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AN ESTIMATE OF THE PREVALENCE OF BIOCOMPATIBLE AND HABITABLE PLANETS

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A Monte Carlo computer model of extra-solar planetary formation and evolution, which includes the planetary geochemical carbon cycle, is presented. The results of a run of one million galactic disc stars are shown where the aim was to assess the possible abundance of both biocompatible and habitable planets. (Biocompatible planets are defined as worlds where the long-term presence of surface liquid water provides environmental conditions suitable for the origin and evolution of life. Habitable planets are those worlds with more specifically Earthlike conditions). The model gives an estimate of 1 biocompatible planet per 39 stars, with the subset of habitable planets being much rarer at 1 such planet per 413 stars. The nearest biocompatible planet may thus lie ~14LY distant and the nearest habitable planet ~31 LY away. If planets form in multiple star systems then the above planet/star ratios may be more than doubled. By applying the results to stars in the solar neighbourhood, it is possible to identify 28 stars at distances of < 22 LY with a non-zero probability of possessing a biocompatible planet.

1. INTRODUCTION

It is likely that life was already present by a billion years after the formation of the Earth. Unless our planet was "seeded" with life from without, a hypothesis only taken seriously by a small minority of scientists, its genesis must have occurred spontaneously within a few hundred million years following the Earth's accretion. One interpretation of this fact leads to the speculation that life may originate comparatively rapidly in any planetary environment similar to that of the early Earth and that the Galaxy may be strewn with numerous life-bearing planets. The origin of terrestrial life is still an unsolved problem but the most popular theory takes, as its starting point, Darwin's "warm little pond", containing an aqueous solution of organic chemicals produced from reactions between atmospheric gases, triggered by energy sources such as lightning and ultra-violet light. Thus, for a planet to give rise to and maintain an indigenous biosphere, one of its prime features must be the presence of large and stable bodies of liquid water on its surface. This requirement sets strong constraints on surface temperature and atmospheric pressure, ensuring that similar environmental conditions will prevail as do on the Earth.

How abundant are such biocompatible "water worlds" likely to be in the Milky Way galaxy? Although there is, as yet, no unequivocal evidence for a planetary system about any other star than our own, it is expected that extra-solar planets may be common.

Knowledge of modern astrophysics and planetology is now sufficient to permit a reasonable estimate of the mass range of stars about which biocompatible planets are likely to exist. This is done below by using a simple computer model of planetary system formation and evolution. An estimate of the frequency per field star of biocompatible planets then allows a study to be made of stars within the near-solar neighbourhood to identify candidates upon which the search for extraterrestrial life might be concentrated.

2. THE ECOSPHERE

The orbital radius of a biocompatible planet about its primary must lie within a zone thermally compatible with life, where the average global surface temperature lies between a little less than 0°C up to some value at which a runaway greenhouse effect occurs. This zone, the *ecosphere*, has inner and outer boundaries defining the values at which environmental conditions are respectively either too hot or too cold to permit the genesis or sustenance of life.

Before the space age, it was thought quite possible that both Venus and Mars were environmentally benign and inhabited by life. Some models of Venus painted the picture of vast steamy swamps or a world girdling seltzer ocean, while observations of the changing colours of Mars suggested the presence of plant growth, fluctuating with the seasons [1]. Thus, the Sun's ecosphere would have extended at least between the orbits of these planets giving the distances from the Sun of the inner boundary $r_1 = 0.71$ AU and the outer boundary $r_2 = 1.52$ AU (fig. 1).

Dole has presented a model of an Earthlike planet with an optically thin atmosphere which was subjected to variations in illumination and axial inclination [2]. Assuming that such a planet was "habitable" if at least 10% of the surface had average

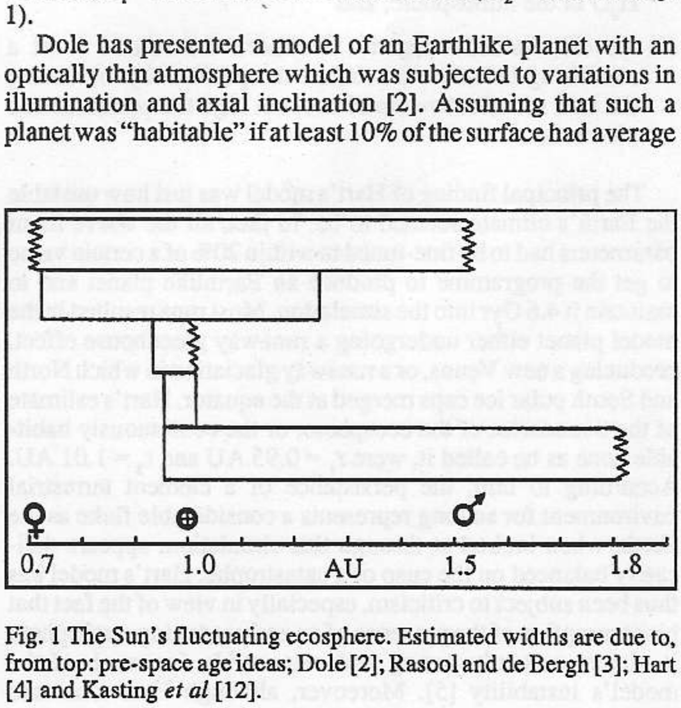

Fig. 1 The Sun's fluctuating ecosphere. Estimated widths are due to, from top: pre-space age ideas; Dole [2]; Rasool and de Bergh [3]; Hart [4] and Kasting *et al* [12].

yearly temperatures between 0 and 30°C, with the most extreme daily temperature between -10 and 40°C, he was able to estimate the width of the ecosphere. According to his calculations, the ecosphere was still quite wide with r_1 = 0.725 AU and r_2 = 1.24 AU: viz close to the orbit of Venus and half way out to the orbit of Mars.

However, the atmosphere of the Earth is not optically thin. Its water vapour and carbon dioxide components add up to exert a greenhouse effect that maintains the surface about 33 K above the planet's effective temperature. Rasool and de Bergh [3] pointed out that a terrestrial planet might undergo a runaway greenhouse effect upon outgassing if situated too near the Sun. As H_2O and CO_2 build up in the atmosphere, the temperature of the surface is raised too high to permit the condensation of oceans. They calculated that the Earth would have suffered such a fate if situated closer than 0.93-0.95 AU from the Sun. Such a value of r_1 so close to the orbit of the Earth prompted a reassessment of previous optimistic estimates of the width of the ecosphere.

