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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 determine. 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:

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

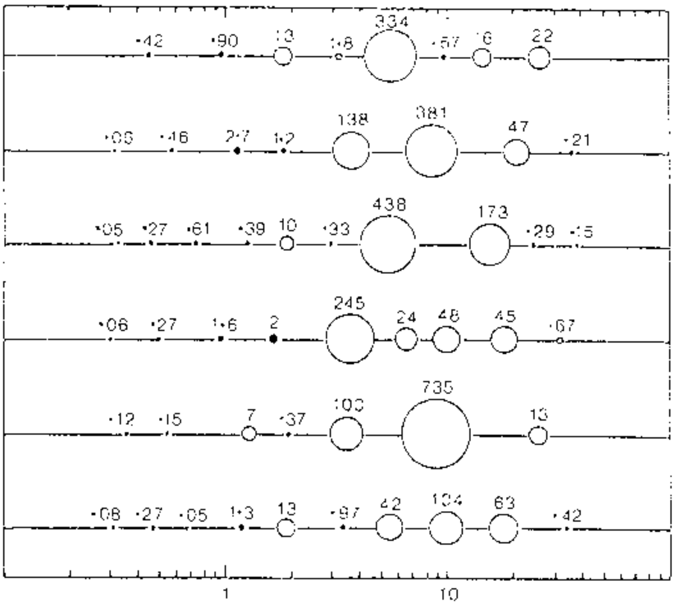

Fig. 1. Planetary system mass distribution, generated by 'Silicon Creation' for a primary of 1M⊙. The horizontal scale represents orbital distance in A.U. Planetary mass is in units of M⊕. Solid circles represent 'terrestrial' planets that have accreted dust only from the nebula, open circles represent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

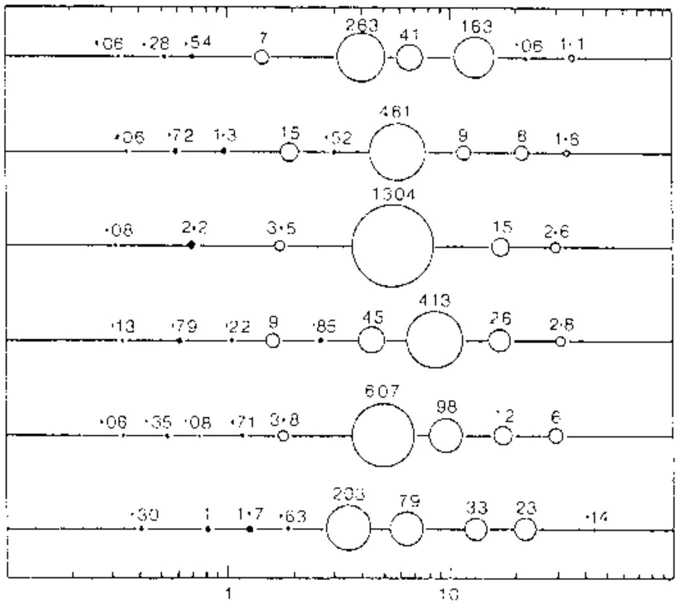

Fig. 2. Planetary system mass distribution – primary 1M⊙.

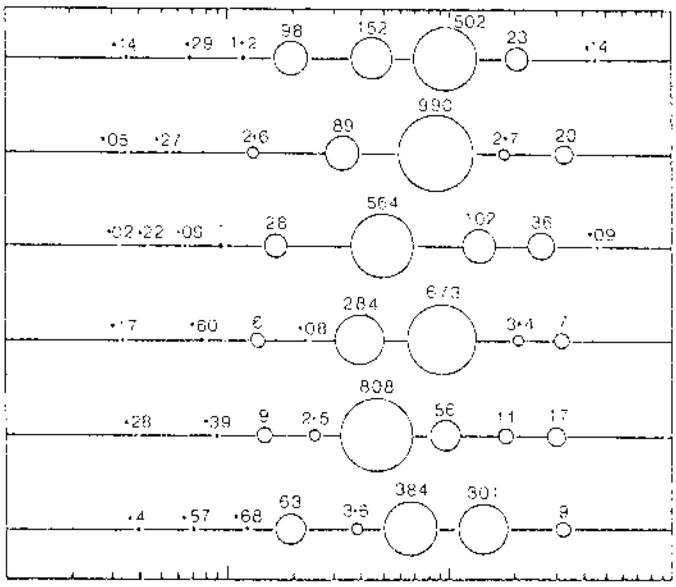

Fig. 3. Planetary system mass distribution – primary 0.6M⊙.

