GRAVITY DRIVEN INFLATION

Janna J. Levin
Canadian Institute for Theoretical Astrophysics
McLennan Labs
60 St. George Street
Toronto, ON M5S 1A7

Abstract

The union of high-energy particle theories and gravitation often gives rise to an evolving strength of gravity. The standard picture of the earliest universe would certainly deserve revision if the Planck mass, which defines the strength of gravity, varied. A notable consequence is a gravity-driven, kinetic inflation. Unlike standard inflation, there is no potential or cosmological constant. The unique elasticity in the kinetic energy of the Planck mass provides a negative pressure able to drive inflation. As the kinetic energy grows, the spacetime expands more quickly. The phenomenon of kinetic inflation has been uncovered in both string theory and Kaluza-Klein theories. The difficulty in exiting inflation in these cases is reviewed. General forms of the Planck field coupling are shown to avoid the severity of the graceful exit problem found in string and Kaluza-Klein theories. The completion of the model is foreshadowed with a suggestion for a heating mechanism to generate the hot soup of the big bang.

To appear in the conference proceedings, “Unified Symmetry: In the Small and the Large II” (Eds: B.N. Kursunoglu, S. Mintz, and A. Perlmutter).
The theory of inflation [1] has become the new paradigm for the early universe. The inflation, or accelerated growth of the universe, provides a dynamical explanation for the observed smoothness on large-scales, the apparent local flatness, and the lack of undesirable monopole relics. Further, seeds to catalyze the formation of galactic structures on large-scales are predicted. Though inflation occurs in the first fraction of a second, the industry of designing inflation models aspires to explain the universe we live in today; that is, to explain the specific features in the cosmic background radiation and the formation of structure.

For all of its successes, there remain some imposing questions. In particular, there is no model of inflation predicted from a fundamental theory. It might be hoped that quantum gravity would provide such a prediction. However, the most successful attempt at unifying gravity with particle theory to date, namely string theory, is inconsistent with the standard inflationary paradigm [2]. While one might be willing to abandon strings or inflation, the point is we are no closer to a consistent union of the evolution of our universe and a fundamental field theory. Though superstrings may not survive as the fundamental theory, some of the salient features must. By investigating elements common to strings and other particle theories in a cosmological context, our larger view of physics can be tested.

A common element of many high-energy theories is a dynamical Planck mass. In the low-energy string action the dilaton acts as a dynamical Planck field and thus supplants the fundamental constant of the Einstein theory. Outside of superstrings, dynamical Planck fields are often generated in particle theories. Even simple quantum corrections to a field theory in a curved spacetime will contribute to a variable Planck field. In a higher dimensional or Kaluza-Klein approach [3], the variable Planck mass has a geometric interpretation. It is related to the radius of the compact internal dimensions.

A completely new source of inflation is predicted in such extensions of Einstein gravity, as we showed in references [4,5]. The phenomenon is manifest in string cosmology but is not unique to string theory. The nonminimal coupling of the Planck field to gravity allows for an unusual elasticity associated with the kinetic energy of the field. The kinetic energy density can grow with time, fueling a more rapid expansion of the universe, that is, an inflation. It
is worth stressing that there is no potential and no cosmological constant. Independently, Gasperini and Veneziano considered the specific case of superstrings [6].

In standard inflation, a potential energy density drives an era of accelerated expansion. The characteristic feature is the potential. Previously, string theories were shown to interrupt potential dominated inflation [2]. The kinetic energy in the dilaton field overwhelmed the potential energy. As a result, standard inflation could not proceed unhindered.

Since the Planck field can actually drive inflation, in lieu of the potential, string theory may not only be compatible with, but actually predicts inflation. I found an analogous type of behavior in Kaluza-Klein models of additional spacetime dimensions [8]. In vacuum, the shear from contracting dimensions is able to drive an inflation of a three-volume. When the extra dimensions are integrated over, the scenario is equivalent to a four-dimensional model of a dynamical Planck field.