The Sun's shrinking ecosphere reached its narrowest with the model of Hart [4]. Ambitious in scale, Hart constructed a computer simulation of the evolution of the atmosphere of the Earth, starting with the origin of the Earth and running it to the present day. The model included a wide range of processes, "*... the rate of degassing from the interior and the mean composition of juvenile volatiles; condensation of water vapour into oceans; solution of atmospheric gases in the oceans; photodissociation of water vapour in the upper atmosphere; escape of hydrogen from the exosphere; chemical reactions between atmospheric gases; the presence of life, and variations in biomass; photosynthesis and burial of organic sediments; the Urey reaction; oxidation of surface minerals; variations in the solar luminosity; variations in the Earth's albedo; and the greenhouse effect.*"

The regulation of surface temperature was modelled by three feedback loops:

(1) the ice positive feedback that accentuated any climatic cooling by increasing the amount of high albedo ice cover,

(2) the water vapour greenhouse positive feedback that accentuated any warming trend by increasing the mass of H_2O in the atmosphere, and

(3) the cloud-albedo negative feedback that would exert a stabilising influence on surface temperature by increasing the area of reflective cloud cover at high temperatures and vice versa.

The principal finding of Hart's model was just how unstable the Earth's climate seemed to be. In fact, all the above input parameters had to be fine-tuned to within 20% of a certain value to get the programme to produce an Earthlike planet and to maintain it 4.6 Gyr into the simulation. Most runs resulted in the model planet either undergoing a runaway greenhouse effect, producing a new Venus, or a runaway glaciation in which North and South polar ice caps merged at the equator. Hart's estimate of the boundaries of the ecosphere, or the continuously habitable zone as he called it, were r_1 = 0.95 AU and r_2 = 1.01 AU. According to him, the persistence of a clement terrestrial environment for so long represents a considerable fluke as the Earth, when looked at through this simulation, appears delicately balanced on the cusp of a catastrophe. Hart's model has thus been subject to criticism, especially in view of the fact that his assumption of the presence of an early reducing atmosphere is almost certainly wrong and responsible for much of the model's instability [5]. Moreover, although Hart took into account the weathering of silicate rocks by CO_2 to produce carbonates he did not model the geological recycling of carbon between gaseous and mineral phases that is carried out by terrestrial tectonic processes.

It is this cycling of carbon which has recently been put forward as a major stabilising influence on the Earth's climate. Carbon dioxide dissolved in water reacts with silicate rocks to produce carbonate minerals, such as the formation of calcite from wollastonite:

$$CaSiO_3 + CO_2 \dashrightarrow CaCO_3 + SiO_2 \qquad (1)$$

Thus CO_2 in the atmosphere of even a lifeless world with surface liquid water, tends to be consumed gradually by chemical weathering. On Earth, this process is not all one-way, due to the fact that carbonate sediments are not permanently deleted from the geochemical carbon cycle. Tectonic movements within the crust, such as subduction, may bury carbonates deep enough to be thermally decomposed, releasing CO_2 which might then be carried back up to the surface dissolved in magmas. Walker *et al* [6] presented evidence that the CO_2 weathering rate is temperature sensitive with higher rates at higher temperatures. This, and the fact that CO_2 on the Earth is cycled back into the atmosphere by volcanism, prompted them to suggest the *geochemical carbon cycle* as the basis for a powerful negative feedback with influence over long term climatic fluctuations. When temperatures rise, weathering increases and CO_2 is drawn out of the atmosphere, resulting in a reduced greenhouse effect and lower temperatures. Conversely, weathering is reduced when temperatures fall, resulting in CO_2 building up in the atmosphere from volcanic degassing, increasing the greenhouse effect and warming the planet. Such a process offers an explanation of why the Earth has maintained a surface temperature and atmospheric pressure compatible with the presence of liquid water from the earliest times discernable in the geological record. Such conditions would have been maintained cybernetically from an initial situation where oceans were present and volcanism and tectonics were ongoing. The formation of the Earth's first oceans may thus have set the scene for the entire climatic evolution of our planet up to now. As the Sun's luminosity increased from its initial value of ~ 0.7 $L_\odot$, the carbon dioxide partial pressure might have declined from ~1 bar to its current value of 3 x 10^{-4} bar [7].

Geochemical carbon cycling also helps explain some of the oldest geological features on Mars. The planet's ancient catered terrain, dated at > 3.5 Gyr old, is extensively cut by numerous "runoff channels" [8] that have been interpreted as dried up river beds. These structures have been cited as evidence for an early warm phase of Martian history when the persistence of liquid water at the surface of the planet was possible. This, in turn, would require Mars to have had a dense atmosphere with sufficient greenhouse effect to keep the Martian surface temperature at > 273 K. Pollack *et al* [9] have suggested that this atmosphere consisted of several bars of CO_2, maintained by a geochemical carbon cycle involving intense volcanic recycling of carbonate sediments. They calculate that such a process could have kept the Martian environment in this biocompatible state for up to a billion years, possibly long enough to allow for the brief appearance of life [10]. However, this wet and warm epoch eventually came to an end when volcanic and tectonic activity on Mars declined to the point at which the equilibrium mass of the atmosphere was not sufficient to stop the planet from freezing over completely. Over the aeons since then, the atmosphere would have dwindled further, reacting perhaps with silicate minerals in moist pockets within the soil [11], to produce the thin remnant we see today.

Such a model has profound implications for the position of the outer boundary of the ecosphere [7,12]. It suggests that, *so long as a planet remains sufficiently geologically active to maintain a geochemical carbon cycle*, biocompatible environmental conditions are possible for planets with irradiancies as low as that for Mars > 3.5 Gyr ago. Since the Sun's luminosity was then ~ 0.7 $L_\odot$, this means that the present outer boundary of the Sun's ecosphere is r_2 > 1.8 AU.

