The life span of the biosphere revisited

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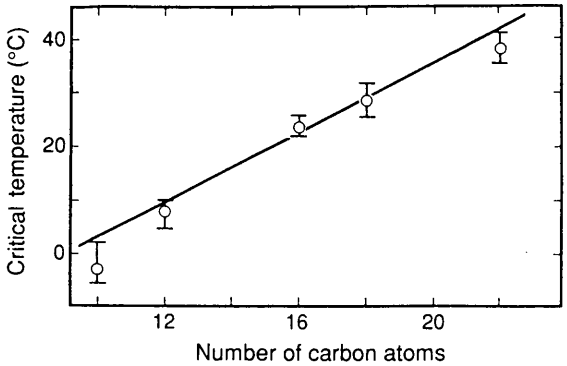

FIG. 4 Threshold temperature T_c for optimum grafting against the chain length *n* of the *n*-alkyltrichlorosilane. A linear variation of T_c is observed with a slope of ~3.5 °C per additional methylene group.

above or below a characteristic temperature T_0, the 'triple point'[13]. This temperature varies linearly with the alkyl chain length[14], and it is striking that values published for fatty acids fall in the region as in the present experiments. If such an interpretation turns out to be correct, it would suggest that a lateral rearrangement occurs within the monolayer, following physisorption onto the substrate, and preceding chemical grafting. ☐

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The life span of the biosphere revisited

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A DECADE ago, Lovelock and Whitfield[1] raised the question of how much longer the biosphere can survive on Earth. They pointed out that, despite the current fossil-fuel induced increase in the atmospheric CO_2 concentration, the long-term trend should be in the opposite direction: as increased solar luminosity warms the Earth, silicate rocks should weather more readily, causing atmospheric CO_2 to decrease. In their model[1], atmospheric CO_2 falls below the critical level for C3 photosynthesis, 150 parts per million (p.p.m.), in only 100 Myr, and this is assumed to mark the demise of the biosphere as a whole. Here, we re-examine this problem using a more elaborate model that includes a more accurate treatment of the greenhouse effect of CO_2 (refs 2–4), a biologically mediated weathering parameterization, and the realization that C4 photosynthesis can persist to much lower concentrations of atmospheric CO_2(<10 p.p.m.)[5,6]. We find that a C4-plant-based biosphere could survive for at least another 0.9 Gyr to 1.5 Gyr after the present time, depending respectively on whether CO_2 or temperature is the limiting factor. Within an additional 1 Gyr, Earth may lose its water to space, thereby following the path of its sister planet, Venus.

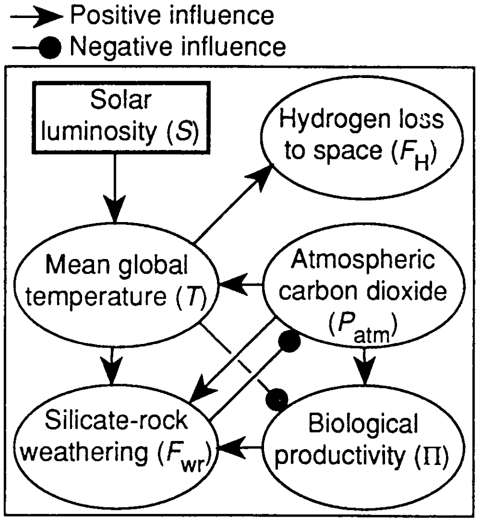

FIG. 1 Diagram illustrating the positive and negative influences represented in our model. System behaviour may be understood by examining the response to an increase in solar luminosity (*S*). Increasing *S* warms the Earth, increasing *T*. This enhances both the weatherability of silicate rocks (F_{wr}) and the rate of hydrogen escape to space (F_H). At temperatures approaching 50 °C, temperature increases have a negative influence on biological productivity (Π). Enhanced silicate-rock weatherability draws down the atmospheric CO_2 concentration (P_{atm}). The lower CO_2 concentration tends to buffer *T* and F_{wr} and to reduce Π. Eventually, either lack of CO_2, high temperatures, or the loss of water will limit the life span of the biosphere.

