuss briefly three international acts.

The Space Treaty [1] of 27 January 1967, is the basic international space act, and several later agreements rely on it. Some basic principles stated in this treaty are: "Exploration and the use of outer space including the Moon and other celestial bodies shall be carried out for the benefit and in the interests of all countries..." (Art. I) and "maintaining international peace" (Art. III), further "States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies..." (Art. VI).

The duty to report about an encounter with extraterrestrial life or intelligence can be considered as being stated in

> Art. V (3) Space Treaty: "States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary General of the United Nations of any phenomena they discover in outer space, including the Moon and other celestial bodies, which could constitute a danger to the life or health of astronauts."

Such a phenomenon could be an encounter with extraterrestrials and the danger could face mankind as well.

A more direct sentence relating to extraterrestrial life is contained in

> Art. IX Space Treaty: "... States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth..."

The Space Treaty contains control instruments stating rights for the States Parties to the Treaty such as "to observe flight of space objects" (Art. X) and "to obtain information about them" (Art. XI), further "all stations... on the Moon and other celestial bodies should be open" (Art. XII) to visitors from States Parties to the Treaty. Art. XII could have been formulated generally, e.g. for some special cases. An encounter with extraterrestrials could activate Art. XII.

The Space Rescue Agreement [2] of 22 April 1968, develops some corresponding principles in the Space Treaty. Art. 1 states that each Contacting Party should pass over information when noticing any emergency case, while Art. 2-5 discusses various means/ways of assistance. This agreement would be activated as well, provided an encounter with extraterrestrials is declared to be an emergency.

The Moon Agreement [3] of 18 December 1979, is much more specific relating to space activities on the Moon. Art. 5(1) calls on to provide free information on Moon-research, and so does Art. 7(3). Art. 7(1) calls to avoid a harmful contamination of the Moon and of the Earth. Besides calling to provide free information about possible dangers to peoples, Art. 5(3) mentions extraterrestrials life explicitly; it calls to inform or to report about any signs of organical life.

3. CONCEPT OF AN AGREEMENT

An ammendment to an existing space act could state some principles of personal behaviour and international conduct in case of an encounter with extraterrestrial life or intelligence. A new treaty or agreement, in the way [2] or [3] followed the Space Treaty [1], might be better however.

A preamble about motivation, and further references to

Space Law and difinitions, would be followed by statements of internationally accepted humanitarian principles concerning an encounter with extraterrestrials.

An encounter with extraterrestrials should/could activate some international organisations and additional steps might follow. A international scientific body, e.g. IAU Commission No. 51, could assume the task of watching the state of art in research and might receive some kind of diplomatic function. It could play a coordinating role as well.

It is conceivable to link such an agreement to some behaviour guidelines elaborated by a scientific body, which are to be renewed according to the state of the art in research.

There have been developed languages for sending messages to extraterrestrial intelligence in outer space and/or celestial bodies, principles of behaviour when encountering such living beings could be seen as a special language, the way we talk of body language. The author does not know whether such a behaviour language exists or not. The history of mankind provides some useful examples as well, e.g. discoverers who met an unknown people and had to communicate with it.

It was not the intention of the present paper to produce a draft of an "Extraterrestrial Intelligence Contact Treaty," but to call attention to a possibly relevant problem.

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(Reference is made to documents contained in General Assembly Resolutions at the United Nations, mentioning their codes. The text of such documents is usually published in national official bulletins, in case of ratification. It is usual to use short forms of titles.)