Kasting and co-workers have also estimated a value for the inner edge of the ecosphere by studying the response of a model terrestrial atmosphere with fully saturated, cloud free, conditions to increases in solar flux [7,12,13]. At a solar irradiance value of 1.4 $S_\odot$, (where $S_\odot$ is the Earth' solar constant), the oceans evaporate entirely, producing he classical runaway greenhouse effect. However, at a lesser irradiance of 1.1 $S_\odot$ they identified another possible planetary environment, the "wet greenhouse". Here, scalding oceans at ~100°C are still stable as they are prevented from boiling by the pressure of a massive ~2 bar water-laden atmosphere. In both greenhouse states the water vapour rises high up in the atmosphere where it can be photodissociated by UV light resulting, as in the case of Venus, in the ultimate desiccation of the planet. In fact, the wet greenhouse model can better account for the present scarcity of water on Venus, so Venus may have started its history with an ocean which was gradually lost to space over ~500 Myr. Once the water was gone, CO_2 would have built up in the atmosphere with no way of weathering back into the surface, resulting in the present day massive Venusian atmosphere. In neither case, however, can it be said that Venus was likely to have been biocompatible and so Kasting *et al* arrived at r_1 = 0.95 AU, the same value as Rasool and de Bergh and Hart's estimate of the position of the inner edge of the ecosphere, albeit for a different reason.

Thus, for present purposes, the boundaries of the Sun's present ecosphere are chosen to be r_1 = 0.95 AU and r_2 = 2 AU, given the condition that such boundaries are only meaningful for a planet with a closed geochemical carbon cycle. However, when looking at ecospheres about other stars with different luminosities and when taking into account the variation in stellar luminosities with time, the definition of ecospheric boundaries in terms of distance is clumsy. A universal definition of r_1 and r_2 can be obtained if, instead, the value of planetary irradiance at those distances is used. The average irradiance of a planet in terms of $S_\odot$ is:

$$S = L/R^2, \tag{2}$$

where L is the stellar luminosity in $L_\odot$ and R is the planetary semi-major axis in AU. Thus the redefined values of ecospheric boundaries that apply to all stars are $r_1 = 1.1\ S_\odot$ and $r_2 = 0.25\ S_\odot$.

The discussion in this section is summarized in fig. 2 where the evolutions of Venus, the Earth and Mars are displayed on a graph of irradiance, $S/S_\odot$, vs a scale of geological activity, T/T_{PT} (explained later). Intervals of 1 Gyr are marked on each planet's evolutionary track. The central dividing line at $\log(T/T_{PT}) = 0$ represents the point in a planet's evolution where it can no longer sustain a geochemical carbon cycle.

The ecosphere is divided into three climatic zones:

(1) *Juvenile Martian*, ($0.25\ S_\odot < S < 0.7\ S_\odot$) where biocompatible planets would be similar to early Mars;

(2) *Juvenile Terran*, ($0.7\ S_\odot < S < 0.94\ S_\odot$) where such worlds would be similar to the Earth in the Precambrian; and

(3) *Habitable*, ($0.94\ S_\odot < S < 1.1\ S_\odot$) where a biocompatible planet would be receiving sufficient sunlight to permit the evolution of a similar environment to that on the Earth since the start of the Phanerozoic Aeon ~ 600 Myr ago.

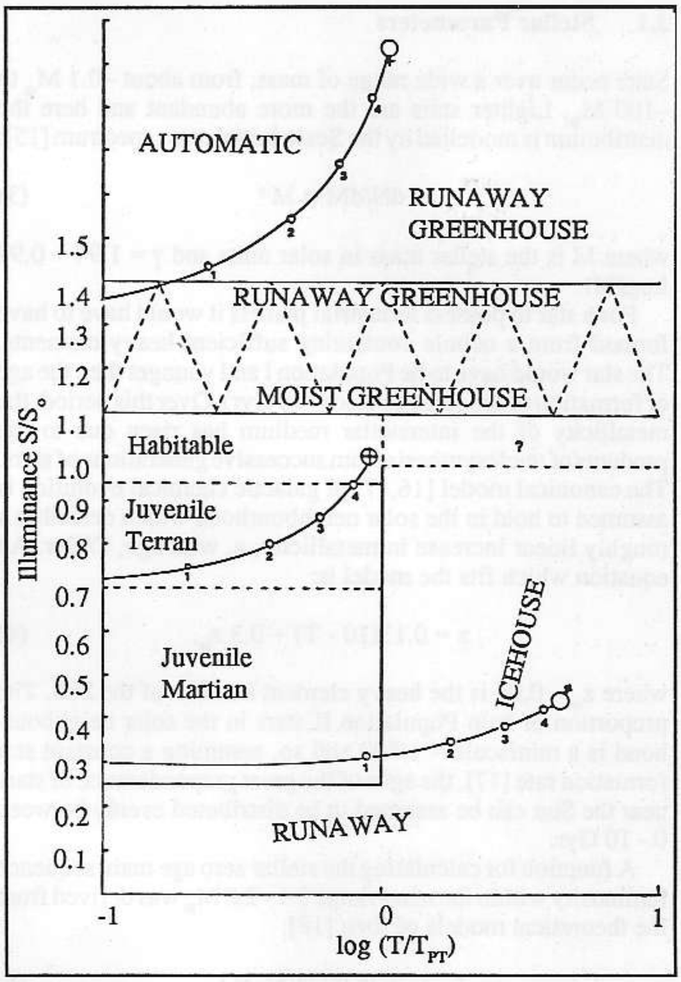

Fig. 2 Climatic evolutionary tracks for Venus the Earth and Mars, comparing illuminance versus geological activity over time, marked in intervals of 1 Gyr on the respective curves. The central dividing line at $\log(T/T_{PT}) = 0$ represents the point in a planet's geological evolution at which it can no longer sustain plate tectonics or a geochemical carbon cycle.

It will be seen that Venus was never within the ecosphere and, if it ever possessed oceans, these were likely to have been lost early on. Mars, because of its rapidly declining volcanic activity, left the ecosphere after ~ 1 Gyr. The Earth, however, has remained biocompatible throughout the history of the Solar System, though the diagram warns of possible trouble in the next billion years.

Such a biocompatible zone will exist about other stars, scaled up or down in size, so when estimating he galactic abundance of biocompatible planets the concept of the ecosphere must be embedded within a broader astronomical framework.

3. A BRIEF MODEL OF EXTRA-SOLAR PLANET FORMATION AND EVOLUTION

The model to be described forms the basis for a Monte Carlo computer simulation, the results of which are presented in Section 5. Earlier results of this simulation can be found in [14].

3.1 Stellar Parameters

Stars occur over a wide range of mass, from about ~0.1 $M_\odot$ to ~100 $M_\odot$. Lighter stars are the more abundant and here the distribution is modelled by the Scalo initial mass spectrum [15]:

$$dN/dM \propto M^{-\gamma} \quad (3)$$

where M is the stellar mass in solar units and $\gamma = 1.94 + 0.94$ Log(M).