The problem of the life span of the biosphere has implications not only for the future of our planet, but also for the probability of finding biologically active planets in our galactic neighbourhood. As the Sun converts hydrogen to helium, its core becomes denser and hotter, increasing the rate of thermonuclear fusion; hence, standard solar models predict that the Sun has been getting more luminous with time[7-9]. As solar luminosity increases, silicate rocks should weather more easily, thereby drawing down CO_2 from the Earth's atmosphere. This feedback mechanism should tend to buffer the Earth's temperature near its present value, both in the future and in the past[10]. Eventually, the CO_2 concentration may become so low that the megaflora existing at present will not be able to engage profitably in photosynthesis, effectively cutting off the carbon supply for the biosphere[1]. Vanishingly low CO_2 concentrations would preclude further CO_2-modulated thermal buffering. The Earth would then warm more rapidly, and much of the remaining biota might be pressed against thermal barriers to their survival. Ultimately, as the Sun continues to grow brighter, the Earth's surface water will be lost through photodissociation and escape of hydrogen to space. The loss of surface water would bring an indisputable end to the lifetime of the biosphere.

We developed a computer model (see Box 1 and Fig. 1) to analyse the situation described above. Because our model maximizes both the greenhouse effect and stratospheric water loss, and because we have estimated temperature and carbon requirements for the biosphere conservatively, our model should produce a minimum estimate for the biosphere's life span. We assume that future CO_2 emissions from volcanic and mid-ocean-ridge sources will continue at roughly the present rate, although there is some possibility that these rates will increase in the future[11]. Thus, as long as most of the calcium and magnesium

BOX 1 Model description

Our computer model couples solar luminosity (S), the silicate-rock weathering rate (F_{wr}), and the global energy balance, to estimate the partial pressure of atmospheric carbon dioxide (P_{atm}), and biological productivity (Π) as a function of time (t) into the future.

The luminosity (S) of the Sun on the main sequence as measured at the Earth was calculated for this work by A. I. Boothroyd (personal communication) using a standard solar model[9] with updated physical constants and ^{7}Be(e$^-$, ν)^{7}Li reaction rate. A curve fit to these model results yields

$$S(t)=(1-0.38t/\tau_0)^{-1}S_0 \tag{1}$$

with a mean error $<0.6\%$ for the interval $-4.5\ \text{Gyr} < t < 4.77\ \text{Gyr}$. Here t is time expressed as years from the present, $\tau_0=4.55$ Gyr, and the subscript 0 refers to present-day values ($S_0=1{,}368\ \text{W m}^{-2}$). An energy balance may be written for the Earth by setting incoming shortwave radiation equal to the outgoing longwave radiation

$$(1-a)S/4=\sigma T_{eff}^4 \tag{2}$$

where a is the planetary albedo, σ is the Stefan-Boltzmann constant, and T_{eff} is the effective black-body radiation temperature of the Earth. T may be related to T_{eff} by the expression

$$T=T_{eff}+\Delta T \tag{3}$$

The greenhouse warming factor (ΔT) is a function of T (in K) and $\psi=\log P_{atm}$ (in bars):

$$\Delta T=815.17+(4.895\times10^7)T^{-2}-(3.9787\times10^5)T^{-1}$$
$$-6.7084\psi^{-2}+73.221\psi^{-1}-30{,}882T^{-1}\psi^{-1} \tag{4}$$

The planetary albedo (a) is a function of T

$$a=1.4891-0.0065979T+(8.567\times10^{-6})T^2 \tag{5}$$

Equations (4) and (5) were developed using least-square fits to the results of 143 runs of a radiative-convective climate model[2-4] with $0\ °\text{C} \leq T \leq 100\ °\text{C}$ and $10^{-8}\ \text{bar} \leq P_{atm} \leq 10^{-2}$ bar; the mean errors were <0.5 K and <0.01 for equations (4) and (5), respectively. This radiative-convective climate model[2-4] has an H_2O-saturated troposphere, producing maximum infrared trapping and maximum stratospheric water loss. Hence, this model should generate lower bounds on the potential life span of the biosphere. Because it is not known how clouds will respond to surface temperature changes, the effect of clouds on shortwave radiation forcing ($14\ \text{W m}^{-2}$) and planetary albedo were held constant. We consider this to be a conservative assumption because, for large perturbations, clouds would probably act to stabilize Earth's temperature[16].