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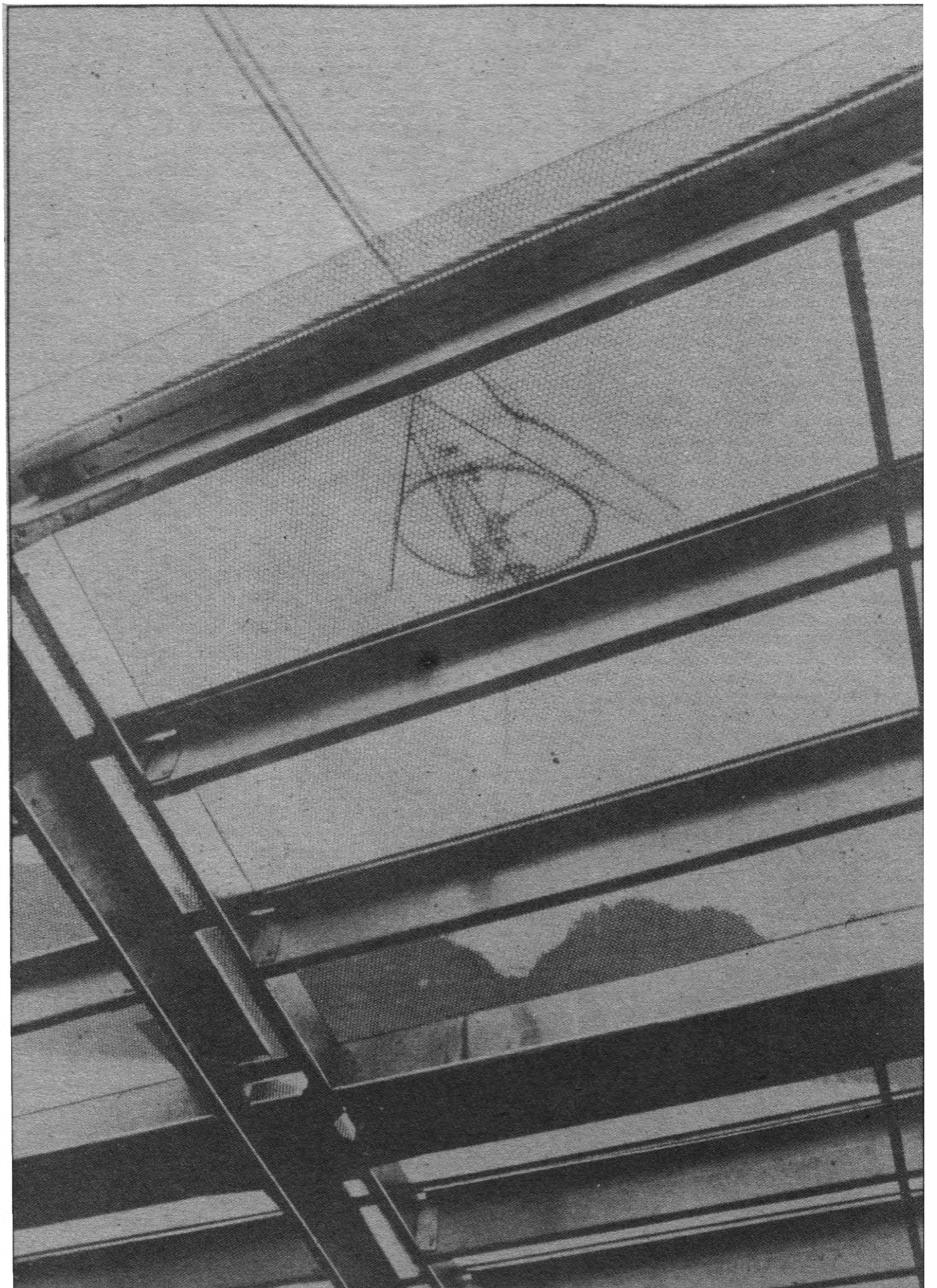

The 38,778 new panels covering the reflector surface of the Arecibo telescope are made of perforated sheets of aluminium stapled to aluminium frames and supported on a network of steel cables. The panels allow as much sunlight to reach the vegetation under the 300 m dish as shines on the surface of Mars.

National Astronomy and Ionosphere Center

Journal of the British Interplanetary Society, Vol. 38, pp. 524-526, 1985.

CETI: WHAT ARE THE BENEFITS?

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Some Flying Saucer cultists have been rightly accused of preying on the fears of us mortal terrestrials when they seek disciples to their movement. The world today is a fearful and impersonal one. But, not to worry, the Space Brothers will save the world from itself. So believe in them and follow me!

Or, some Flying Saucer cultists decry that we should all mend our individual and institutional ways, least, and before, we pose a threat to the Space Brothers and they, against their enlightened wishes, be forced to destroy us. Those who believe and mend their ways will be individually saved before the end of the world, and whisked away to Paradise in a Flying Saucer.

Both scenarios are modern space-age versions of the more traditional fundamentalists hell, fire, and brimestone religious points of view. But, are those space-age cultist points of view that far removed from what are considered to be legitimate 20th Century scientific paradigms when it comes to how we imagine extraterrestrial intelligences and their potential impact on terrestrial society? I suggest the two are close – and wrong. I shall dismiss the Flying Saucer cultists now from further consideration to concentrate on 20th Century science's points of view.

