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Cosmological natural selection as the explanation for the complexity of the universe

Lee Smolin[a,b,*]

[a] Perimeter Institute for Theoretical Physics, 35 King Street North, Waterloo, Ont., Canada N2J 2W9
[b] Department of Physics, University of Waterloo, Waterloo, Ont., Canada N2L 3G1

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Abstract

A critical review is given of the theory of cosmological natural selection. The successes of the theory are described, and a number of published criticisms are answered. An observational test is described which could falsify the theory.

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1. Introduction

One of the great mysteries of cosmology is why the universe is set up in such a way that complex systems can exist at all. While most of those studying complex systems have been concerned with how, given the laws of physics, life can emerge, there turns out to be a prior issue: why are the laws of physics chosen so that complex, stable structures form? Why are there stars? Why do some burn long and stably enough to allow life to begin and evolve? Why are the atoms such as carbon and oxygen necessary for life stable and plentiful?

It turns out there can only be stars and carbon chemistry if the parameters of the laws of physics take values in narrow ranges around their present values [1–4]. Were the masses and charges of the elementary particles moderately different, the universe would be nothing but hydrogen gas in thermal equilibrium. The fact that our universe

* Corresponding author. Perimeter Institute for Theoretical Physics, 35 King Street North, Waterloo, Ont., Canada N2J 2W9.

E-mail address: lsmolin@perimeterinstitute.ca (L. Smolin).

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is as structured as it apparently is, from the scales of galaxies to the existence of many stable nuclei, and hence stars and chemistry, is based on a series of apparent coincidences relating the values of the fundamental dimensionless parameters of physics and cosmology.

Thus, an important part of the mystery of why we live in a complex universe rests on understanding why the masses and coupling constants of the elementary particles take the values they do. It is then remarkable that fundamental physics has nothing to say about the choices of these parameters. Our best understanding of physics is contained in the standard model of elementary particle physics. The masses and charges of the elementary particles turn out to be free parameters in this theory, they are set by hand to agree with the measured values. Nor has any subsequent development given rise to an explanation for the choices of parameters. Hypothetical theories such as supersymmetry, string theory, quantum gravity etc., turn out to extend rather than decrease the number of free parameters of fundamental theory.

In Refs. [5–10] a theory aimed at explaining the parameters of the standard model of particle physics was introduced, which assumes the following two hypothesis about fundamental physics:

(1) Black hole singularities bounce, leading to new expanding regions of spacetime, one per each black hole.
(2) When this happens the dimensionless parameters of the standard model of low energy physics of the new region differ by a *small* random change from those in the region in which the black hole formed. Small here means with small with respect to the change that would be required to significantly change $B(p)$, the expected number of black holes produced in the classical region of spacetime produced by the bounce. Here $p \in \mathscr{P}$, the space of dimensionless parameters of the standard model.

With the exception of the *small* in (2), these are not new hypotheses, and have been discussed, for example in Refs. [11,12]. Their conjunction leads to a predictive theory, because, using standard arguments from population biology, after many iterations from a large set of random starts, the population of regions, given by a distribution $\rho(p)$, is peaked around local extrema of $B(p)$.

The argument for this is straightforward, and follows the methodology of explanation in population biology.

We let $\mathscr{P}$ be the space of dimensionless parameters, p. We can define an ensemble of universes by beginning with an initial value p^* and letting the system evolve through N generations. Let us define a function $B(p)$ on $\mathscr{P}$ that is the expected number of future singularities generated during a lifetime of a universe with parameters [1] p. We may observe that, for most p, $B(p)$ is one, but there are small regions of the parameter

[1] We may note that even if the universe is open it is very unlikely that the number of black holes produced during its lifetime is infinite. Thus, it is not necessary to make the assumption made in Ref. [5] that the universe is closed. This was pointed out by Rothman and Ellis [13] and Ellis [14].

space where $B(p)$ is very large. The present values of the parameters must be in one such region because there are apparently at least 10^{17} black holes in our universe. [2]

After N generations the ensemble then defines a probability distribution function $\rho_N(p)$ on $\mathscr{P}$. To give meaning to the postulate that the random steps in the parameter space are small, we may require that the mean size of the random steps in the parameter space is small compared to the width of the peaks in $B(p)$. It then follows from elementary statistical configurations that, for any starting point p^* there is an N_0 such that for all $N > N_0$, $\rho_N(p)$ is concentrated around local maxima of $B(p)$. This is because (from the above restriction on step size) it is overwhelmingly probable that a universe picked at random from the ensemble is the progeny of a universe that had itself many black holes. But, again, because the parameters change by *small* amounts at each almost-singularity this means that it is overwhelmingly probable that a universe picked at random from the ensemble itself has many black holes. Thus, we conclude that

- $\mathscr{S}$: *If p is changed from the present value in any direction in $\mathscr{P}$ the first significant changes in $B(p)$ encountered must be to decrease $B(p)$.*

The conjunction of (1) and (2) thus constitute a theory that if true would explain the values of the parameters of the standard model without recourse to the anthropic principle. This theory has been called, "cosmological natural selection". It should be emphasized that it is completely consistent with our knowledge of fundamental physics. [3] For example, recent work in string theory has revealed that theory has a large number of stable vacua, or phases, in which the standard model parameters differ. When string theory becomes better understood, present knowledge seems to indicate that the likely effect will be not to fix p in $\mathscr{P}$ but to replace it with a microscopic parameter m in the space $\mathscr{M}$ of string vacua. It should also be mentioned that recent work has shown that singularities do bounce when quantum effects on the dynamics of spacetime are taken into account [26–29].

