GEOPHYSIOLOGY AND HABITABLE ZONES AROUND SUN-LIKE STARS

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Discussions of the subject of habitable zones around stars date back to the early years of the SETI research program (e.g., Dole, 1964; Shklovskii and Sagan, 1966). Hart (1978, 1979) introduced the notion of the continuously habitable zone (CHZ), the zone around a star in which an Earth-like planet could maintain habitable conditions for the evolution of complex life. He computed an inner boundary at 0.95 AU for the sun, from a model of climatic evolution; this limit is set by a runaway greenhouse at this distance from the sun (D). Kasting (1988) argued that water would be rapidly lost from Earth-like planets by photodissociation at $D \leq 0.95$ AU, in coincidental agreement with Hart, since Kasting computed runaway greenhouse conditions at $D \leq 0.85$ AU. Hart computed an outer boundary to the CHZ of 1.01 AU, limited by the onset of global glaciation. However, negative feedback controls on climate involving the cycling of carbon could significantly widen the CHZ (Schwartzman, 1981; Tang, 1982; Kasting et al., 1988; Schwartzman and Rickard, 1988a, 1988b).

If atmospheric composition some 2 billion years ago were the same as today's, the Earth's oceans would have been frozen because of lower solar luminosity. This is known as the "faint young sun paradox" (Sagan and Mullen, 1972). Since the Earth has had liquid oceans for at least the last 3.5 billion years, since marine sedimentary rocks date back that far, a regulatory mechanism for surface temperature is needed, probably involving the greenhouse gas carbon dioxide. The carbonate-silicate cycle provides just such a geochemical mechanism for the stabilization of climate since the early Archean (Walker et al., 1981). This mechanism entails the chemical weathering of CaMg silicates on land (reaction with carbonic acid producing bicarbonate) and the deposition of calcium carbonate on the ocean floor (a net "sink" for atmospheric carbon dioxide), with a steady-state atmospheric carbon dioxide level being achieved by balancing the sink with the volcanic source. The atmospheric carbon dioxide level along with solar luminosity determines temperature. The heart of this climatic stabilizer is the temperature dependence of the weathering rate. This rate increases with increasing temperature; thus negative feedback is obtained, regulating global temperature.

An important question is whether the carbonate-silicate cycle would keep the Earth's surface habitable, without the presence of the biota, as Kasting et al. (1988) have argued. Precipitation of calcium carbonate would surely occur on an abiotic Earth, but what would be the weathering rate in the absence of life? Lovelock and Watson (1982) proposed that the atmospheric carbon dioxide level (and therefore surface temperature) has been regulated by biological acceleration of weathering. We have argued that the Earth would be likely uninhabitable to all but thermophilic microbes, i.e., with temperatures $\geq$ 50°C, were the Earth abiotic, because of the absence of the biotic amplification of weathering rates (Schwartzman and Volk, 1989, 1990). The biotic enhancement of weathering is apparently a factor of at least 100 times, plausibly 500 times or more, ie., the weathering sink for CO2 is $\geq$ 100 times the rate for an abiotic Earth surface at the same atmospheric CO2 level and temperature. This geophysiological (Lovelock, 1987) rather than purely geochemical regulator includes the biota as an integral part of the exogenic system. It apparently arose with the origin of life near 100°C and the initial microbial colonization of land in the early Archean.

Biotic acceleration of chemical weathering arises mainly out of soil stabilization insuring a high surface area/land area for reaction of silicates with carbonic acid. Other biotic effects contributing to higher weathering rates include carbon dioxide elevation in soils and organic acid production. Before higher plants, microbes alone apparently stabilized soil (a modern analogue is cryptogamic soil, now largely restricted to desert areas where algae and lichens face little competition from higher plants). In spite of some 2 billion years of evolution, apparently, eucaryotes cannot survive at temperatures higher than 50-60°C, because of the thermolability of their proteins and cellular membranes. Thus, we take 2 billion years and 50°C to be the minimum time and maximum temperature, respectively, required for habitability of Earth-like planets around sun-like stars leading to human-like intelligence, with another 2 billion years required to evolve eucaryotes from a procaryotic ancestor.