Popular science authors, even scientists themselves who write and speculate on the potential impact to our affairs should we ever detect artificial, intelligent, and extraterrestrial radio signals, seem to be one of two minds. You will either find references to something akin to "for God's sake don't answer" least we give away our civilisation's location and risk alien invasion, or, that their advanced knowledge and wisdom of the Cosmos will be ours in a fraction of the time had we toiled and sweated for it ourselves. In the latter paradigm we would be the recipients of the entire contents of the *Encyclopaedia Galactica* – the cosmic edition of our *Encyclopaedia Britannica.* This cosmic knowledge would provide us the keys to turn our imperfect and troubled civilisation into a Garden of Eden. Alas, both extremes are just that – extremes in the entire spectrum of possibilities.

We are not likely to be targeted for invasion, even if we did reply, given the vastness of astronomical distances. Such distance barriers would give us a fair grace period in which to prepare for their attack, should their signals hint at a warlike and aggressive nature. To attack over such distances suggest that the aliens like to undertake extraterrestrial invasions at whatever cost, just for the sake of invasion, or perhaps, as some may say, as preventative medicine. But if that advanced, and so inclined, we would have been discovered and conquered/colonised eons ago. We cannot hide, and never could, an object the size of the planet Earth from alien eyes.

Further, there is nothing we have in the way of natural resources, and other physical goods and services, that such an advanced alien race would not be able to obtain and construct in quantities orders of magnitudes over what we have, and closer to their home ground too. Outer space is abundant with unowned mineral and energy resources there for the taking.

Invasion is the minority extreme. The majority extreme, now ingrained as being conventional wisdom in such matters, sees the receipt of such a signal as the dawn of our cosmic Golden Age. Aliens, because they would be so advanced (scientifically, morally, socially, etc.) to us, would obviously delight in giving us the cures for all our worst diseases, show us the way to social and political enlightenment, explain the ultimate secrets of the micro and macro universes, provide the key to unlimited energy supplies, and, basically tell us the answers to "life, the Universe and everything." This, I suggest is a point of view not unlike that of the Flying Saucer cultist and his Space Brothers. This, I suggest, is clinging to too optimistic a point of view. Both are attractive; both for the same reasons.

There will of course be a dramatic terrestrial impact if radio SETI (search for extraterrestrial intelligence) succeeds. From the outset SETI will yield to, and become, CETI (communications with extraterrestrial intelligence), even if the "communication" was accidental in intent and uni-directional. However, I suggest that the impact of this communication, coming from remote distances, will be somewhat better than that of a Dark Age hell resulting from invasion, and somewhat less than a Golden Age enlightened paradise. At what point on this spectrum do the improbabilities melt into what we can suggest is a probability?

Clearly the cheapest, most valuable, and easiest commodity to send and exchange rapidly over interstellar distances is information carried on the waves of the electromagnetic spectrum. Within that EM spectrum, radio has the edge of the medium best suited to carry bits of information. This transmission of knowledge, is, in the first instance, them-to-us, as we are deliberately listening, not deliberately sending. (We are of course unintentionally signalling all the time.) So, we start by leaning toward the Golden Age and away from the Dark Age extremes.

Assume we do detect an unambiguous artificial extraterrestrial radio signal. From the outset we will learn many things. Even if their signals represented radio "leakage" we picked up while doing radio SETI, we would immediately know that we were not alone in the Universe. We could state with some degree of confidence that life was a statistic, not a miracle. Such a discovery could come quite by accident tomorrow without a formal radio SETI programme in the course of normal radio astronomical research. Were that to be the case, all such normal work would immediately stop. Existing radio telescopes would be positioned to learn where the aliens were, and in conjunction with optical telescopes to reveal how far away their parent stellar systems was and whether or not that system was single or multiple. Detailed analysis of the signal would probably reveal the distance of their home planet from that star(s) as the effect of the planet's revolutionary period would be obvious upon the signal. Ditto the planet's rotation rate and axis tilt.