The activity of H^+ in fresh soil water (a_{H^+}) can be calculated assuming equilibration of rain water with the soil CO_2 concentration (P_{soil}) and the atmospheric SO_2 concentration (0.2 p.p.b.). Equilibrium constants and relations for the carbon and sulphur systems may be found in refs 14 and 23, respectively. Experimental results in the acid pH range at 25 °C with low CO_2 concentrations indicate that silicate dissolution rates are typically proportional to the hydrogen-ion activity to roughly the 0.5 power[24,25]. Hence, incorporating the temperature dependency proposed by Walker *et al.*[10], the silicate-rock weathering rate (F_{wr}), may be represented

$$\frac{F_{wr}}{F_{wr,0}}=\left(\frac{a_{H^+}}{a_{H^+,0}}\right)^{0.5}\exp\left(\frac{T-T_0}{13.7\ \text{K}}\right) \tag{6}$$

The exponent in equation (6) is in good agreement with the original formulation of Walker *et al.*[10] (with an implied exponent of 0.6), developed using experimental results[26,27] obtained at 100 to 200 °C and 2 to 20 bars CO_2.

Volk[28] parameterized P_{soil} as a function of Π and P_{atm}

$$\frac{P_{soil}}{P_{soil,0}}=\frac{\Pi}{\Pi_0}\left(1-\frac{P_{atm,0}}{P_{soil,0}}\right)+\frac{P_{atm}}{P_{soil,0}} \tag{7}$$

We extended Volk's[28] representation of Π by including a multiplicative, temperature-dependent term that produces maximum productivity when T is 25 °C and zero productivity when T reaches 50 °C

$$\frac{\Pi}{\Pi_{max}}=\left(1-\left(\frac{T-25\ °\text{C}}{25\ °\text{C}}\right)^2\right)\left(\frac{P_{atm}-P_{min}}{P_{1/2}+(P_{atm}-P_{min})}\right) \tag{8}$$

A maximum possible biological productivity (Π_{max}) equal to twice the present productivity (Π_0) was deemed by Volk[28] to be the most defensible value, and is adopted for this study. The minimum CO_2 concentration under which C4 plants can grow (P_{min}) was conservatively estimated to be 10 p.p.m.. The value of $P_{1/2}$ is calculated by forcing equation (8) to yield $\Pi=\Pi_0$ when $T=T_0$ (=15 °C) and $P_{atm}=P_{atm,0}$ (=320 p.p.m.). Following Volk[28], we use $P_{soil,0}=10\ P_{atm,0}$, as a representative soil $pCO_2(P_{soil})$.

The model is solved by setting $F_{wr}=F_{wr,0}$ until $P_{atm}=1$ p.p.m.; thereafter, P_{atm} is maintained at this value.

released in the weathering process accumulates in carbonate sediments, future weathering rates should be roughly the same as today's.

A principal difference between our model and that of Lovelock and Whitfield[1] is that our climate model is much more sensitive to CO_2 decreases below the present level of 350 p.p.m. Their proposed constant temperature relation between the atmospheric CO_2 partial pressure (P_{atm}) and solar luminosity (S) ($P_{atm}{}^{0.5} \propto 1.017\ S_0-S$) implies that the infrared trapping by 320 p.p.m. CO_2 is only $\sim4\ \text{W m}^{-2}$. We calculate however, that the actual amount of infrared trapping by this concentration of CO_2 is $20.4\ \text{W m}^{-2}$, using a radiative-convective model[2-4] at 15 °C with relative humidity as specified by Manabe and Wetherald[12]. This is about six times the radiative forcing ($3.4\ \text{W m}^{-2}$) that would result from a CO_2 doubling in this model. (The absorption of infrared radiation increases roughly logarithmically with the CO_2 concentration because the strongest absorption bands, for example the 15-μm band, are already saturated near their centres.) If S increases with time according to equation (1) ($\sim0.12\ \text{W m}^{-2}\ \text{Myr}^{-1}$), then reductions in atmospheric CO_2 concentration could maintain a constant temperature for the next 0.9 Gyr. If we use the critical value for photosynthesis suggested by Lovelock and Whitfield ($P_{min}=150$ p.p.m.), our model calculates that 0.5 Gyr of the biosphere's life span remains, five times the Lovelock and Whitfield estimate. But, Lovelock and Whitfield ignored C4 plants, some of which can survive at CO_2 concentrations below 10 p.p.m. (refs 5 and 6). Using this criterion ($P_{min}=10$ p.p.m.), our model calculates that the remaining life span of the biosphere is 0.9 Gyr (Fig. 2).