The task at hand is to uncover a successful end to the scenario. Currently, both string cosmology [9] and Kaluza-Klein cosmologies [8] are unable to exit the inflationary phase. Instead the universe is ushered toward a future singularity. The graceful exit problem is more serious than the usual obstacle which plagues potential-driven inflation. In string cosmology, the inflationary branch of solutions is totally distinct from the branch of solutions which describes our universe today. There is no overlap. A branch change is needed to move from inflation to a more temperate evolution. The nature of the graceful exit will be elaborated on here.

Fortunately, the graceful exit problem does not plague all models of a Planck-driven inflation. As will be described, there are entire families which are able to both inflate and match onto an expanding universe today. A means by which to heat the universe, thereby completing the model, will also be described.

The gravitational action can be written in generality as

$$A_G = \int d^4x \sqrt{-g} \left[ -\Phi R + \frac{\omega}{\Phi} (\partial \Phi)^2 \right].$$

(1.1)

The fundamental Planck scale of the Einstein theory is replaced by the field $\Phi = m_P^2$ and
$\mathcal{R}$ is the Ricci scalar. The kinetic coupling constant which determines the theory, $\omega(\Phi)$, is left general. To condense the notation it is worthwhile to introduce the parameter

$$f(\Phi) \equiv (1 + 2\omega(\Phi)/3)^{1/2} \ .$$

In string theory, the dilaton is described by the action (1.1) with $\omega = -1$. In a Kaluza-Klein model with $n > 1$ contracting dimensions, the radius of the internal dimensions obeys the action (1.1) with $\omega = -1 + 1/n$. Notice that in both cases it happens that $f < 1$.

In a flat, Friedman-Robertson-Walker universe, the Einstein equation which determines the expansion rate of the universe is simply

$$H^2 = \frac{8\pi}{3\Phi} (\rho_\Phi + \rho) \ ,$$

where the undecorated $\rho$ represents the energy density in everything but the Planck field. The kinetic energy density in $\Phi$ is given by

$$\frac{8\pi}{3\Phi} \rho_\Phi = \frac{2\omega}{3} \left( \frac{\dot{\Phi}}{\Phi} \right)^2 - H\dot{\Phi} \ .$$

As a consequence of the direct coupling of the Planck field to gravity, $\rho_\Phi$ involves $H$ directly. The pressure associated with this kinetic energy is roughly a measure of the change in energy with unit volume, $p_\Phi \sim -dE_\Phi/dV$. As a result of the direct coupling to the Ricci scalar, the kinetic energy acquires a unique elasticity. In fact, for certain couplings $f$, the kinetic energy can actually grow leading to a negative pressure. In full glory, the pressure associated with the kinetic energy can be written

$$\frac{8\pi}{3\Phi} p_\Phi = \frac{2}{3} \left( \frac{\dot{\Phi}}{2\Phi} \right)^2 \left( 1 + \omega \pm f - 2\frac{d\ln f}{d\ln \Phi} \right) \ .$$

The origin of the two branches is discussed below. As in standard Einstein gravity, a negative pressure can lead to inflation.

Inflation refers to an accelerated growth of the scale factor. The scale factor is accelerated if the following condition is satisfied:

$$f \pm 1 - \frac{\Phi}{f^2} \frac{df}{d\Phi} < 0 \ .$$
If $\omega$ is a negative constant so that $f < 1$, as is the case for strings and Kaluza-Klein, then condition (1.6) will only be satisfied for the $-$ sign branch. The condition becomes $f - 1 < 0$, which is automatically satisfied. If $\omega(\Phi)$ is variable, then it is possible to satisfy condition (1.6) for the $+$ sign branch. The branch taken turns out to be important.