The immediate benefits (or consequences) could be, apart from the scientific, religious, and philosophical ones, political ones. It would be reasonable to imagine that there would be a start, however slowly, toward terrestrial unification of peoples and nations as the realisation that we are one cosmic entity out of many other sinks in. The cosmic perspective drives home the point that terrestrial differences pale relative to extraterrestrial ones. Another point, frequently mentioned

in the literature, is that we would realise that advanced technological societies (as this alien civilisation would have to be) do not of necessity have to self-destruct. What is then not as often mentioned is that the alien's signals could cease again within an hour of our detection as they have launched their own version of World War III. Just because we have beamed out one deliberate radio signal to the cosmos and her inhabitants (those in the great globular cluster in Hercules, M13) does not of necessity mean that human life on this planet would not have suicided by the time our message is received 25,000 years from now. However, the odds would be that the signal we receive would have been sent by an extraterrestrial civilisation tens, hundreds, thousands, even millions of times our senior. Such would increase our confidence that if we return the call, the contact will not have been severed by that civilisation having, in their immediate (cosmic) future, played and lost the game of nuclear Armageddon.

And, unless we could actually decode their radio "leakage" which would be difficult in the extreme, that is just about all we would learn.

If, however, the aliens deliberately send out high-power, anti-cryptic broadcasts, with the view to attracting attention to themselves in a "here we are and this is what we are about" fashion, we will learn a lot more – but not enough to bring about the degree of cosmic enlightenment suggested by the wishful thinking of some writers. Let us assume these cosmic teachers broadcast and re-broadcast and re-re-broadcast the entire contents of their *Encyclopaedia Galactica* to the cosmos. Planet Earth, and our radio telescopes, intercept one of these educational sessional broadcasts. Because the message is anti-cryptic, we will be able to decode it easily. Having done so, we will obviously learn lots of things about them, their world, philosophy, politics, history, science, religion, society, culture, etc. But most of that information will widen our knowledge, not advance or greatly alter what we already know or believe. In other words, the next edition of our *Encyclopaedia Britannica*, incorporating their *Encyclopaedia Galactica*, will end up needing more volumes of more pages, relative to replacing volumes and pages found in the current existing edition.

That is a sweeping generalisation. The specifics depend on the exact nature of the topics being transmitted from the *Galactica*. If the broadcast is chock-a-block with details of their history, it will not alter our terrestrial history very much – if at all.

If, on the other hand, the message is chock-full of physics, we could have the key to inexhaustible fusion energy supplies within a fortnight.

Should, however, the message be of interest to biologists, biochemists and the medical profession, the contents are not probably going to translate ever, farless immediately, into details that will unlock the secrets to preventing, controlling, or curing terrestrial diseases. The odds are too great against that their biochemistry would match our biochemistry down to the last minute detail. We would need that Nth detail. That is not to say their biology, biochemistry and medicine would not be interesting – it would be. It might provide the "Eureka, I've got it" light globe that our medical Einsteins need in terms of new horizons and suggestions of where to look for the answers. But the message will not, cannot, actually provide the answers for them.

Then again their broadcast could have a cosmic theme. Volume 4 of the *Galactica* could be an astronomical tome. If so, it is a safe prediction that the corresponding *Britannica* volume will need extensive revision, not merely expansion. Would not our astronomers be thrilled to receive that extraterrestrial message confirming that, for example, the centre of the Milky Way does contain a massive black hole; that the Universe is an oscillating one; that anti-matter does not exist in large quantities naturally, but gravity waves do and here is how to detect them; that solar systems are an inevitable part of stellar formation. Such knowledge would cause our astrophysical textbooks to be in need of near total re-writes.

But, if the message is political, explaining how their Congress or Parliament or whatever it was worked, it would be silly to then expect our politicians to rush out and adopt that system and get their act together, or that the United Nations would become that – united. It might, but more likely because there was a message, not because of the political contents of that message.

The aliens might reveal that they too have a nuclear family society, and one with a zero divorce rate and no domestic violence. But, that does not mean that that will translate, immediately, if ever, into 100% of terrestrial couples living happily ever after.

Economic policies that work for them could be disasters if adopted by ourselves. Our economic textbooks would not in all likelihood need re-writing, just the addition of another chapter.

On the other hand, the alien bombshell could be one which explains how to build a faster-than-light spaceship or a perpetual motion device. Physics textbooks would be useful then only as waste paper. You could not give them away.