For a star to possess terrestrial planets it would have to have formed from a nebula containing sufficient heavy elements. The star would have to be Population I and younger then the age of formation of the galactic disc (~10 Gyr). Over this period, the metallicity of the interstellar medium has risen due to the products of nuclesynthesis from successive generations of stars. The canonical model [16,17] of galactic chemical evolution is assumed to hold in the solar neighbourhood which describes a roughly linear increase in metallicity, z, with age, T/Gyr. An equation which fits the model is:

$$z = 0.13(10 - T) + 0.3\, z_\odot, \quad (4)$$

where $z_\odot \sim 0.02$ is the heavy element fraction of the Sun. The proportion of halo Population II stars in the solar neighbourhood is a miniscule ~ 1/800 and so, assuming a constant star formation rate [17], the ages of the great preponderance of stars near the Sun can be assumed to be distributed evenly between 0 - 10 Gyr.

A function for calculating the stellar zero age main sequence luminosity within the mass range 0.1 - 2.0 $M_\odot$ was derived from the theoretical models of Iben [18]:

$$L_{ZAMS} = 0.71(M/M_\odot)^n\, L_\odot, \quad (5)$$

where for {0.7 $M_\odot < M < 2.0 M_\odot$}: n = 4.75 and for {0.1 $M_\odot$ < $M < 0.7 M_\odot$}: n = 3.75($M/M_\odot$) + 2.125.

The amount of hydrogen burned by a star on the main sequence is roughly proportional to its mass and the main sequence lifetime, T_{MS}, of a 1 $M_\odot$ star is ~ 10 Gyr. Thus:

$$T_{MS} = 10(M/M_\odot)^{1-n}\ \mathrm{Gyr} \quad (6)$$

The luminosity of a main sequence star gradually increases with time. The following function was adapted from Gough's luminosity/time relation for the Sun [19], assuming in addition that for all stellar masses $\Delta L/\Delta(T/T_{MS})$ is a constant:

$$L(T) = L_{ZAMS} \exp\,[0.045(10T/T_{MS})^{1.33}], \quad (7)$$

where $T < T_{MS}$.

3.2 Planetary Parameters

Model planetary systems are constructed by the "ACRETE" Monte Carlo computer algorithm written by Dole [20]. This gives the number of planets within the simulated system, calculating a semi-major axis, R, orbital eccentricity, e, and mass, m_p, for each one. Although many of the details of cosmogony are yet to be understood, the use of ACRETE here is a justifiable simplification as planetary systems different in detail but similar in overall form to the Solar System are produced (fig. 3). This is what might be expected for extra-solar planetary systems if the Principle of Mediocrity applies to our own system, making it an average and unremarkable example of a common phenomenon.

However, Dole's simulations were all performed on the assumption that the mass of the central star was 1 $M_\odot$. Isaacman and Sagan [21] explored ACRETE further and showed that, within limits, it was possible to alter the programme's parameters without producing an output that appeared physically unrealistic. Here, the algorithm must be specifically modified to accommodate a wider range of stellar masses. Logically, one might expect the maximum mass condensation radius within the pre-planetary nebula to vary with stellar luminosity:

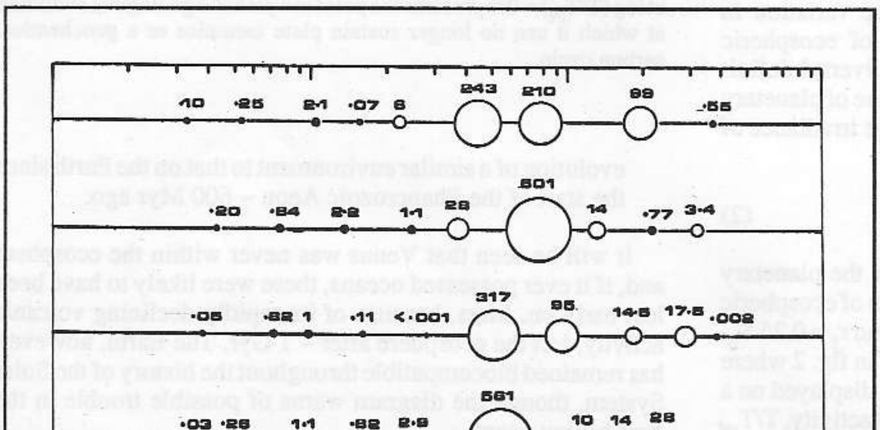

Fig. 3 Planetry systems produced by the Dole "ACRETE" algorithm. The primary star is 1 $M_\odot$, the masses of planets are given in Earth units and the horizontal axis is a logarithmic scale of AU. The Solar System is included third from top for comparison.

$$R_m = 5.8(L_{ZAMS}/0.71)^{1/2}\ \text{AU}. \tag{8}$$

Moreover, the central density of nebular dust, A, the parameter from which the mass of the nebula is scaled, might vary in direct proportion to the mass and metallicity of the central star. Thus when revised, Dole's relevant equation becomes:

$$A = (\alpha^9 / 1.3 \times 10^9)(M / M_\odot)(z / z_\odot)\, M_\odot/AU^3, \tag{9}$$

where $\alpha = 9R_m^{-1/3}$. However, it would seem likely that the mass of gas within the nebula would only be proportional to the mass of the star and not to the metallicity. Thus, when calculating the total mass of the nebula the gas/dust ratio is assumed to vary as $(z_\odot/z)$.

Running ACRETE with these modifications produces plausible planetary systems. For instance, systems about old, low mass, stars are scaled down in both mass and radial size. The converse is true for massive, young stars (fig. 4).

Investigating any terrestrial planets generated by ACRETE further, the planetary radius, r, and, thus, its bulk density, is found by solving Dole's empirical equation [2]:

$$\tfrac{4}{3}\pi \rho_0 r^3 e^{ar} - m_p = 0, \tag{10}$$

where $a = 1.08 \times 10^{-7}$ and $\rho_0 = 2770$ kg m^{-3}.

The value of planetary axial inclination, i, is determined randomly from Dole's empirical probability distribution [2]:

$$P = 1 - (1 - i/180^\circ)^{4.5}, \tag{11}$$

where P is the probability that the inclination is less than i°.