The physical relevance of these two branches can be seen by solving the quadratic Einstein equation (1.3) for $H$

$$H = -\left(\frac{\dot{\Phi}}{2\Phi}\right) \pm \sqrt{\frac{f^2}{4} \left(\frac{\dot{\Phi}}{\Phi}\right)^2 + \frac{8\pi}{3\Phi} \rho}.$$  \hspace{1cm} (1.7)

The two branches in condition (1.6) and expression (1.5) reflect the two solutions of Einstein's equations. For comparison, the standard model Hubble expansion is given by

$$H_{\text{stand}} = \pm \sqrt{\frac{8\pi}{3M_p^2} \rho}.$$ \hspace{1cm} (1.8)

The standard Einstein equation (1.8) also allows two branches, one expanding ($+$) and one contracting ($-$). The expanding branch is singled out as the physically relevant one. In the case of a dynamical Planck mass on the other hand, both branches can expand if $\dot{\Phi} < 0$ and $f(\Phi) < 1$. In fact, for both Kaluza-Klein and strings, the $+$ branch expands without inflation while the $-$ branch inflates.

The pathology of the $-$ branch can now be seen. Even if a mechanism exists to stabilize the Planck mass, the universe would ultimately contract. Today the universe is described by $+$ branch solutions of the form (1.8). A branch change is needed to connect smoothly onto our expanding cosmology. To induce such a branch change requires negative energies so that the total energy density drops to zero. Obviously this is no mean feat.

The cure for string theory may lie in higher order stringy corrections to the Einstein equations. A different tactic can be suggested. If we allow for a variable $\omega(\Phi)$, then the hardship of the branch change can be circumvented. The branch which inflates can also be the branch which smoothly connects onto an expanding universe today. Entire families of couplings can satisfy the inflationary condition (1.6) on the healthier, $+$ branch. Some examples of toy models include
\begin{align}
f_1(\Phi) &= \ln(\Phi/M_o^2) \\
f_2(\Phi) &= \left(\frac{1}{4 \ln(M_o^2/\Phi)}\right)^{1/2} \\
f_3(\Phi) &= \frac{\Phi}{M_o^2} \\
f_4(\Phi) &= \frac{\Phi}{M_o^2 - \Phi}.
\end{align}  \tag{1.9}

The question remains if any such coupling can be generated from quantum corrections to a low-energy effective action or non-perturbatively from a high-energy theory.

An accelerated expansion alone does not an inflationary model make. The universe must expand enough to envelop our entire observable universe. Furthermore, the universe must then heat up to restore the standard hot big bang picture. Gravitational particle production due to the gravity-driven inflation may be able to heat the universe [10].

During inflation quantum fluctuations in any underlying field theory can be amplified. For wavelengths well within the event horizon, the amplified fluctuations can propagate as particles. The gravitational field transfers energy into the virtual quantum field thereby creating a hot bath. On wavelengths which exceed an event horizon, the mode cannot propagate as a particle but instead contributes to the fluctuation in an inhomogeneous classical background. The long wavelength fluctuations are the usual density perturbations generated during inflation. The short wavelength fluctuations are the analog of Hawking-Unruh radiation.

In de Sitter inflation, the short wavelength fluctuations are redshifted away as rapidly as they are generated. The equilibrium of classical de Sitter is therefore left undisturbed. The main contribution of these high-frequency quantum fluctuations is to build up the long wavelength $\delta \rho/\rho$ as the modes cross outside the event horizon. In kinetic inflation however, particle production can run away when the expansion is fiercest. The back-reaction of the spacetime in turn drains energy from the Planck field. As the Planck field slows, inflation would in principle be exited.

A quick sketch of a gravity-driven, kinetic inflation unfolds as follows. The elastic nature of the kinetic energy in a variable Planck mass can drive an epoch of inflationary expansion.
The kinetic energy in the Planck field can grow as inflation proceeds. Consequently, high-energy physics becomes increasingly important. The final stage of a gravity-driven inflation will thus be marked by the influence of quantum mechanics through gravitational particle production. It must still be shown that conversion of the classical kinetic energy into particles is efficient enough to appease the demands of successful inflation [11]. If a hot universe can be created from this cold beginning, a cohesive model of gravity-driven inflation is within reach.

Acknowledgements

Special gratitude to J.R. Bond, R. Brustein, N. Cornish, K. Freese and G. Starkman for many valuable discussions. I thank Behram Kursunoglu for his continued efforts in organizing the Global Foundation meetings where this talk was given. I am also grateful for the additional support of the Jeffrey L. Bishop Fellowship.
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