We see a pattern developing. In short, there are some universals in the great cosmic scheme of things. We call them "universal laws" and they operate at all times, in all places, for all objects, including intelligent beings. If one of those beings instruct us how to build a faster-than-light spaceship, we can build a faster-than-light spaceship. If we are told that it is possible to construct a 100% neutrino capture device, then construct one we will. But those universals are for the most part found within the hardcore of physics, chemistry, mathematics, and other physical sciences stemming from them. As such, it is not improper to be chauvinistic about what is what. Our physical sciences must correspond one-for-one with their physical sciences. There is only one absolute definitive physics textbook.

When it comes to the softer sciences, the biological sciences, chauvinism and anthropomorphism must be increasingly discarded. There is no reason to believe there is a universal biology. It would be scientific folly in fact to believe that. In the case of our alien message we might learn that their origin of life, hence biochemistry, depended on silicon instead of carbon. Their nuclear family might consist of a half-dozen individuals, each of which is of a unique sex. Perhaps their evolution has a Lamarckian, not Darwinian structure. To expect such a race to hand us on a silver platter the secret to cloning another Einstein just because his organic brain has been pickled and preserved over the years, in unduly optimistic. From them, we shall not learn why *our* dinosaurs died out, even if we find our why *their* "dinosaurs" became extinct.

The social sciences are softer yet. There, all pretence towards terrestrial chauvinism should be totally abandoned. Our two races would have little in common. The lack of such a common base suggests that not only do we not share common solutions to problems, but could not, as we probably do not share common problems!

From any extraterrestrial message it would be unlikely in the extreme that we would learn how to stop incidents of incest, prostitution, and child pornography. To the extraterrestrials, such things may be coveted. Perhaps they have no equivalents, in which case... Examples could be given *ad infinitum*. There is little they could do to improve our social institutions and situations. It would be almost akin to asking them for a better tasting beer when all they know is about milk. The value of course in learning about their society and culture is that they could provide the clues and insights, some of which could result eventually in a better terrestrial society and culture. We still however have to provide the

brainpower in any extrapolation from their lifestyle's problems/solutions to our lifestyle's problems/solutions. In many cases the barrier may prove an impossible one to extrapolate across.

Softest of all would be the contrast between their arts and our arts. In all likelihood we would never see their arts as being such an improvement over ours that we would confine to the rubbish bin the Mona Lisa, Aussie Rules, Beatles records, the plays of Shakespeare, *Playboy* centrefolds, the statues of Easter Island, the triology of *Star Wars* motion picture epics, the novels of Ian Fleming, pizza combinations, and re-runs of *I Love Lucy*, and adopt their alien equivalents as we would in the case of the physical sciences. There are no universals in the arts. Beauty is in the senses and mind of the beholder. Alien art will therefore complement, not replace, terrestrial art.

To achieve a terrestrial Golden Age, we need to re-write more than just the chapters on physical science. We need more than inexhaustible energy supply knowhow and how to treat radioactive substances in order to eliminate the radioactivity. We need advances in the biological sciences, and even more so, in the social sciences. Alien *Encyclopaedia Galacticas*, as we have seen, are not going to be of much use in those areas.

But what if we sent them our *Encyclopaedia Britannica* and also asked them, after suitable study, to provide the solutions for the problems demonstrated in the *Britannica* – the big issues of disarmament, poverty, pollution, crime, population growth, disease, and so on and so on that fall out of the physical arena. We of course would have to keep in mind that there would be a long time delay – the time it would take our message to arrive, be deciphered, studied, answered, plus the return time lag. That very delay could change both the nature of the problem and the relevance of the answer. Apart from that however...

Even if we were to reply to our alien's message and ask them the pressing questions of our time, we would still be unlikely to get absolute Golden Age answers, except in the cases that are addressable through the application of universal laws. If we ask them to solve the quadratic equation $x^2 - 4x - 5 = 0$, they would answer that x is equal to either +5 or -1. That is as certain as death (you cannot say "and taxes" anymore – the citizens of the new independent nation of Brunei do not pay taxes!). If we ask them "does God exist and prove your answer" or request the answer to our dilemma over the issue of drink driving or capital punishment, they could give an answer no doubt, but would it really increase or decrease our convictions – whatever they happened to be? Would every extraterrestrial civilisation, if more than our lone example, give the same answer? They would in the case of x equals +5 or -1.