Following the criteria argued above, we calculate the inner boundary of the habitable zone with the potential for the emergence of human-like intelligence for an abiotic Earth surface , given the probable biotic enhancements of weathering and geologic limits on degassing rates of carbon dioxide and continental growth (land area) as functions of time. These calculations incorporate the inferred variation of solar luminosity over geologic time (Gough, 1981). We do not consider effects of variation of planetary mass, composition, eccentricity etc. (see Dole, 1964); this is a strictly Earth model with variable D, the distance of Earth to the sun (in AU).

(1) $Te = 255/\{(D^{0.5})\ (1 + 0.087\ t)^{0.25}\}$,

where Te is the effective radiating temperature of the Earth (°K) (no greenhouse effect) and t is time in billion of years before present.

Equation (1) was derived from expressions for the variation of solar luminosity with time and Te as a function of L (see Kasting, 1987):

$L(t)/Lo = 1/\{1 + 0.4\ (t/4.6)\}$,

where Lo is the present solar luminosity.

$Te^4 = (S/4\ \sigma)\ (1 - A)$,

where A is the global albedo (assumed = 0.3), σ = Stefan-Boltzman constant and S is the amount of sunlight reaching Earth.

$S \propto L$, $S \propto 1/D^2$, hence $Te \propto 1/D^{0.5}$.

Using the greenhouse function, slightly modified, from Walker et al (1981):

(2) $Ts = 2\ Te + 4.6\ (P)^{0.364} - 226.4,$

where Ts is surface temperature of Earth, P is the ratio of atmospheric carbon dioxide pressure at time t ("pCO_2") to pCO_2now.

On present Earth the chemical weathering rate (carbon sink) Bo, biotically-enhanced, equals the hypothetical abiotic rate, Babiotic, multiplied by factors which constitute the biotic enhancement factor (in { }):

$Bo = Babiotic\ \{P^{\alpha}\ e^{(\beta \Delta T)}\ e^{(\gamma \Delta T)}\},$

where α, β and γ are factors expressing the dependence of silicate weathering rate on pCO_2, temperature and runoff respectively, with $\alpha = 0.4$, $\beta = 0.056$ and $\gamma = 0.017$; ΔT is the temperature elevation required for an abiotic condition over the present global mean, taken as 288°K ($\Delta T = Ts - Tnow$).

The elevation of atmospheric pCO_2 and resultant temperature increase under abiotic conditions is simply the result of requiring atmospheric pCO_2 to "do all the work" in generating a weathering rate which balances the volcanic emission rate (Schwartzman and Volk, 1989). We define B as the biotic enhancement factor:

$B = Bo/Babiotic$

For an abiotic Earth surface of age t:

$Bo\ (V/Vo) = Babiotic\ \{P^{\alpha}\ e^{(\beta \Delta T)}\ e^{(\gamma \Delta T)}\}\ (A/Ao),$

where V is the volcanic CO_2 emission rate (Vo the present rate), A the continental land area (Ao the present area).

Rewriting:

(3) $B = (A/Ao)(Vo/V)\ \{P^{\alpha}\ e^{(\beta \Delta T)}\ e^{(\gamma \Delta T)}\}$

Note that $e^{(\gamma \Delta T)} \leq 2$ (Pollack et al, 1987).

Thus for given values of D, B, A/Ao, V/Vo and t, P and Ts can be computed using equations (1), (2), and (3). For V as a function of time:

$V = Vo\ e^{(\omega t)};$

V parallels the decrease in radioactive heat generation in the Earth to present.

