Dynamical Inflation and Vacuum Selection

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We consider an inflationary scenario in which the energy scale of inflation stems from gauge theory dynamics. Reflecting on inflationary models with moduli fields such as a dilaton, we discuss generic implications of the scenario for vacuum selection of our universe, including determination of spacetime symmetries, in particular, dimension, which is described by the compactification moduli.

The energy scale of primordial inflation is thought to be hierarchically below the gravitational scale,\(^{1}\) which could account for the existence of tiny fluctuations of the cosmic microwave background radiation.\(^{1}\) The origin of the hierarchical scale of inflation may be dimensional transmutation induced by gauge theory dynamics.\(^{2}\)

Gauge theory dynamics for inflation are expected to induce profound effects on the evolution of the universe, since the inflationary process may determine the vacuum of our universe through dominant expansion of the spatial extension of the corresponding inflationary vacuum. In this paper, we consider generic implications of such dynamical inflation for vacuum selection of our universe, including determination of spacetime symmetries, in particular, dimension, which is described by the compactification moduli.

We consider a mixed model of dilaton fixing\(^{2}\) and topological inflation\(^{3}\),\(^{**}\) as a simple example of dynamical inflation that incorporates an inflationary selection of the vacuum of our universe.

Let us consider a four-dimensional supersymmetric field theory with dilaton \(\Phi\) and inflaton \(\phi\) supermultiplets, whose superpotential takes the form

\[ W = X f(\Phi) + Z h(\Phi)(1 - \lambda \phi^2), \]

where \(X\) and \(Z\) denote chiral superfields and \(f(\Phi)\) and \(h(\Phi)\) are functions of the dilaton superfield \(\Phi\):

\[ f(\Phi) = f_1 e^{-a_1 \Phi} - f_2 e^{-a_2 \Phi}, \quad h(\Phi) = he^{-a\Phi}. \]

\(^{1}\) This is adequate for an analysis based on an effective field theory of gravity. Otherwise, quantum fluctuations of the inflaton and gravitational fields might be too large to induce slow-roll inflation.

\(^{2}\) This is analogous to dynamical supersymmetry breaking, which may provide the origin of the hierarchically small scale of electroweak symmetry breaking.

\(^{**}\) The dilaton fixing and topological inflation models are both \(R\)-invariant, and thus so is the mixed model.
Here we set the gravitational scale equal to unity and regard it as a universal cutoff in the theory. We assume that the couplings $f_1, f_2, h$ and $\lambda$ are of order one and $0 < a_1 \sim a_2 \ll a$. The above superpotential can be generated by dynamics of hypercolor gauge interactions, where the dilaton-dependent scales $e^{-a_1\Phi}$ and $e^{-a_2\Phi}$, with $a_i$ and $a$ related to the $\beta$ functions of the gauge interactions,\(^*\) arise from hyperquark condensations with the aid of the superpotential considered in Ref. 2).

The potential in supergravity is given by

$$V = e^K (K_{AB} F^A F^{B*} - 3|W|^2),$$

where $K$ is a Kähler potential, $K_{AB}$ denotes the inverse of the matrix

$$\frac{\partial^2 K}{\partial \phi_A \partial \phi^*_B},$$

with $\phi_A = X, Z, \Phi, \phi$, and $F^A$ is given by

$$F^A = \frac{\partial W}{\partial \phi_A} + \frac{\partial K}{\partial \phi_A} W.$$

For a generic Kähler potential, we have vacua of the model given by

$$F^A = W = 0,$$

which realizes the unbroken supersymmetry and $R$ invariance. Hence the vacuum expectation values of the dilaton are determined by

$$f(\Phi) = 0,$$

which has runaway and fixed solutions:\(^*\)

$$\Phi \rightarrow \infty$$

and

$$\langle \Phi \rangle = \frac{1}{a_1 - a_2} \ln \frac{f_1}{f_2}.$$  \hspace{1cm} (9)

For the fixed dilaton, from Eq. (6), we find $\langle X \rangle = \langle Z \rangle = 0$ and

$$\langle \phi \rangle = \pm \lambda^{-\frac{1}{2}}.$$  \hspace{1cm} (10)

Since $|e^{-a_1(\Phi)}| \gg |e^{-a_2(\Phi)}|$, we may integrate out the superfields $X$ and $\Phi$ to obtain the effective superpotential

$$W_{\text{eff}} = Zh(\langle \Phi \rangle) (1 - \lambda \phi^2),$$

\(^*\) The numerical values of these parameters are chosen\(^2\) so that weak gauge couplings allow for realization of the hierarchical scale needed for slow-roll inflation. If this were not the case, inflation might not take place. (See the footnote \(*\) on p. 1077.)

\(^*\) The gauge coupling constant $g$ is given by $g^2 = 1/\text{Re}(\langle \Phi \rangle)$. \(\phi^2\)
which results in topological inflation between the two vacua Eq. (10) for appropriate values of the couplings.\textsuperscript{3}\textsuperscript{)} In other words, once the dilaton is fixed, the universe may evolve through an inflationary stage. On the other hand, the runaway vacuum, $\Phi \rightarrow \infty$, yields a free theory, which induces no inflation.

Under chaotic initial conditions\textsuperscript{4}\textsuperscript{)} of the dilaton field, the spatial extension of the vacuum corresponding to the fixed dilaton dominates over that of the runaway vacuum through the inflationary process.\textsuperscript{2}\textsuperscript{)}

Although we have considered a specific model to clearly demonstrate our point, the implications of the dynamical inflation scenario seem rather generic. In the above model, the dilaton serves as an example of moduli\textsuperscript{∗}\textsuperscript{)} that determine the form of the low-energy field theory describing our universe. Moduli are not necessarily usual moduli fields but may be any variables that parametrize the moduli space of the underlying high-energy theory. The moduli space may even be disconnected, since chaotic initial conditions of moduli allow highly excited states that interpolate between disconnected pieces of the moduli space.

For example, the spacetime dimension of the low-energy field theory may be determined by moduli that describe the size of the internal space of the high-energy theory. Then, chaotic initial conditions of those moduli imply that the spacetime dimension is determined through the inflationary process. If the corresponding inflation is dynamical, the number of spacetime dimensions is expected to be four or fewer, since the dynamical scale resulting from gauge theory dynamics may not be generated in five or more dimensions (perturbatively, the gauge interaction is not even asymptotically free). That is, in four or fewer dimensions, the universe may evolve through an inflationary stage, whereas in five or more dimensions, dynamical inflation does not take place. Under chaotic initial conditions of the relevant moduli, the spatial extension of regions with four or fewer dimensions dominates over that of regions with five or more dimensions through the inflationary process. In four dimensions, the presence of $\mathcal{N} = 1$ supersymmetry (and not $\mathcal{N} > 1$) may also originate from inflationary selection of this type, since it seems suitable for realizing scalar potentials which satisfy the slow-roll condition for inflation.\textsuperscript{1}\textsuperscript{)}

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\textsuperscript{∗)} For an investigation of stringy modular cosmology, see Ref. 5).