Taking note of a relation between the rotational energy per unit mass of planet with the planetary mass, Dole [2] derived an empirical equation for the initial angular velocity of a planet:

$$\omega = [(2jm_p) / (kr^2)]^{1/2}, \tag{12}$$

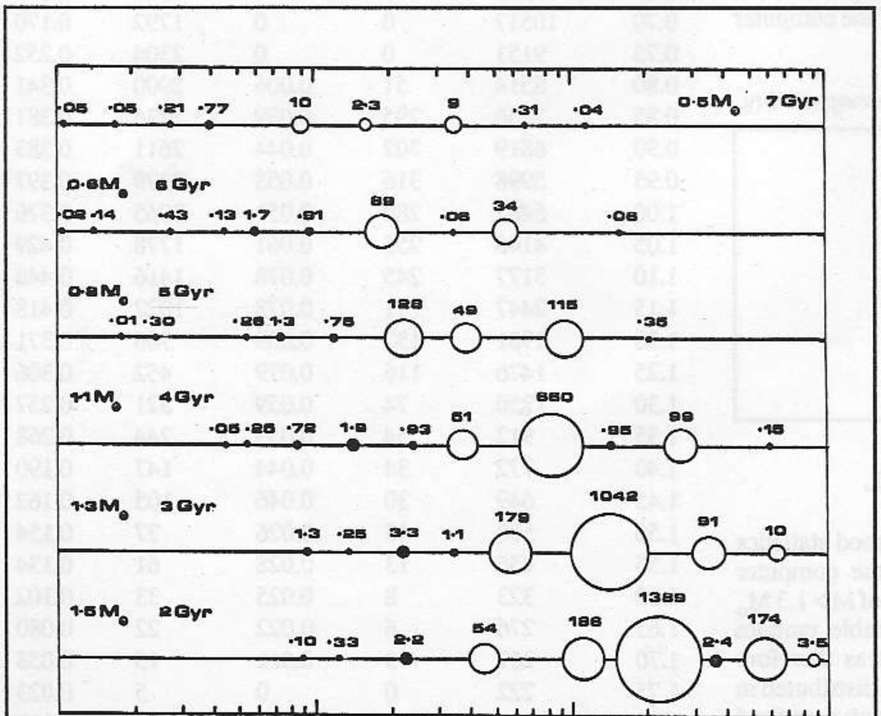

Fig. 4 Planetary systems produced by the modified Dole algorithm about stars of varying age and mass.

where k is the moment of inertia factor, taking a value of ~ 0.33 for a terrestrial planet and $j = 1.46 \times 10^{-20}$ m^2 s^{-2} kg^{-1}.

The final rotation rate is calculated after taking into account deceleration due to tidal breaking from the primary over the age of the system. Tidal forces are proportional to the mass of the tide raising object and inversely proportional to the cube of distance. The tidal deceleration torque is proportional to the square of the tidal force and so:

$$(d\omega/dt) = (d\omega_\oplus/dt)(k_\oplus/k)(r/r_\oplus)(m_\oplus/m_p)(M/M_\odot)^2(R_\oplus/R)^6, \tag{13}$$

where $d\omega_\oplus/dt = -1.3 \times 10^{-6}$ rad s^{-1} / 10^9 yr.

The geochemical carbon cycle model of Walker *et al* [6] is used to define the boundaries of the ecosphere and to suggest a rough atmospheric composition and surface temperature. Thus, any terrestrial planet with an irradiance at age T in the range $0.25\, S_\oplus < S < 1.1\, S_\oplus$, which is still volcanically and tectonically active, has the potential of possessing a biocompatible environment: an $N_2/CO_2/H_2O$ atmosphere, a surface temperature a little above 273 K and stable surface water. The presence of life as an additional stabilizing influence on climate and atmospheric oxygen is not taken into account as the geochemical carbon cycle can operate abiotically.

An estimate of the duration of viable volcanic/tectonic recycling of volatiles on a given planet is crucial as it can also be regarded as an estimate of the timescale for biocompatability. However, the detailed modelling of planetary cooling and crustal overturn is complex, plagued with unknowns, and inappropriate in the context of the simple model described. A solution was found [14] in a function relating tectonic activity to planetary mass derived by fitting to Condie's model of comparative planetary histories [22]. Plate tectonics terminates at the time T_{PT}:

$$T_{TP} = 5.1(m_p / m_\oplus)^{0.71}\ \text{Gyr} \tag{14}$$

This gives $T_{PT} \sim 1.1$ Gyr for Mars, in good agreement with the scenario presented in [9]. For the Earth $T_{PT} \sim 5.1$ Gyr, which accords with Condie's prediction that plate tectonics will largely cease ~500 Myr in the future. Any planet with $T_{PT} > 1$ Gyr will be massive enough to be able to hold on to volatile molecules as light as water for many billions of years without appreciable loss, unless subjected to a wet or runaway greenhouse effect. Thus, for biocompatible planets there is no need to calculate for the loss of atmospheres. The requirement for a functional geochemical carbon cycle also places a lower limit on planetary mass.

4. REQUIREMENTS FOR BIOCOMPATABILITY

The principal criteria assumed for planetary biocompatability are listed in Table 1. All are dictated by the need for the maintenance of planetary surface temperature within a range compatible with the existence of liquid water. The role of the value of stellar irradiance and the presence of crustal tectonics have been outlined. However, even if situated within an ecosphere, drastic variations in irradiance would be expected to compromise the capacity of a planet to sustain life. When a star becomes a red giant, its attendant inner terrestrial planets are incinerated and so the maximum age of a biocompatible planet would be the main sequence lifetime of the primary star. Seasonal or daily extremes of irradiance, caused by a high orbital eccentricity, axial tilt, or rotation period could cause such a violently fluctuating climate as to render the environment unfit for life. The biocompatible threshold values of these parameters are unknown and those in Table 1 are chosen from Dole [2]. A lower biocompatible age threshold of 1 Gyr was chosen to allow for the high impact rate of planetesimals left over form the planetary accretion process to die down to safe levels.

When examining stars within the solar neighbourhood for their potential to host life-bearing planets, the most useful parameter is the biocompatible range of stellar mass. An estimate of this, and that for the subset of habitable planets, can be obtained by statistical analysis of the output of the computer model.