We assume a relation between the rate of continental growth and volcanic outgassing:

$$(dA/dt)t = -c(dV/dt)t,$$

$$\text{giving } (A/Ao) = (1 + cVo) - cVo\, e^{(\omega t)}$$

We constrain (V/Vo)(Ao/A) at t = 3.8 b.y. for two extreme limiting models (models a and c) and a preferred model (b):

Model	(V/Vo)(Ao/A) at t = 3.8 b.y.	cVo	ω
a	1 x 1 = 1	-	0
b	3 x 4 = 12	0.375	0.289
c	8 x 10 = 80	0.129	0.547

These models are consistent with limits derived from isotopic modeling of the evolution of the Earth's crust and mantle (Allegre and Jaupart, 1985; Armstrong, 1981; Des Marais, 1985). The parameters for the preferred model (b) are considered the most likely.

Model calculations are shown in Figures 1-7. Figure 1 shows Ts as a function of t for 3 values of B (D=1); note that for models (b) and (c) Ts decreases to present (except for B $\leq$ 5, t < 2 b.y.) in spite of increasing solar luminosity; increasing land area and decreasing volcanic emissions compensate forcing steady state Ts down. Ts for model (a) simply tracks solar luminosity since A and V are constant for this model. Dcritical is the minimum D for Ts = 50°C at t = 2 b.y. and Ts < 50°C from 2 billion years ago to now; for limiting model (a), Ts is a few degrees lower than 50°C at 2 b.y., and 50°C at present for Dcritical (Figures 2 and 3; Figure 3 shows a blowup of data from Figure 2). Figures 4, 5, 6 and 7 show the variation of Ts as a function of D for different B and t values (model (b) only). Figure 4 illustrates the effect of B variation at t = 0, Figure 5 at t = 2 b.y.. The patterns of variation shown in Figures 6 and 7 are the result of the competing effects of increasing solar luminosity, decreasing volcanic emissions and increasing land area to present.

We conclude that the inner boundary (Dcritical) of the habitable zone with potential for the emergence of human-like intelligence for an Earth surface governed by the purely geochemical climatic stabilizer (ie., abiotic) to be significantly greater than 1 AU, given the probable biotic enhancements of weathering and the most likely histories of volcanic outgassing and continental growth. For biotic enhancements greater than 200, Dcritical is > 1.4 AU, for enhancements of 500, Dcritical is > 3.8 AU, for the preferred model. Even for the extreme limiting model with constant outgassing and land area since 3.8 billion years ago, Dcritical is > 1.1 AU for biotic enhancements greater than 200.

Eucaryotes might have emerged even earlier than 2 b.y. ago; a Giardia-like protist may have appeared more than 3 b.y. ago, leaving no fossil record (Sogin, 1989). If so, Dcritical values would be pushed up even further for B $\geq$ 50, because of longer required durations with Ts $\leq$ 50°C (Figure 8 illustrates the effect of changing the age of origin of eucaryotes, "tcritical", on Dcritical for model (b)).

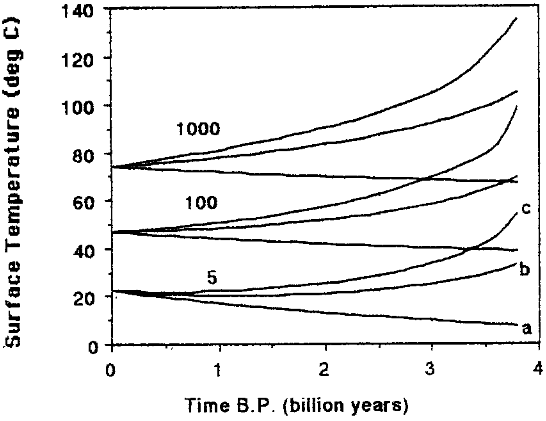

Figure 1. Computed surface temperature versus time for an abiotic Earth; models (a), (b) and (c) (described in text) for different assummed biotic enhancement of weathering factors (B), namely 5, 100, 1000. For B = 100 and 1000, the position of models (a), (b) and (c) is analogous to that for B = 5.