In this essay I will briefly review the successes of the theory, then I will respond to various criticisms that have been made. I close with a description of one observation that would falsify the theory, thus demonstrating that cosmological natural selection is a physical theory, subject to falsification by observations.

2. Successes of the theory

Details of tests of cosmological natural selection are described in Refs. [5–10]. I will only here summarize the discussion.

[2] There are roughly 10^{10} spiral galaxies in the visible universe, each has a supernova rate of roughly one per 50 years. If 10% of these leave black holes as remnants, then after 10^{10} years one has 10^{17} black holes.

[3] Other approaches to cosmology which employ phenomena analogous to biological evolution have been proposed, including Peirce [15], Nambu [16], Wheeler [17], Davies [18], Gribbin [19], Kauffman [20], Linde [21–25], Schweber and Thirring.

The crucial conditions necessary for forming many black holes as the result of massive star formation are,

(1) There should be at least a few light stable nuclei, up to helium at least, so that gravitational collapse leads to long lived, stable stars.
(2) Carbon and oxygen nuclei should be stable, so that giant molecular clouds form and cool efficiently, giving rise to the efficient formation of stars massive enough to give rise to black holes [34–37].
(3) The number of massive stars is increased by feedback processes by which massive star formation catalyzes more massive star formation [38–51]. This is called "self-propagated star formation", and there is good evidence that it makes a significant contribution to the number of massive stars produced. This requires a separation of time scales between the time scale required for star formation and the lifetime of the massive stars. This requires, among other things, that nucleosynthesis should not proceed too far, so that the universe is dominated by long lived hydrogen burning stars.
(4) Feedback processes involved in star formation also require that supernovas should eject enough energy and material to catalyze formation of massive stars, but not so much that there are not many supernova remnants over the upper mass limit for stable neutron stars [46,47].
(5) The parameters governing nuclear physics should be tuned, as much as possible consistent with the forgoing, so that the upper mass limit of neutron stars [55] is as low as possible.

The study of conditions (1)–(4) leads to the conclusion that the number of black holes produced in galaxies will be decreased by any of the following changes in the low energy parameters [5–10].

- A reversal of the sign of $\Delta m = m_{neutron} - m_{proton}$.
- A small increase in Δm (compared to $m_{neutron}$ will destabilize helium and carbon.
- An increase in $m_{electron}$ of order $m_{electron}$ itself, will destabilize helium and carbon.
- An increase in $m_{neutrino}$ of order $m_{electron}$ itself, will destabilize helium and carbon.
- A small increase in α will destabilize all nuclei.
- A small decrease in α_{strong}, the strong coupling constant, will destabilize all nuclei.
- An increase *or* decrease in G_{Fermi} of order unity will decrease the energy output of supernovas. One sign will lead to a universe dominated by helium.

Thus, the hypothesis of cosmological natural selection explains the values of all the parameters that determine low energy physics and chemistry: the masses of the proton, neutron, electron and neutrino and the strengths of the strong, weak and electromagnetic interactions.

However, explanation is different from prediction. These cannot be considered independent predictions of the theory, because the existence of carbon and oxygen, plus long lived stars, are also conditions of our own existence. Hence, selection effects prevent us from claiming these as unique predictions of the theory of cosmological natural selection.

If the theory is to make falsifiable tests, it must involve changes of parameters that do not effect the conditions necessary for our own existence. There are such tests, one of them, having to do with the fifth condition, will be described shortly.

Before discussing it, however, we should address several criticisms that have been made.

3. Answers to criticisms

Several arguments were made that $\mathscr{S}$ is in fact contradicted by present observation [13,14,30,31]. These were found to depend either on confusions about the hypothesis itself or on too simple assumptions about star formation. For example, it was argued in Refs. [13,14] that star formation would proceed to more massive stars were the universe to consist only of neutrons, because there would be no nuclear processes to impede direct collapse to black holes. This kind of argument ignores the fact that the formation of stars massive enough to become black holes requires efficient cooling of giant molecular clouds. The cooling processes that appear to be dominant require carbon and oxygen, both for formation of CO, whose vibrational modes are the most efficient mechanism of cooling, and because dust grains, consisting of carbon and ice provide efficient shielding of star forming regions from starlight. But even processes cooling molecular clouds to 5–20 K are not enough, formation of massive stars appears to require that the cores of the cold clouds are disturbed by shock waves, which come from ionized regions around other massive stars and supernova. For these reasons, our universe appears to produce many more black holes than would a universe consisting of just neutrons. [4]

Vilenkin [33] raised the following issue concerning the cosmological constant, Λ. He notes that were Λ (or vacuum energy) raised from the present value, galaxy formation would not have taken place at all. one can also add that even at slightly smaller values, galaxy formation would have been cut off, leading only to small galaxies, unable to sustain the process of self-propagated star formation that is apparently necessary for copious formation of massive stars. This of course counts as a success of the theory.

