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A cyclic universe approach to fine tuning

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ABSTRACT

We present a closed bouncing universe model where the value of coupling constants is set by the dynamics of a ghost-like dilatonic scalar field. We show that adding a periodic potential for the scalar field leads to a cyclic Friedmann universe where the values of the couplings vary randomly from one cycle to the next. While the shuffling of values for the couplings happens during the bounce, within each cycle their time-dependence remains safely within present observational bounds for physically-motivated values of the model parameters. Our model presents an alternative to solutions of the fine tuning problem based on string landscape scenarios.

1. Introduction

A fundamental problem in particle physics and cosmology concerns the specification of the constants of nature, in particular the 19 free parameters of the Standard Model. It appears that these parameters are fine-tuned to allow for the formation of complex structure and eventually life [1]. While the coupling constants of our universe are not the only ones which could lead to such structures, only some subset of all possible coupling constants could do so. Possible solutions require new physics at high energies, as is the case with superstring theory [2]. For example, the Heterotic string gives rise to a four dimensional chiral gauge theory with many of the ingredients to realize the Standard Model. However, these four dimensional compactifications present a landscape of vacua and coupling constants. The dynamics of strings in the early universe were investigated in order to build models of string cosmology [3,4]. While it was the hope that string theory would univocally determine the measured couplings of the Standard Model, another approach emerged: the multiverse hypothesis [5,6].

Eternal inflation generically predicts that while inflation ended in our local Hubble radius, it continues in other regions, triggering the emergence of a plethora of causally-disconnected bubble universes. If each bubble universe is endowed with different coupling constants – as generically realized in string theory – then one can use anthropic reasoning to justify the values found within our cosmic horizon, given that we are here to ask the question. This marriage between eternal inflation and the landscape of possible perturbative string compactifications provides a resolution to the pressing question of fine tuning in modern physics. One can, however, wonder whether there are alternatives to the string landscape as a dynamical mechanism to determine the couplings of the Standard Model.

In this work, we propose a model to explain the apparent fine-tuning of coupling constants without recourse to the multiverse. We show that in a cyclic universe the fundamental constants can change pseudo-randomly from cycle to cycle. (We will qualify “pseudo” later.) Our current universe is then just the cycle which happens to contain a set of constants conducive to life. Cyclic universe models have previously been investigated as alternatives to inflation [7]. The idea that different string vacua could be explored in different cycles has been suggested in the context of explaining the value of the cosmological constant [8]. A recent development in the path towards well-behaved cyclic cosmologies is the proposal of the anamorphic universe [9]. This approach solves the problem of anisotropic instabilities which often plague bouncing models. It also provides a mechanism for producing a nearly scale-invariant spectrum of perturbations.

Here we will present a toy model for how a cyclic universe with pseudo-randomly changing constants might be realized. One key ingredient is to promote all coupling constants to moduli fields, and dynamically demonstrate two features: i. During each bounce the coupling constants vary pseudo-randomly; ii. During the expansion phase in each cycle the time variation of the coupling constants remains consistent with current observational bounds.

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For simplicity, we will focus on the gauge sector of the Standard Model and propose how to generalize to the Yukawa sector in the conclusion.

2. The model

The possibility of a cyclic universe with changing constants has been investigated before [10]. In that work, the bounce is caused by a free ghost scalar field whose kinetic energy is negative and scales as a^{-6}, where $a(t)$ is the FRW scale factor. The ghost dilaton field determines the value of a coupling constant, in this case the electromagnetic coupling constant. The universe is also assumed to be closed and to contain radiation. These ingredients allow for a series of closed universes separated by bounces. The value of the ghost field (and thus of the coupling) increases quickly and by the same amount during each bounce and then remains approximately constant during the following expansion/contraction cycle. The monotonically increasing coupling limits the feasibility of the model as a solution to the fine tuning problem. We note that while ghost fields remain problematic, we adopt the same phenomenological semi-classical approach as the authors in [10], which is to avoid its quantization. Indeed, ghost fields have found widespread applications in field theory and cosmology, for example as candidates for phantom dark energy [11] and k-essence inflation [12]. Additionally, in the anamorphic universe approach mentioned in the Introduction, a kinetic term with the wrong sign can be rendered ghost free in the presence of a non-minimal coupling to gravity [9]. We are currently investigating whether our model can be embedded in the anamorphic framework and plan to report on this in future work.

Our model incorporates a potential for the ghost field in a Friedmann universe. The action is

$$S=\int d^4x\sqrt{-g}\left[\frac{R}{16\pi G}-\frac{1}{2}\left[\epsilon\partial_\mu\psi\partial^\mu\psi+2V(\psi)\right]+S_{gf}\right], \quad (1)$$

with

$$S_{gf}=-\frac{1}{4}\sum_i\frac{1}{(g^i_{YM})^2}F^i_{\mu\nu}F^{\mu\nu i}, \quad (2)$$