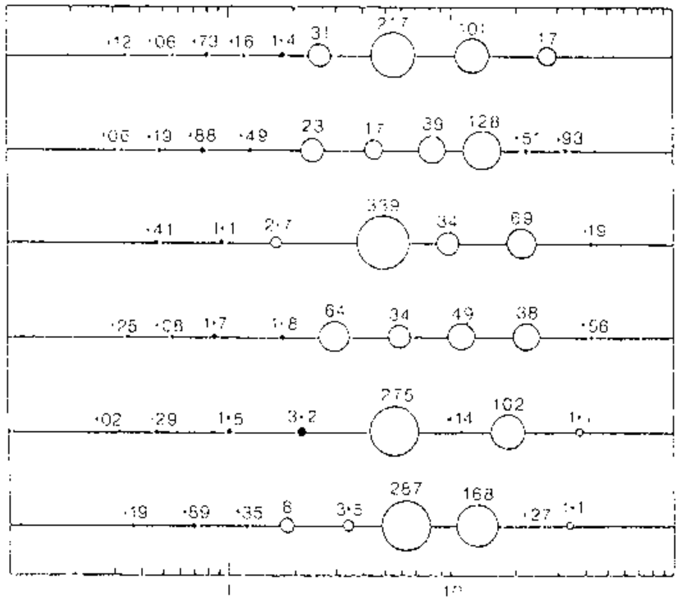

Fig. 4. Planetary system mass distribution – primary 1.2M⊙.

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 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

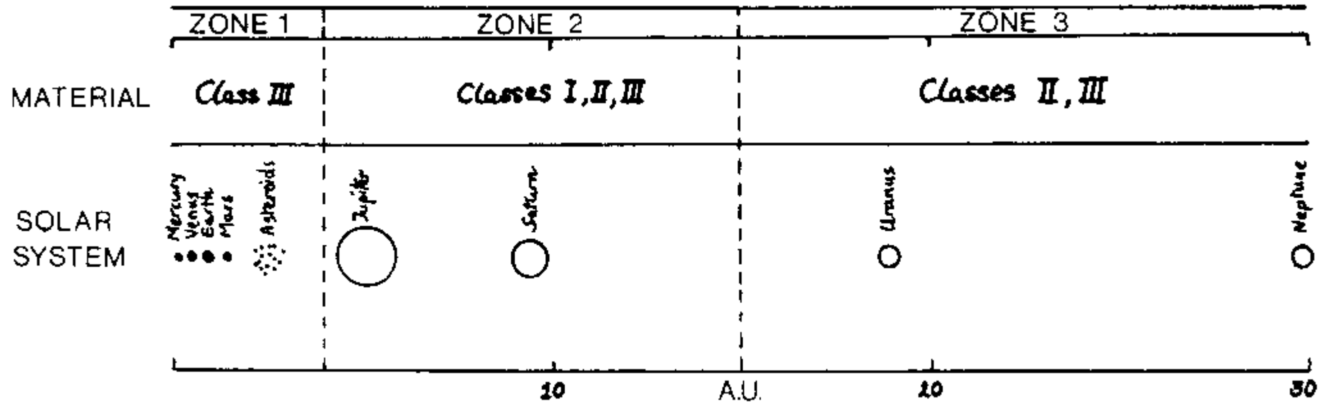

Fig. 5. The Solar System and planetary formation zones in a solar nebula for a 1M⊙ star.