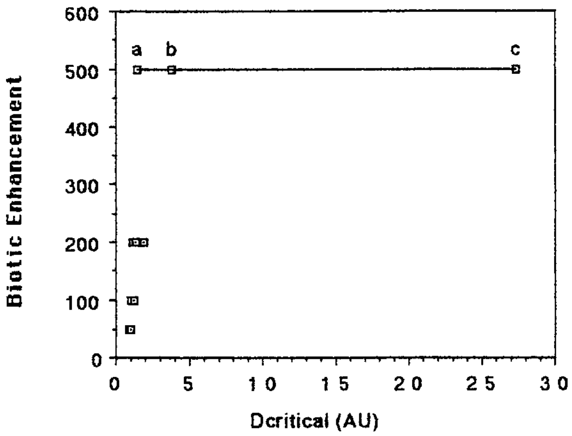

Figure 2. Biotic enhancement versus the minimum distance from Sun for surface temperature to have been less than 50°C for the last 2 billion years (Dcritical) for an abiotic Earth; models (a), (b) and (c) indicated.

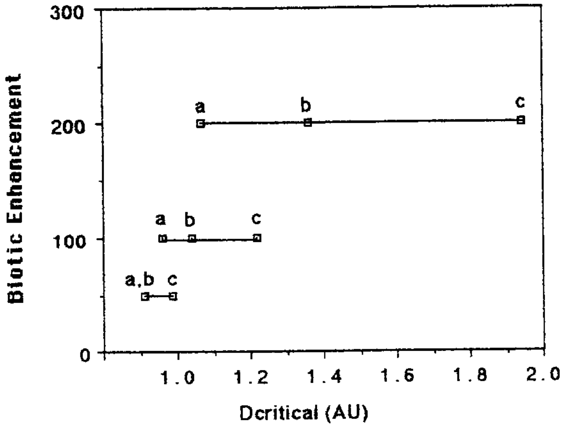

Figure 3. Biotic enhancement versus Dcritical; blowup of points from Figure 2 for B = 50, 100, 200.

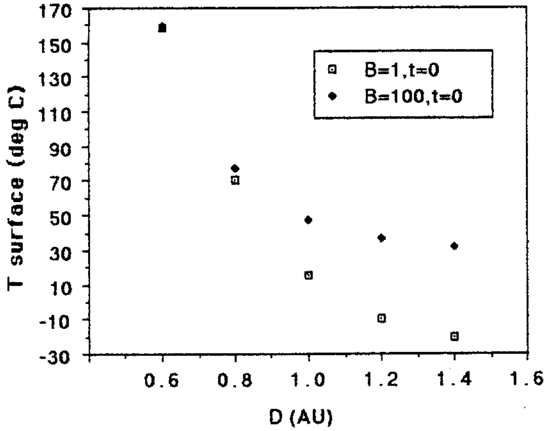

Figure 4. Surface temperature (Tsurface) versus distance from sun (D) for an abiotic Earth, B = 1, 100 at present (t=0); model (b) results only.

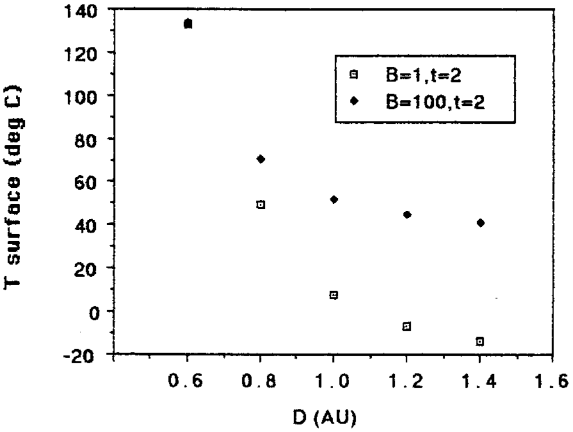

Figure 5. Tsurface versus D for an abiotic Earth, B = 1, 100, for 2 billion years ago (t = 2); model (b) results only.