There is reason to suspect that CO_2 starvation may not limit the life span of the biosphere. As solar luminosity continues to increase, atmospheric CO_2 should continue to be drawn down; however, it may reach a minimum at which some C4 plants could survive. Equation (6) indicates that when the global mean temperature is above 300 K, silicate dissolution may proceed more rapidly than CO_2 and H_2SO_4 are supplied to the atmosphere by volcanism. This would leave an excess of Ca^{2+} and Mg^{2+} cations which could not be precipitated as carbonates or sulphates. They would probably precipitate in the oceans in a variety of silicate phases. Geological carbon inputs to the ocean and atmosphere must be largely balanced by carbonate sedimentation, suggesting that the oceans will continue to be saturated with respect to some carbonate phase. If future ocean waters are roughly in chemical equilibrium with silicates and carbonates, ocean pH would be buffered close to its present value[13]. If ocean pH increases by no more than half a pH unit and the oceanic Ca^{2+} concentration changes by no more than an order of magnitude, then application of carbonate equilibria[14] indicates that atmospheric partial pressure of CO_2 (pCO_2) would be reduced no more than two orders of magnitude from today's value. Even if ocean chemistry is not this well buffered, Henry's law will partition more CO_2 into the atmosphere on a warmer Earth, so the atmosphere may still contain a few parts per million of CO_2. Some present-day C4 plants could survive at these CO_2 concentrations[5,6], and aquatic microbial-based food chains could flourish at even lower CO_2 concentrations[15].

If CO_2 starvation does not limit the life span of the nonmicrobial biosphere, high temperatures may. Even with negligible atmospheric CO_2, global mean temperatures in our model exceed 50 °C after $\sim$1.5 Gyr. Our model does not include the possible negative feedback of increasing cloud cover[16]; hence 1.5 Gyr should be considered a minimum time at which this

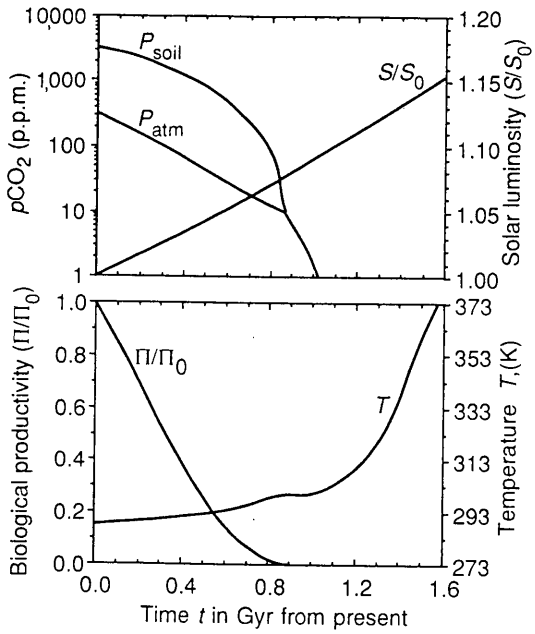

FIG. 2 Model results for the next 1.6 Gyr. The terrestrial biosphere, whose productivity (Π/Π_0) depends on an adequate supply of atmospheric CO_2, maintains a gradient between soil and atmospheric CO_2 concentrations. For ~1 Gyr, the partial pressure of soil CO_2 (P_{soil}) and Earth's mean temperature (T) covary such that silicate-rock weathering consumes CO_2 at the modern rate. T is a function of both solar luminosity (S/S_0) and the atmospheric CO_2 concentration (P_{atm}). As S/S_0 increases, P_{atm} decreases, diminishing Π/Π_0 and with it the difference between P_{soil} and P_{atm}. When P_{atm} is too low for C4 plants to survive (~0.9 Gyr), then $P_{soil}=P_{atm}$. (In a C3-only world with $P_{min}=150$ p.p.m., C3 plants survive ~0.5 Gyr.) After ~1 Gyr, silicate-rock dissolution exceeds volcanic CO_2 degassing; P_{atm} is then held at 1 p.p.m. The timescale for the loss of the oceans through hydrogen escape becomes limited by solar extreme ultraviolet when T climbs above 80 °C (~1.5 Gyr). The loss of surface water by this process would take ~1 Gyr, and could ultimately limit the life span of the biosphere to ~2.5 Gyr.

