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GUT scale inflation and leptogenesis

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Abstract. We reconsider supersymmetric hybrid inflation in which inflation is associated with the breaking of a gauge symmetry G to H, with the symmetry breaking scale $M \sim 10^{16}$ GeV. The models discussed feature a spectral index $n_s \geqslant 0.98$ while $\mathrm{d}n_s/\mathrm{d}\ln k \lesssim 10^{-3}$ and the tensor to scalar ratio $r \lesssim 10^{-4}$. If G corresponds to $SO(10)$ or one of its rank five subgroups, the observed baryon asymmetry is naturally explained via leptogenesis.

1 Introduction

Supersymmetric grand unified theories in four and higher dimensions continue to play a prominent role in high energy physics, and it is therefore tempting to speculate that they may also play a key role in realizing an inflationary epoch in the very early universe. Indeed, in a class of realistic supersymmetric models, inflation is associated with the breaking either of a grand unified symmetry or one of its subgroups.

In the simplest models, inflation is driven by quantum corrections generated by supersymmetry breaking in the early universe, and the temperature fluctuations $\delta T/T$ are proportional to $(M/M_P)^2$, where M denotes the symmetry breaking scale of G, and $M_P = 1.2\times10^{19}$ GeV denotes the Planck mass [1]. It turns out that for $M \sim 10^{16}$ GeV, one predicts an essentially scale invariant spectrum which is consistent with a variety of CMB measurements including the recent WMAP results [2]. With inflation 'driven' solely by radiative corrections the scalar spectral index n_s is very close to 0.98, if the number of e-foldings N_Q after the present horizon scale crossed outside the inflationary horizon is close to 60.

As an example, if $G = SO(10)$, one could associate inflation with the breaking of $SO(10)$ to $SU(5)$. A realistic model along these lines is most easily realized in a five dimensional setting [3], in which compactification on an orbifold can be exploited to break $SO(10)$ down to the MSSM. Interesting examples for G in four dimensions include the gauge symmetry $G_{PS} \equiv SU(4)_c \times SU(2)_L \times SU(2)_R$ [4,5,6] as well as $G_{LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [7,8]. If the unified gauge group G is identified with $SO(10)$ or one of its subgroups listed above, the inflaton naturally decays into massive right-handed neutrinos whose out of equilibrium decay lead to the observed baryon asymmetry via leptogenesis.

2 Supersymmetric hybrid inflation

The simplest supersymmetric hybrid inflation model [1] is realized by the renormalizable potential (consistent with a $U(1)$ R-symmetry) [9]

$$W_1 = \kappa S(\phi\overline{\phi} - M^2) \qquad (1)$$

where $\phi(\overline{\phi})$ denote a conjugate pair of superfields transforming as nontrivial representations of some gauge group G, S is a gauge singlet superfield, and κ (> 0) is a dimensionless coupling. In the absence of supersymmetry breaking, the potential energy minimum corresponds to non-zero (and equal in magnitude) vevs ($= M$) for the scalar components in ϕ and $\overline{\phi}$, while the vev of S is zero. (We use the same notation for superfields and their scalar components.) Thus, G is broken to some subgroup H.

In order to realize inflation, the scalar fields ϕ, $\overline{\phi}$, S must be displayed from their present minima. For $|S| > M$, the ϕ, $\overline{\phi}$ vevs both vanish so that the gauge symmetry is restored, and the tree level potential energy density $\kappa^2 M^4$ dominates the universe. With supersymmetry thus broken, there are radiative corrections from the $\phi - \overline{\phi}$ supermultiplets that provide logarithmic corrections to the potential which drives inflation.