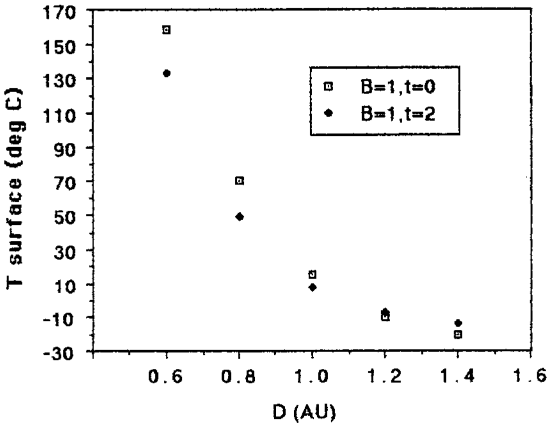

Figure 6. Tsurface versus D for an abiotic Earth, B = 1, for t = 0, 2; model (b) results only.

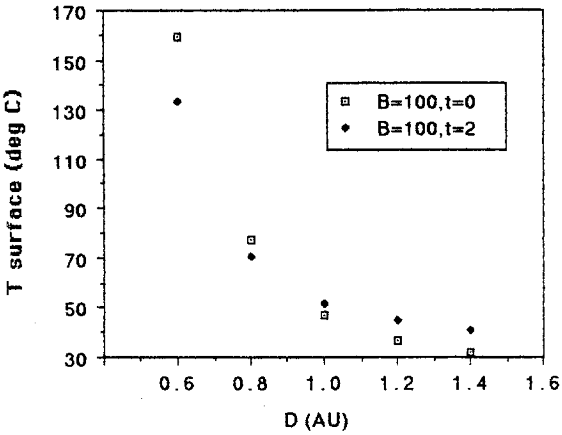

Figure 7. T surface versus D for an abiotic Earth, B = 100, for t = 0, 2; model (b) results only.

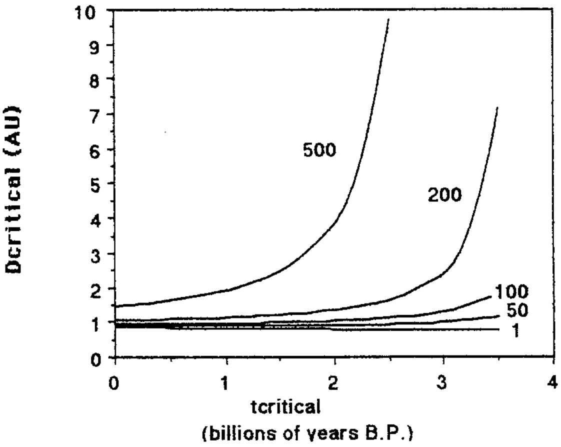

Figure 8. Dcritical versus time required for surface temperature to have been less than 50°C for the last (t) billion years (tcritical), with (t) assummed to be the time of origin of eucaryotes, for an abiotic Earth, B=1, 50, 100, 200 and 500; model (b) results only.

In summary, were it not for the biota's crucial participation in the geochemical climatic regulation of surface temperature, the Earth at 1 AU up to perhaps > 3.8 AU would not have evolved eucaryotes, including of course intelligent life. Since the outer boundary for the formation of terrestrial planets is on the order of 1.5 AU, intelligent life might well be absent altogether were it not for the emergence of the geophysiological mechanism outlined. Exogenic systems with similar geophysiologies to Earth (alien biospheres) should likewise emerge on terrestrial-like planets around sun-like stars, increasing the frequency of intelligent life in the galaxy.

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Discussion

G. MARX: Is your model detailed enough to give an answer to the question: how stable the present climate (temperature) is to sustain developed life?

D. SCHWARTZMAN: We have calculated, as Lovelock had earlier, the time in the future when the habitability limit (for eucaryotes, i.e., T > 50°C) is reached because of increasing solar luminosity. Assuming the same biotic enhancement of weathering as now, the limits will be reached 3.2 billion years from now, not taking into account other effects. However, conditions are likely to become very unpleasant in only 1 billion years from now with the loss of the surface water of the Earth by photodissociation (Kasting, 1988).