In conclusion, we will learn and benefit much from CETI, even if uni-directional. That such communications will be, even could be, the ways and means to a Golden Age is absurd. To most of us, most of life's meaningful issues and their resolutions are not physical, chemical, mathematical, or astronomical. They are not composed of universal elements. They are not black or white; yes or no. They are in all probability unique to our planet, our life form, our mental makeup, our society and our time. As such, they lie outside the bounds of things extraterrestrial. They have their problems which we could not umpire; we have ours which they should not be expected to umpire. Solutions on the road to our Golden Age therefore must come from within. They are our problems – we will solve them.

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CORRESPONDENCE

Solar System Stellar Flybys

Sir, In response to requests for information concerning the Solar System's past stellar 'encounters,' we have undertaken the current brief analysis as a follow-up to the data provided in Ref. 1. The enclosed table lists only four such past 'encounters' at distances of five light years (L.Y.) or less. For completeness, we have tabulated the future events under three L.Y. as taken from Ref. 1 and included additional events between three and five L.Y. As in the earlier work, the Gliese Catalogue of Nearby Stars [2] was used as the source of stellar astrometric data. The rectilinear stellar trajectory propogation method was employed again, as it was in Ref. 1.

The results show a sparseness of past events which is somewhat discouraging for catastrophe hunters. However, it should be kept in mind that only the stars provided in Ref. 2 were used. In the time spans covered by the analysis, many more stars could have closely approached the Solar System neighbourhood, and these events would be unknown to us. Note also that the closest approach distance uncertainties, as illustrated by the semi-major axis of the dispersion ellipsoid (last column of table), are typically very large, over 100 per cent for the past events. This is primarily due to uncertainties in stellar radial velocity coupled with the long propagation times.

Also, events which occur more than about 300,000 years from the present epoch are susceptible to additional flyby uncertainties on the order of one L.Y. or more, arising from the fact that effects due to differential galactic rotation were not modelled. The > symbols, occurring in the last column, indicate stars for which the star catalogue [2] provided no parallax uncertainty. Thus the tabulated values are the minimum uncertainty.

Finally, there are some future events which are predicted with greater certainty. These manifest themselves as having dispersion ellipse semi-major axes of about one L.Y. or less, and occur for well-studied stars with relatively short times for the errors to propogate.

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A. B. SERGEYEVSKY
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Light Sail Windmills

Sir, Matloff [1] has considered Light Sail Windmills [2] for energy storage during interstellar flight. Unfortunately, his analysis of the specific energy stored is in error.

The rotational energy of a windmill in free space must be contained by means of its structural strength; like a flywheel, it will not be able to store in excess of $\sigma_m/2\rho \sim$ 1-10 MJ/kg.

The Light Sail Windmills described in Ref. 2 overcame this limitation with stationary ballast weight in the gravitational field of the Earth or Sun providing the necessary centripetal force. The relatively short blades were therefore enabled to spin at very high velocities, at high power. This is not a method a starship could use.

However, in an accelerated system other methods of storing kinetic energy are possible.

Work to be submitted describes a method suitable for

SOLAR SYSTEM STELLAR FLYBYS UNDER 5 LIGHT YEARS, PAST AND FUTURE

STAR	α_{1950} (DEG)	δ_{1950} (DEG)	R_{1950} (L.Y.)	VIS. MAG.	SPEC. TYPE	T_{FLYBY} (YRS FROM 1950)	R_{FLYBY} (L.Y.)	σ_{SMAA} (L.Y.)
DM+11 878	83.43	11.30	37.49	8.82	M0	-483,076**	4.03	5.41
DM-21 2007	112.98	-22.19	55.29	4.45	F5	-269,980	4.43	8.06
DM+27 2055	176.08	27.30	45.31	8.70	K3	-1,685,677**	3.83	>41.0
DM-23 15935	299.60	-22.88	38.38	5.96	G7	-1,413,860**	4.99	13.0
DM+58 155	14.89	59.02	62.73	7.70	K2	749,368**	3.88	>9.20
DM+62 274	22.99	62.83	44.69	6.79	K1	477,816**	1.61	8.13
DM+61 366	29.59	61.67	32.62	7.41	K5	814,872**	0.29	20.9
LALANDE 21185	165.15	36.31	8.22	7.50	M2	20,069	4.62	0.18
AC+79 3888	176.14	78.96	16.64	10.92	M4	40,598	2.96	0.95
DM+45 2014	183.55	44.68	39.30	8.60	K4	221,964	1.54	8.65
PROX. CENTAURI	216.58	-62.47	4.29	11.05	M5	24,716	3.57	0.30
α CENTAURI*	219.05	-60.63	4.39	-0.01	G2	23,078	3.89	0.09
BARNARD'S STAR	268.84	4.56	5.91	9.54	M5	9,788	3.75	0.12
DM-1 3474	274.31	-1.96	45.31	9.40	M1	587,811**	3.08	6.10
DM+25 3719	285.82	25.85	43.49	7.22	K2	175,944	1.66	9.48
ROSS 248	354.85	43.92	10.26	12.29	M6	34,923	2.90	0.47