where the coupling field for the i-th sector of the Standard Model is $g^i_{YM}=g^i_0 e^{\psi_i/M_*}$, with g^i_0 constant, and M_* some mass scale, which from here on we will take to be the Planck scale M_p. For clarity, we will focus on only one gauge sector; our approach is easily generalized to other sectors. With our metric signature, $(-,+,+,+)$, $\epsilon=+1$ corresponds to a regular scalar field, while $\epsilon=-1$ corresponds to a ghost field. We take the potential to be periodic but *negative*,

$$V(\psi)=-\Lambda^4(1+\cos(\psi/f)). \quad (3)$$

The negativity of the potential ensures that there is no net cosmological constant during an expansion cycle, given that the negative kinetic energy density will drive the field to the potential maximum, where $V(\psi)=0$. The energy density and pressure of the field ψ are

$$\rho_\psi=\frac{\epsilon}{2}\dot\psi^2-\Lambda^4(1+\cos(\psi/f)) \quad (4)$$

$$P_\psi=\frac{\epsilon}{2}\dot\psi^2+\Lambda^4(1+\cos(\psi/f)) \quad (5)$$

where f sets the energy scale as in axion-like models.

The equation of motion for ψ in an FRW spacetime is

$$\ddot\psi+3H\dot\psi-\frac{\Lambda^4}{f}\sin(\psi/f)=0, \quad (6)$$

where $H=\dot a/a$. We assume that other relativistic degrees of freedom are modeled by a generic radiation term, so that the Friedmann equations are

$$H^2=\frac{8\pi G}{3}\left(-\frac{1}{2}\dot\psi^2-\Lambda^4(1+\cos(\psi/f))+\frac{\rho_{r0}}{a^4}\right)-\frac{K}{a^2}; \quad (7)$$

$$\frac{\ddot a}{a}=-\frac{8\pi G}{3}\left(-\dot\psi^2+\Lambda^4(1+\cos(\psi/f))+\frac{\rho_{r0}}{a^4}\right), \quad (8)$$

where ρ_{r0} is the radiation energy density at $a=1$, $K=\pm1, 0$ gives the spatial curvature and we have taken $\epsilon=-1$.

The hope is that the field ψ will climb onto one of the potential maxima as the universe expands so the coupling constant that it determines will not change significantly. As the universe contracts, the ψ field accelerates. Its negative kinetic energy increases until it counteracts the radiation energy density and causes a bounce. At the bounce, the field is traveling quickly and can run across many maxima of the potential in both directions, resembling a sphaleron solution in electroweak baryogenesis. The precise location in the potential where it settles will set up new initial conditions for the next bounce. The field can then move in either direction the next time there is a bounce, possibly leading to a random walk among maxima over many cycles. (Our model can evade the Tolman problem that plagues cyclic universes by adding interaction terms that create entropy via the mechanism discovered in [13].)

We will work in conformal time as the bounces occur over a longer period of conformal time than cosmic time making numerical solution easier. Writing Eqs. (6) and (8) in dimensionless form in terms of conformal time we have

$$\Psi''=-2\mathcal{H}\Psi'+\frac{a^2\beta}{\tilde f}\sin(\Psi/\tilde f); \quad (9)$$

$$a''=\frac{a'^2}{a}-\frac{1}{3a}+\frac{a\Psi'^2}{3}-\frac{a^3\beta}{3}(1+\cos(\Psi/\tilde f)), \quad (10)$$

where $\Psi=\psi/M_p$, $\mathcal{H}=a'/a$, $\beta=\Lambda^4/\rho_{r0}$, $\tilde f=f/M_p$, and the dimensionless conformal time is $\tilde\eta=(\sqrt{\rho_{r0}}/M_p)\eta$, with primes denoting derivatives by $\tilde\eta$ and $M_p=1/\sqrt{8\pi G}$. The first Friedmann equation becomes

$$\mathcal{H}^2=-\frac{\Psi'^2}{6}-\frac{a^2\beta}{3}\left(1+\cos(\Psi/\tilde f)\right)+\frac{1}{3a^2}-\frac{KM_p^2}{\rho_{r0}}. \quad (11)$$

When $\beta=0$, these equations reduce to the model of Barrow et al. [10] and we have exact solutions

$$\Psi'=\frac{\sqrt\lambda}{a^2}; \quad (12)$$

$$a^2(\eta)=\frac{1}{6}\left[1+\sqrt{1-6\lambda}\sin(\eta+\eta_0)\right], \quad (13)$$

for constants λ and η_0 depending on initial conditions. The normalization of a is fixed by choosing the dimensionless curvature, $KM_p^2/\rho_{r0}=+1$. The maximum and minimum values of a are

$$a_{\rm max,min}=\frac{1}{6}\left(1\pm\sqrt{1-6\lambda}\right). \quad (14)$$

When $\beta=0$ we can expand the solution about the bounce as

$$a(\eta)=a_{\rm min}\left(1+\frac{1}{2}\left(\frac{\eta}{\eta_{\rm bounce}}\right)^2\right), \quad (15)$$

with the bounce occurring at $\eta=0$. We can plug this into Eq. (10) and set $\eta=0$ to get

$$\eta_{\rm bounce}=a_{\rm min}\sqrt{\frac{3}{1-6a^2_{\rm min}}}\approx\frac{a_{\rm min}}{a_{\rm max}}. \quad (16)$$