TABLE 1: *Prime Requirements for Planetary Biocompatibility.*

Age: $1 \text{ Gyr} < T < T_{MS}$,
Orbital Eccentricity < 0.2,
Axial Inclination < 55°,
Rotation Period < 96 hr,
Illuminance: $0.25\, S_{\odot} < S < 1.1\, S_{\odot}$,
Active Volcanism and Tectonics

5. RUNNING THE COMPUTER MODEL

A large number of runs were required to obtain good statistics from the output of the model. In Ref. [14] the computer processed 10^5 star systems but the number of stars of $M > 1.3\, M_{\odot}$ was still not great enough to prevent unacceptable random fluctuations in the output data. The computer was therefore given the task of investigating a million field stars distributed in increments of $0.05\, M_{\odot}$ over the initial mass spectrum described by Equation (3) and ranging in age evenly between 0 - 10 Gyr. Since the stellar number density in the solar neighbourhood is $0.116\ pc^{-3}$ and the relative binary frequency is 0.55 [23], this represents a spherical volume of space ~830 LY across containing 449,440 single Population I stars. All such stars of age between 1 Gyr and T_{MS} and ranging in mass between 0.45 - 1.8 $M_{\odot}$ were passed to the planetary generation algorithms for further processing.

The numerical results are set out in Table 2. Listed are data for N(M), the number of single M/S stars in the stellar mass increment M, and n(HP) and n(BP), the number of habitable planets and biocompatible planets in each stellar mass increment respectively. Also included are the ratios n(HP)/N(M) and n(BP)/N(M) the frequencies of habitable and biocompatible planets about stars of mass M. The total number of generated habitable planets was 2419 giving the overall HP frequency for the solar neighbourhood to be n(HP)/N = 0.0024; about 1 in 413 stars are accompanied by a habitable planet the spacial separation of such worlds being ~ 31 LY. Biocompatible planets as a whole were much more common, 25875 being produced, giving a BP frequency of n(BP)/N = 0.0259; about 1 in 39 stars possess such a planet the spacial separation of them being ~14 LY.

The number of planets of each type in each stellar mass increment are plotted on fig. 5a and their frequencies are plotted on fig. 5b. It is noticeable that habitable planets occur over the stellar mass range 0.8 - 1.8 $M_{\odot}$, over 50% of them being

TABLE 2: *Analysis of N = 1,000,000 Star Systems, 449,440 Single, Population I Stars, Data for M/S Single Stars Mass Range 0.45 - 1.8 $M_{\odot}$.*

Stellar Mass, M.	N(M)	n(HP)	n(HP)/N(M)	n(BP)	n(BP)/N(M)
0.45	19549	0	0	0	0
0.50	17141	0	0	52	0.003
0.55	15446	0	0	308	0.020
0.60	13609	0	0	792	0.058
0.65	11998	0	0	1389	0.116
0.70	10517	0	0	1792	0.170
0.75	9151	0	0	2304	0.252
0.80	8514	51	0.006	2900	0.341
0.85	7556	295	0.039	2876	0.381
0.90	6819	302	0.044	2611	0.383
0.95	5998	316	0.053	2379	0.397
1.00	5487	280	0.051	2065	0.376
1.05	4146	255	0.061	1778	0.429
1.10	3177	245	0.078	1416	0.446
1.15	2447	191	0.078	1022	0.418
1.20	1901	132	0.069	706	0.371
1.25	1476	116	0.079	452	0.306
1.30	1250	74	0.059	321	0.257
1.35	912	54	0.059	244	0.268
1.40	772	34	0.044	147	0.190
1.45	649	30	0.046	105	0.162
1.50	500	13	0.026	77	0.154
1.55	456	13	0.028	61	0.134
1.60	323	8	0.025	33	0.102
1.65	276	6	0.022	22	0.080
1.70	257	3	0.011	15	0.058
1.75	222	0	0	5	0.023
1.80	177	1	0.005	3	0.017

Summary: n(BP)/N = 0.026 d(BP) = 14 LY
n(HP)/N = 0.002 d(HP) = 31 LY

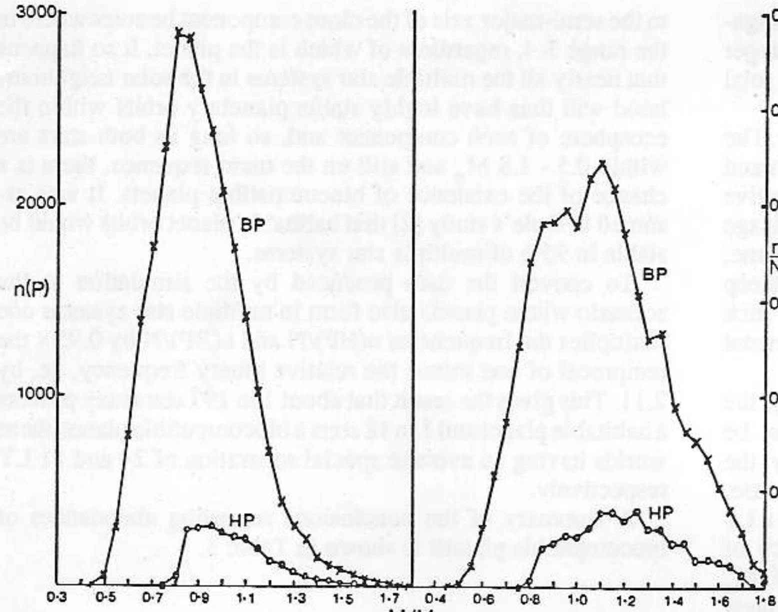

Fig. 5 Plot of data from Table 2.
a) The number of BPs and HPs produced about stars of mass M.
b) The frequency of BPs and HPs.