*Double Stars

**Errors due to linear assumptions may exceed 1 L.Y.

solar sail missions: with minor modifications, then, Matloff's results still stand [3].

Nonetheless, I suggest that it would be unwise to develop such interstellar arks (taking ~ 1000 years to reach the nearest star), unless faster modes of travel prove impracticable a few hundred years from now (an eventuality I consider most unlikely). Solar sail technology would be applied more usefully to comparatively short-term interplanetary and interstellar precursor [4] missions.

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Reply by G. L. Matloff

After receiving the communication from Birch I checked my derivation and the values for tensile strength I used for diamond and copper. I still stand by my derivation, unless errors are pointed out. The values of σ_m I used are essentially identical to those in A. R. Martin, 'Structural Limitation on Interstellar Spaceflight,' *Astron. Acta*, **16**, 353 (1971).

In the real world of engineering materials, however, the limiting tensile strength for copper is rarely approached. A number of reference sources revealed a very wide range of values for σ_m copper depending upon method of preparation, history, etc.

The Light Sail Windmill (LSW) could still, even under non-ideal stress conditions, be utilised for energy storage on a starship. A ~ 10^8 kgm windmill could utilise its ~ 5 x 10^{10} kgm world ship as ballast, in the manner recommended by Birch for his stationary windmills.

Birch's last paragraph is, of course, a matter of opinion. Nobody advocates interstellar colonisation missions until the limitations and potentials of our propulsion options are known.

Technological Civilizations

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 could not "think alien," and this led me to thinking about the demonstrable inability of humans to understand 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 this viewpoint ties in with a very different culture. If we don't understand other humans, could we understand aliens?

I believe there is a strategy we can employ to make matters easier. The obvious "answer" is to have an ambassador familiar with both cultures; failing that, we can analyse the social and mental "worlds" of the creatures on Earth; store in exchangeable form software relating to the instincts, the reflexes, the types of "reason" used by 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 pseudo-earthly reflexes, but will also possess reflexes adapted to their totally alien environment, so that it SEEMS like tracking a New Guinea tribesman with a French phrase book, doesn't it? But the real resource we have after analysing wolves, ants, dolphins, etc., is not the phrase book in itself but our familiarity with the theory of reflex and instinct – the "philological" experience in taking cultures apart (metaphorically) – not only humans but animal cultures.

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 software or another – human, bee, trout, alien, solid state entity, etc. From there we can, when we meet aliens, communicate and learn still more about ways of looking at life. It is the beginning of what the human race are going into space for – evolution – the fusion of alien knowledge with our own. Several centuries of learning in one package: a perspective gained from two points of view. We do not know everything about the Universe and neither might aliens; the real potential of the Universe is millions of years beyond our primitive understanding. We want to develop, to evolve, if we are ever to have any hope of understanding the Universe in which we merely exist. It is the beginning of a new kind of evolution: not selection by elimination of the weakest but *via* the fusion of the strongest. This evolution will begin in our computers and in a few understandings but will expand to encompass all creatures of all races. And all sorts of new things are out there, waiting to be discovered once we recognise them. I see the potential pinnacle of our species as a species with no boundaries, physical, social or mental; or maybe thinking *via* other species: not Homo Galactis, but Pan Galactis. A Galactic mongrel? Maybe, but immeasurably advanced – a sort of Galactic Gaia. And it won't begin in several million years, when we reach the stars, but here, in our Solar System, as our colonists' descendants' physiologies adapt, and hence their body-chemistry-balances, and hence their psychologies adapt to lesser gravities and alien biorhythms and environments; even if they forever live in steel and glass domes in a barren vacuum, or in O'Neill colonies, the tides will get through. And there will be cultural evolution affecting their psychologies, affecting their cultures – even now.

So, with the points of view of earthly and then solar races (and species); let us begin.

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