temperature would be reached. Only prokaryotes and protozoa can live much above this temperature[17]. Beyond this time, planetary warming will probably accelerate. Atmospheric water vapour content increases exponentially with surface temperature if the relative humidity remains constant. This water vapour should trap outgoing longwave radiation and decrease the planetary albedo by absorbing solar near-infrared radiation. Both processes should contribute to planetary warming. In our model, the Earth's surface temperature increases from 50 °C to 100 °C in <0.2 Gyr. Some archaebacteria might survive even higher temperatures[18,19], but all higher forms of life would certainly be eliminated by this stage.

The final sterilization of the Earth will occur when the planet loses its water. Today, the timescale for the loss of the oceans through photodissociation and hydrogen escape is much longer than the age of the Earth; as the atmosphere warms beyond 60 to 70 °C, however, the H_2O mixing ratio in the stratosphere increases markedly[20]. As surface temperatures approach ~80 °C, the stratospheric H_2O mixing ratio reaches ~2.5%. Above this mixing ratio, the loss of hydrogen to space is limited by the solar extreme ultraviolet heating rate to $\sim 6\times 10^{11}$ atoms H cm^{-2} s^{-1} (ref. 21), giving a timescale for ocean loss of ~1 Gyr. Hence, the complete elimination of water ~2.5 Gyr from now could bring terrestrial life to its final close. After Earth's water is lost, silicate-rock weathering will cease; hence, volcanic CO_2 should accumulate in the atmosphere, creating a climate much like that of Venus.

Events such as a collision with the giant comet Chiron[22] or a radical reorganization of the carbonate-silicate cycle[11] could possibly bring the life of the biosphere to an earlier close. But given the otherwise conservative assumptions that we have made in constructing our model, our results indicate that the biosphere will probably survive at least another 1 Gyr, and possibly much longer. This prediction ought to be encouraging to humans, as well, because it implies that we could survive for geologically long time periods if we can manage to cope with our other societal problems. ☐

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Electrical conductivity of carbon-bearing granulite at raised temperatures and pressures

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It has long been recognized that the electrical conductivity of the lower continental crust is anomalously high. Both pore-saturating brines[1-5] and conducting films of carbon at grain boundaries[6-10] have been proposed to explain this, but the evidence remains inconclusive. Here we report measurements of electrical conductivity at high temperatures and pressures[11-13] on samples of carbon-bearing and carbon-free granulites with a range of electrolyte saturations. The application of pressure to nominally dry carbon-free samples reduces the electrical conductivity as a result of a progressive reduction in pore connectivity, whereas the carbon-bearing samples show an increase in conductivity under the same conditions—an effect that we ascribe to reconnection of carbon conduction pathways during compaction. Moreover, we find a greater increase in conductivity with temperature for the carbon-bearing samples. In the light of work indicating that the abundance of carbon in high-grade rocks has been underestimated in the past[7,8], our results provide strong evidence for the role of carbon in lower-crustal conductivity.

Very few laboratory experiments have been done under fully simulated lower-crustal conditions to estimate the contribution of electrolytes to the *in situ* rock conductivity, and only one study, to our knowledge, examined carbon-bearing rock[14]. Here we examine carbon-bearing and carbon-free granulites under a

When climate and life finally devolve

It is traditional, as the year draws to a close, to try to predict what the future holds in store. It is less common to ask, as Caldeira and Kasting do in this issue, "how much future?".

NEW calculations by Caldeira and Kasting on page 721 of this issue[1] are about the destiny and ultimate demise of the biosphere — which is both dependent on and vulnerable to the evolution of our main-sequence star, the Sun. Their calculations provide the best estimate to date as to when the Earth's staple of abiotic and biotic processes that draw down atmospheric CO_2 will be unable to offset a rising solar flux.

Predictions of the heat death of the biosphere have traditionally come from astronomers. But ten years ago, Earth scientists Lovelock and Whitfield showed that the biota would face a crisis[2] long before our planet is scorched as the Sun expands into a red-giant phase, in about 5 billion years. The crisis will be a scarcity of atmospheric CO_2.