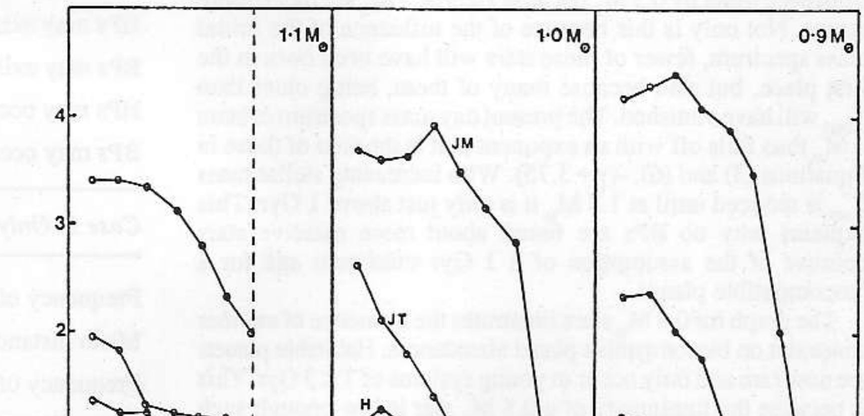

Fig. 6 Biocompatible planetary abundance data for stars of 0.6 - 1.1 M$_\odot$. JM= Juvenile Martian, JT = Juvenile Terran, H = Habitable.

concentrated about stars of 0.85 - 1.05 M$_\odot$. The peak HP frequency is however ~ 8% about stars of 1.25 M$_\odot$. Biocompatible planets may be found over the stellar mass range 0.5 - 1.8M$_\odot$, with about 60% of them occurring about stars in the range 0.75 - 1.0 M$_\odot$. The peak BP frequency is ~ 45% about stars of 1.1 M$_\odot$.

These data can be explained by considering how HP and BP abundances vary with the mass and age of the primary star.

Figure 6, from Ref. [14], shows the results of such an investigation. For stars between 0.6 - 1.1 $M_\odot$, 1000 runs for each integer Gyr between 1 Gyr and T_{MS} were performed and the total number of BPs of each type plotted.

The results for 0.9 and 1.0 $M_\odot$ are simple to account for. The relative abundances of Juvenile Martian, Juvenile Terran and Habitable BPs reflect the differing widths of their respective zones within the ecosphere (fig. 2). The decline in n(P) with age is caused by the decline in planetary tectonic activity with time, as modelled by Equation (14). The fall off is particularly steep after T = 6 Gyr as few terrestrial planets formed about such relatively metal poor stars are massive enough to sustain crustal recycling to the present day.

The graph for 1.1 $M_\odot$ shows that, for stars of > $M_\odot$, the decline into planetary senescence will, in many cases, be irrelevant as such a situation would be preempted by the primary star evolving off the main sequence. In this case, several hundred BPs still survive at 7 Gyr which is T_{MS} for a 1.1 $M_\odot$ star. This has the effect of increasing the frequency of biocompatible planets about M/S stars of 1.05 - 1.35 $M_\odot$ because such a star is more likely to be younger than a typical star of < $M_\odot$. However, the peaks of figs. 5a and 5b are displaced from each other by 0.3 $M_\odot$ because stars of > $M_\odot$ are much more scarce. Not only is this because of the influence of the initial mass spectrum, fewer of these stars will have been born in the first place, but also because many of them, being older than T_{MS}, will have vanished. The present day mass spectrum of stars > $M_\odot$ thus falls off with an exponent that is the sum of those in Equations (3) and (6), $-(\gamma + 3.75)$. With increasing stellar mass T_{MS} is reduced until at 1.8 $M_\odot$ it is only just above 1 Gyr. This explains why no BPs are found about more massive stars because of the assumption of a 1 Gyr minimum age for a biocompatible planet.

The graph for 0.8 $M_\odot$ stars illustrates the influence of another constraint on biocompatible planet abundances. Habitable planets are now rare and only occur in young systems of T < 3 Gyr. This is because the luminosity of a 0.8 $M_\odot$ star is low enough such that the warmer regions of the ecosphere are situated so close to the primary that any planet there is subjected to excessive stellar tidal forces which rapidly despin its rotation to a synchronous state. Since stellar luminosity is such a strong function of stellar mass ($L \alpha M^{4.75}$) and tidal forces so crucially dependent on distance (tides $\alpha R^{-3}M$), the tidal force on a planet within the ecosphere of a given star is roughly proportional to M^{-6}. The data for stars of 0.7 $M_\odot$ reveals that a drop of a mere 0.1 $M_\odot$ rules out the existence of habitable planets and all but the very youngest juvenile terran planets. However, planets of the juvenile Martian type remain sufficiently distant from the primary to be unaffected by tides over the timescale considered. A further reduction to 0.6 $M_\odot$ shows that even the abundances of JM biocompatible planets are being reduced by the effects of stellar tides. At 0.45 $M_\odot$ it was found that no biocompatible planets were possible at all.

6. THE QUESTION OF MULTIPLE STAR SYSTEMS

This analysis was done on the assumption that only single stars have planets. This is valid if planets cannot form in binary or multiple star systems [24]. However, the validity of this conjecture is difficult to assess in view of the continuing uncertainty associated with the planetary formation process [25]. Planetary orbits can be dynamically stable about binary stars, either circling each component, or both components of a very close pair. Harrington [26] has estimated from three-body problem numerical integrations that the limitation for stability is that the ratio of the periastron distance of the outer tertiary component to the semi-major axis of the close component be somewhere in the range 3-4, regardless of which is the planet. It so happens that nearly all the multiple star systems in the solar neighbourhood will thus have highly stable planetary orbits within the ecosphere of each component and, so long as both stars are within 0.5 - 1.8 $M_\odot$ and still on the main sequence, there is a chance of the existence of biocompatible planets. It was assumed in Dole's study [2] that habitable planet orbits would be stable in 95% of multiple star systems.

To convert the data produced by the simulation to the scenario where planets also form in multiple star systems one multiplies the frequencies n(HP)/N and n(BP)/N by 0.95 x the reciprocal of one minus the relative binary frequency, i.e. by 2.11. This gives the result that about 1 in 197 stars may possess a habitable planet and 1 in 18 stars a biocompatible planet, these worlds having an average spacial separation of 24 and 11 LY respectively.

A summary of the conclusions regarding abundances of biocompatible planets is shown in Table 3.

TABLE 3: *Summary of Simulation Results.*

HPs may exist about stars between 0.8 - 1.8 $M_\odot$.
BPs may exist about stars between 0.5 - 1.8 $M_\odot$.
HPs may occur about > 3% of stars between 0.85 - 1.45 $M_\odot$.
BPs may occur about > 30% of stars between 0.8 - 1.25 $M_\odot$.
Case 1: Only Single Stars Possess Planets.
Frequency of Habitable Planets 1 HP/ 413 stars.
Mean distance between Habitable Planets ~ 31 LY.
Frequency of Biocompatible Planets 1 BP / 39 stars.
Mean distance between Biocompatible Planets ~ 14 LY.
Case 2: Planets Can Form in Multiple Star Systems.
Frequency of Habitable Planets 1 HP / 196 stars.
Mean distance between Habitable Planets ~ 24 LY.
Frequency of Biocompatible Planets 1 BP / 18 stars.
Mean distance between Biocompatible Planets ~ 11 LY.