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:

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

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:

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

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:

$$\frac{k_2}{2} \omega^2 r^2 = jm \tag{11}$$

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:

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

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:

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

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

$$(1 - e) / (1 + e) \tag{14}$$

for Mercury this gives $(1\text{-}0.2)/(1 + 0.2) = 2/3$.

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:

$$V_e = \sqrt{2gr} \tag{15}$$

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

The RMS velocity of an atom or molecule is:

$$V_0 = \sqrt{\frac{2kT}{m_a}} \tag{16}$$

where k is Bolzmann's constant, m_a is the atomic or molecular mass and T is the exospheric temperature ~ 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 ~ 5 x 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:

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

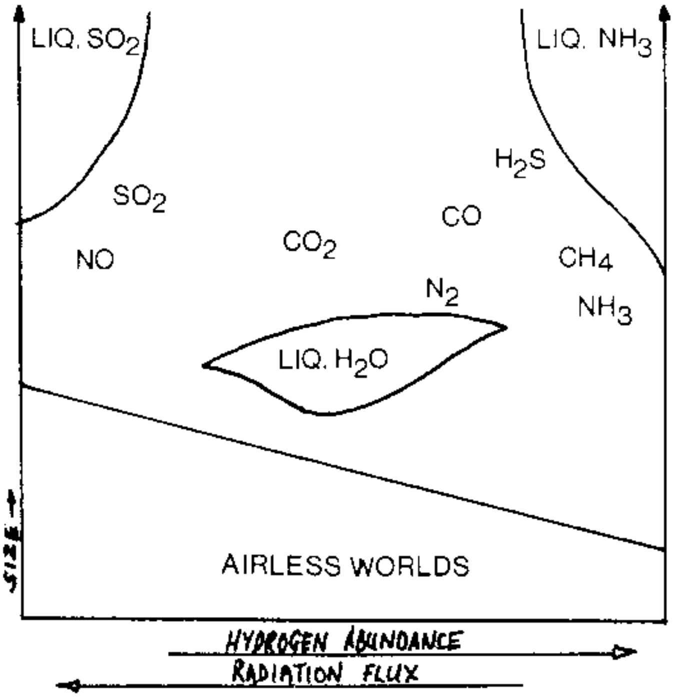

Fig. 6. Possible major atmospheric gases for terrestrial planets, from oxidising to reducing composition.

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:

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

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

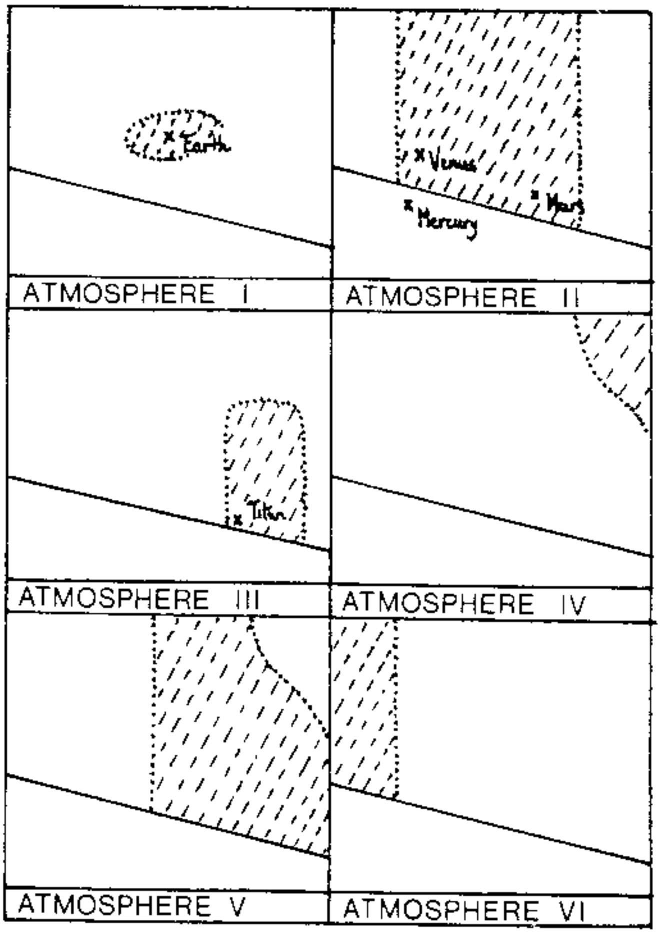

Fig. 7. Six types of atmosphere into which the continuum of composition is divided.