The trend over geological time has been for atmospheric levels of CO_2 to decrease. (Current rising levels of CO_2 from industrial and agricultural sources are, by comparison, just a blip on the geological landscape.) Driving this long-term steady decrease has been a combination of factors[3]: the growth of continents, a declining geothermal heat flux, a sequence of evolutionary developments that increase the weatherability of the terrestrial surface, and an increasingly radiant Sun, all of which alter the dynamics of the geochemical system that balances the CO_2 supplied by volcanism with its removal by global weathering. The ultimate consequences of this downward trend were spelled out by Lovelock and Whitfield: in just 100 million years, CO_2 will drop below the minimum level necessary to support photosynthesis.

Caldeira and Kasting have recalculated the life span of the biosphere, using a more refined set of biological and physical inputs. These include a precise greenhouse function, increased photosynthetic efficiencies from C4 plants at reduced CO_2 and allowance for a functional dependence of silicate weathering upon respiration from roots and soil organisms. With these modifications, Caldeira and Kasting have extended the tenure of the biosphere to ten times that predicted by Lovelock and Whitfield: we can breathe easy for about a billion more years. But finally, temperatures will soar to the upper limits tolerable to the most primitive microbes, and in another billion years again the Earth will undergo a final sterilization with the loss of the hydrogen from photolysed water to space.

Is an event so distant in time any cause for concern today? We certainly have more immediate problems during the coming century in trying to prevent our own selves from ravaging the biosphere. Nevertheless, Caldeira and Kasting's work raises issues that are hauntingly familiar: the role of CO_2 as a greenhouse gas, a possible need for planetary engineering in maintaining the Earth's habitability (or rather its comfort for humans), and fundamental questions about the ultimate persistence of life and the pace of evolution.

None of the models, of course, allows for possible evolutionary innovations that might buy time for life as we know it (or do not know it). The current plenitude of life's biochemical cycling mechanisms — within cells, organisms and ecosystems — is impressive, and has probably evolved in response to times of scarcity[4]. For example, C4 plants (such as maize) concentrate CO_2 in special bundle sheath cells, away from the sites of wasteful photorespiration; this innovation has evolved in the past 100 million years[5], probably in response to falling levels of atmospheric CO_2.

Future responses to scarcity could be technologically driven. In experiments for advanced life support, such as NASA's programme in closed ecological life-support systems, Biosphere 2 in Arizona, and the Russian Bios 3, carbon is assiduously cycled and CO_2 is managed at levels well above that of the Earth. Such research is intended to give us the rudiments of understanding that could someday lead to the propagation of mini-biospheres across the Galaxy. The future ancestral Earth — dry, burnt, and dead — would then be fondly recalled in Heinleinian space songs as that mythic place of "cool green hills".

Our descendants or descendent species would not have to run from the devolution, however — they could fight. Shades in space or mirrors on the Earth that keep out a small fraction of the elevated future solar flux would be an option. Carbonates could be heated to release CO_2, a technique proposed[6] for the industrial stewardship of the carbon cycle on a 'terraformed' Mars[7] to make up for the lack of the CO_2-generating plate tectonics that we have on Earth.

More importantly, long before the solar-induced devolution of the biosphere comes to pass, the ability of *Homo sapiens* to persist will be tested not only by our own earthly transgressions, but by impacts from asteroids and comets. An impact that could destroy civilization and wipe out a quarter of the world's population is estimated to occur about every 500,000 years[8].

Calculations of the life span of the biosphere bring to focus one additional matter of great philosophical import. If devolution-computing life forms evolved with just a billion years to spare, following a 3.5 billion year genealogy, we are presented with an intriguingly close temporal match between two essentially decoupled, developing systems. The time it takes for life and then technological intelligence to evolve is nearly identical, in the only case we know, to the window of opportunity afforded by an atmospheric resource, which is yoked, in part, to the luminosity history of a main-sequence star. That this window was open just long enough for our arrival will add impetus to the arguments used by proponents of the anthropic cosmological principle[9], who find the Universe uncannily fine-tuned.

Overall, Caldeira and Kasting's study adds to our understanding of what Lovelock calls geophysiology and NASA calls Earth-system science: the Earth as an interconnected system of life, atmosphere, hydrosphere and lithosphere, a system whose organizational properties we are still discovering. While our concerns over habitability are often for the shorter term, in exploring the interplay of life and climate over geological timescales, we forge an appreciation for where knowledge must go. **Tyler Volk**

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