On the other hand, were Λ smaller than its present value, there might be somewhat increased massive star formation, due to the fact that at the present time the large spiral galaxies are continuing to accrete matter through several processes. These include the accretion of intergalactic gas onto the disks of galaxies and the possible flow of gas from large gaseous disks that the visible spiral galaxies may be embedded in. It is of course difficult to estimate exactly how much the mass of spiral galaxies would be increased by this process, but Vilenkin [33] as much as 10–20%.

However, lowering the cosmological constant would also increase the number of mergers of spiral galaxies with dwarf galaxies and other spiral galaxies. These mergers

[4] For details, see the Appendix of [10], which addresses the objections published in Refs. [13,14,31] and elsewhere.

are believed to convert spiral galaxies to elliptical galaxies, by destroying the stellar disk and heating the gas. The result is to cut off the formation of massive stars, leaving much gas not converted to stars.

There is then a competition between two effects. Raise Λ and galaxies do not form, or do not grow large enough to support disks and hence massive star formation. Decrease Λ and the dominant effect may be to cut of massive star formation, due to increased mergers and absorptions converting spiral to elliptical galaxies. One can conjecture that the present value of Λ maximizes the formation of black holes.

4. Why a single heavy neutron star would refute $\mathcal{S}$

One objection that has been made to the hypothesis of cosmological natural selection is that $\mathcal{S}$ is not testable [31,32]. I will show now that $\mathcal{S}$ is in fact falsifiable, by showing that a possible observation would refute it. This has to do with the dependence of the upper mass limit of neutron stars on the mass of the strange quark.

Bethe and Brown, in Refs. [52–54] introduced the hypothesis that neutron star cores contain a condensate of K^- mesons. For the present purposes their work can be expressed in the following way. Calculations show [52–54] that there is a critical value μ_c for the strange quark mass μ such that if $\mu < \mu_c$ then neutron star cores consist of approximately equal numbers of protons and neutrons with the charge balanced by a condensate of K^- mesons. The reason is that in nuclear matter the effective mass of the K^- is renormalized downward by an amount depending on the density ρ. Given a choice of the strange quark mass, μ, let $\rho_0(\mu)$ be the density where the renormalized Kaon mass is less than the electron mass. At this density, electrons decay to kaons. This will happen as the star collapses, so long as this density is reached before the density at which electrons react with protons to form neutrons. Thus, there is a critical value of the strange quark mass, μ_c such that, for all smaller masses, decay of electrons to kaons wins over conversion of protons to neutrons. In either case one neutrino per electron is produced, leading to a supernova.

Bethe, Brown and collaborators claim that calculations show that $\mu < \mu_c$ [52–54]. But their calculations involve approximations such as chiral dynamics and may be sufficiently inaccurate that in fact $\mu_c > \mu$. However, we can be reasonably sure of the existence of such a critical value μ_c. Then we may reason as follows. If $\mu < \mu_c$ then, as shown by calculations [52–54] the upper mass limit is low, approximately $1.5M_\circ$. If $\mu > \mu_c$ neutron stars have the conventional equations of state and the upper mass limit is higher, almost certainly above 2 [55]. Therefore a single observation of a neutron star whose mass M was sufficiently high would show that $\mu > \mu_c$, refuting Bethe and Brown's claim for the opposite. Sufficiently high is certainly $2.5M_\circ$, although if one is completely confident of Bethe and Brown's upper limit of 1.5 solar masses, any value higher than this would be troubling. Furthermore, this would refute $\mathcal{S}$ because it would then be the case that a decrease of μ would lead to a world with a lower upper mass limit for neutron stars, and therefore more black holes.

Presently all well measured neutron star masses are from binary pulsar data and are all below $1.5M_\circ$ [56,57]. [5] But an observation of a heavy neutron star may be made at any time.

We may note that this argument is independent of any issue of selection effects associated with "anthropic reasoning", because the value of the strange quark mass μ may be varied within a large range before it produces a significant effect on the chemistry. [6]

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[5] Other methods yield less precise estimates [58].

[6] Skeptics might reply that were $\mathscr{S}$ so refuted it could be modified to a new $\mathscr{S}'$, which was not refuted by the addition of the hypothesis that μ is not an independent parameter and cannot be varied without also, say, changing the proton–neutron mass difference, leading to large effects in star formation. It is of course, a standard observation of philosophers of science that most scientific hypotheses can be saved from refutation by the proliferation of ad hoc hypotheses. In spite of this, science proceeds by rejecting hypotheses that are refuted in the absence of special fixes. There are occasions where such a fix is warranted. The present case would only be among them if there were a preferred fundamental theory, such as string theory, which had strong independent experimental support, in which it turned out that μ was in fact not an independent parameter, but could not be changed without altering the values of parameters that strongly affect star formation and evolution.

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