7. THE SOLAR NEIGHBOURHOOD

Combining data on nearby stars with the results of the model permits the identification of stars which may possess biocompatible planets and which are candidates in the search for extraterrestrial life. Qualifying stars within 22 LY from the Sun are listed in Table 4 along with their spectral types and estimated masses. Parameters are taken from [27] or, when not included in this reference from [2]. The probability of the existence of a habitable planet P_{HP} = n(HP)/N(M) and a biocompatible planet P_{BP} = n(BP)/N(M) are also tabulated with an asterisk denoting that the value listed only applies on the assumption that planets exist within multiple star systems.

Table 4 shows that there are numerous potentially biocompatible locations within the solar neighbourhood. The stars ε Eridani, ε Indi, τ Ceti, σ Draconis, δ Pavonis, 82 Eridani, β

TABLE 4: *Star Systems with biocompatible potential within 22 light years.*

Star	Distance	Spectral Type	Mass/Solar Units	P_{HP} (%)	P_{BP}
α Centauri A	4.38	G2V	1.1	7.8*	44*
α Centauri B	4.38	K6V	0.89	4.4*	38*
ε Eridani	10.69	K2V	0.8	0.6	34
61 Cygni A	11.17	K5V	0.59	0	5.8*
61 Cygni B	11.17	K7V	0.50	0	0.3*
ε Indi	11.21	K5V	0.71	0	18
Lac 9352	11.69	M2	0.47	0	<0.3
τ Ceti	11.95	G8V	0.82	1.5	35
Lac 8760	12.54	M1V	0.54	0	1.5
Grm 1618	15.03	K7	0.56	0	2.5
70 Ophiuchi A	16.73	K1	0.89	4.4*	38*
70 Ophiuchi B	16.73	K6	0.68	0	16*
36 Ophiuchi A	17.73	K0V	0.77	0	28*
36 Ophiuchi B	17.73	K1V	0.76	0	27*
36 Ophiuchi C	17.73	K5V	0.63	0	9.0*
HR 7703 A	18.43	K3V	0.76	0	27*
σ Draconis	18.53	K0V	0.82	1.5	35
δ Pavonis	18.64	G5	0.98	5.1	39
η Cassiopeiae A	19.19	G0V	0.85	3.9	38*
η Cassiopeiae B	19.19	M0	0.52	0	0.7*
HD 36395	19.19	M1V	0.51	0	0.5
Wolf 294	19.41	M4	0.49	0	<0.3
+ 53° 1320 A	19.65	M0	0.52	0	0.6*
+ 53°1320 B	19.65	M0	0.51	0	0.5*
- 45° 13677	20.6	M0	0.48	0	<0.3
82 Eridani	20.9	G5	0.91	4.4	38
β Hydri	21.3	G1	1.23	7.5	35
HR 8832	21.4	K3	0.74	0	23

Notes: P_{HP} = % probability of the occurance of a habitable planet, P_{BP} = % probability of the occurance of a biocompatible planet.
Probabilities marked * only apply if planets form and have stable orbits in binary star systems.

Hydri and HR 8832, being single and > 0.7 $M_\odot$, are the best candidates, all having a >> 10% chance of possessing a biocompatible planet. All except ε Indi and HR 8832 may also be accompanied by a habitable planet, although ε Eridani is borderline, being of ~ 0.8 $M_\odot$. (A recent report [28] claiming that ε Eridani is a close binary system of semi-major axis 0.35 AU, which would rule out the existence of any biocompatible planets, is based on discredited data and is thus in error [29,30]).

All the multiple star components listed in Table 4 can have stable planetary orbits within their respective ecospheres. If planets have formed in these regions then the biocompatible potential within the solar neighbourhood is substantially increased. α Centauri, 70 Ophiuchi and 36 Ophiuchi have significant probabilities of possessing biocompatible planets about each component; 36 Ophiuchi, being triple, actually has a ~ 0.6% chance of possessing 3 BPs. The primaries of 61 Cygni, HR 7703 and η Cassiopeiae also merit serious consideration. As for the subset of habitable planets, the star the model predicts as having the highest probability of possessing such a world is α Centauri A - a sun that is right on our cosmic doorstep.

8. CONCLUSIONS

If Kasting *et al* [12] are correct in speculating that the outer ecospheric boundary lies much further from the Sun than previously supposed, then the biocompatible range of stellar mass may extend to quite low masses, ~ 0.5 $M_\odot$. Although most biocompatible planets would occur about stars of spectral type early K, through G, to late F, the entire range of main sequence stars from earliest M to late A should be considered in the search for extraterrestrial life. Biocompatible planets may thus be common throughout the Universe, the model presented here estimating one such planet per 18-39 stars of metallicity > 0.3 Z_o.

Table 5 reveals how this conclusion runs counter to previous trends. It lists estimates of the abundance of three previous studies of the prevalence of "habitable" planets. These estimates vary enormously, due partially to differing definitions of the parameter space defining a habitable planet. Dole [2], for instance, included multiple stars in his analysis, whereas Bond and Martin [31] and Pollard[32] adopted the ecosphere of Hart [4] and set out, deliberately, to come to a conservative conclusion. The present study concurs with the data in Table 5 in that it suggests that specifically Earthlike, habitable, planets are likely to be quite rare (1 in 188 - 413 stars) but contends that such planets are only a subset of a greatly more abundant set of potentially lifebearing biocompatible planets.

We may thus require another explanation for "The Great Silence" other than the lack of suitable sites for the origin of life.

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TABLE 5:

Ref	$\frac{n(HP)}{N}$	d(LY)
Dole [4]	1/200	~25
Bond & Martin [5]	1/6000 - 1/12000	80 - 100
Pollard [6]	10^{-5} - 10^{-7}	200 - 1000

Note added in proof:

Dr Schwartzman and T. Volk, *Nature*, **340**, 457-460 (1989), have shown that chemical weathering of basalt is greatly facilitated by the presence of plants and microorganisms. A geochemical carbon cycle assisted by biology would therefore act as an even more robust planetary thermostat. This effect has not been included in this paper because the probability of the origin of life is completely unknown and because the geochemical carbon cycle can operate abiotically.

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