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:

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

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:

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

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 $\triangleleft$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 $1M_{\odot}$, which facilitates easy comparison with the Solar System. Planet 3 appears to be potentially habitable. As

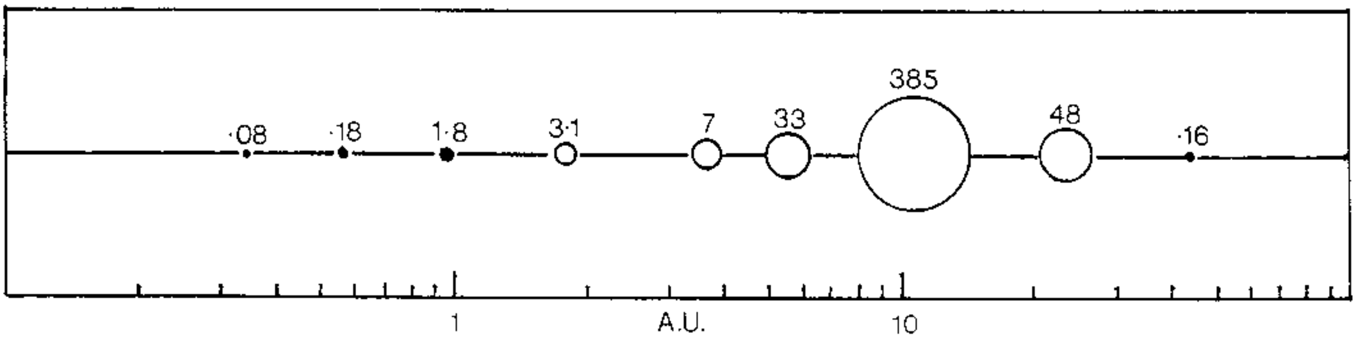

Fig. 8. Mass distribution of planets in the demonstration system.

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	$> = 1 \times 10^9$ yr	$> = 4 \times 10^9$ yr
Life	-	L-amino acid based proteins

```
SYSTEM JB15

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      22.004  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:            0.53        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:                     5.93        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:               12.02      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
DISTANCE FROM STAR:          22.8        AU
ORBITAL ECCENTRICITY:        0.14
YEAR:                        39662       days

AXIAL INCLINATION:           40
EQUATORIAL RADIUS:           43843       km
DENSITY:                     0.82        g cc
MASS:                        2.9E26      kg
GRAVITY:                     1.01        G
ROTATION RATE:               12.87       hours

ALBEDO:                      0.4
AVERAGE TEMPERATURE:         -221.62     C
HYDROSPHERE:                 0           %

GAS GIANT ATMOSPHERE
METHANE ENRICHED

LIFE: NO LIFE FORMS

SUMMARY OF PLANET: 8

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

```
PLANET: 9
DISTANCE FROM STAR:          43.54       AU
ORBITAL ECCENTRICITY:        2E-2
YEAR:                        104706      days

AXIAL INCLINATION:           8
EQUATORIAL RADIUS:           5130        km
DENSITY:                     1.7         g cc
MASS:                        9.63E23     Kg
GRAVITY:                     0.25        G
ROTATION RATE:               31.13       hours

ALBEDO:                      0.7
AVERAGE TEMPERATURE:         -240.98     C
HYDROSPHERE:                 100         %
                         PERMANENTLY FROZEN

ATMOSPHERIC PRESSURE:        16          mb

ATMOSPHERE: MOSTLY FROZEN ON SURFACE
A LITTLE He AND SUBLIMATED N2 & CH4
STILL GASEOUS

BULK COMPOSITION             ICE

LIFE: NO LIFE FORMS

SUMMARY OF PLANET: 9

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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