The inflationary scenario based on the superpotential W_1 in (1) has the characteristic feature that the end of inflation essentially coincides with the gauge symmetry breaking. Thus, modifications should be made to W_1 if the breaking of G to H leads to the appearance of topological defects such as monopoles, strings or domain walls. For instance, the breaking of $G_{PS} \equiv SU(4)_c \times SU(2)_L \times SU(2)_R$ [4] to the MSSM by fields belonging to $\phi(\overline{4}, 1, 2)$, $\overline{\phi}(4, 1, 2)$ produces magnetic monopoles that carry two quanta of

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Dirac magnetic charge [10]. As shown in [6], one simple resolution of the monopole problem is achieved by supplementing W_1 with a non-renormalizable term:

$$W_2 = \kappa S(\overline{\phi}\phi - \mu^2) - \beta \frac{S(\overline{\phi}\phi)^2}{M_S^2}\,, \qquad (2)$$

where μ is comparable to the GUT scale, $M_S = 5 \times 10^{17}$ GeV is a superheavy cutoff scale, and the dimensionless coefficient β is of order unity. The presence of the non-renormalizable term enables an inflationary trajectory along which the gauge symmetry is broken. Thus, in this 'shifted' hybrid inflation model the magnetic monopoles are inflated away.

After the end of inflation, the system falls toward the SUSY vacuum and performs damped oscillations about it. The inflaton, which we collectively denote as χ, consists of the two complex scalar fields $(\delta\overline{\phi} + \delta\phi)/\sqrt{2}$ ($\delta\overline{\phi} = \overline{\phi} - M$, $\delta\phi = \phi - M$) and S, with equal mass m_χ. In the presence of $N = 1$ supergravity, SUSY breaking is induced by the soft SUSY violating terms in the tree level potential and S acquires a vev comparable to the gravitino mass $m_{3/2}$ ($\sim$ TeV). This (mass)^2 term provides an extra force driving S to the minimum, but its effect is negligible for $\kappa \gtrsim 10^{-6}$.

As noted in [11,12], for large values of κ the presence of SUGRA corrections (due to the minimal Kähler potential) can give rise to n_s values that exceed unity by an amount that is not favored by the data on smaller scales. SUGRA corrections also become important for tiny values of κ. Nevertheless, they remain ineffective for a wide range of κ ($10^{-6} \lesssim \kappa \lesssim 10^{-2}$), for which the power spectrum is essentially scale invariant ($n_s \simeq 0.99 \pm 0.01$ and $|\mathrm{d}n_s/\mathrm{d}\ln k| < 10^{-3}$ [12]), consistent with a variety of CMB measurements including the recent WMAP results [2,13]. The spectral index n_s as a function of κ for SUSY hybrid inflation is shown in Fig. 1.

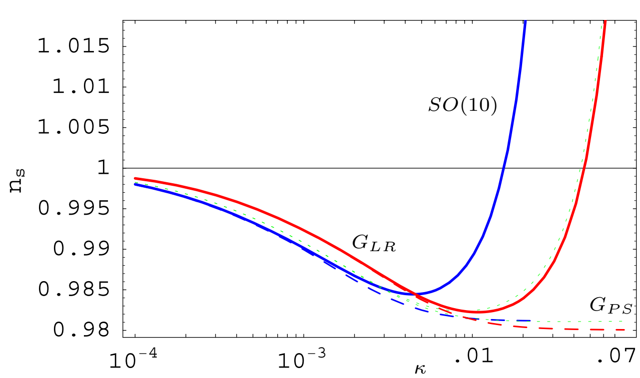

Fig. 1. The spectral index n_s at $k = 0.05\ \mathrm{Mpc}^{-1}$ as a function of the coupling constant κ, for SUSY hybrid inflation with $G = SO(10)$ and $G_{LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ (dashed line–without SUGRA correction, solid line–with SUGRA correction). The spectral index for shifted hybrid inflation with $G = G_{PS}$ is similar (dotted lines)

3 Reheating and leptogenesis

The observed baryon asymmetry of the universe can be naturally explained via leptogenesis in SUSY hybrid inflation models [14]. If inflation is associated with the breaking of the gauge symmetry $G = SO(10)$ [3] or one of its subgroups such as $G_{PS} \equiv SU(4)_c \times SU(2)_L \times SU(2)_R$ [6] and $G_{LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [7], the inflaton decays into right handed neutrino superfields [15]. Their subsequent out of equilibrium decay to lepton and Higgs superfields leads to the observed baryon asymmetry via sphaleron effects [16].

An important constraint that is independent of the details of the seesaw parameters arises from considering the reheat temperature T_r after inflation, taking into account the gravitino problem which requires that $T_r \lesssim 10^{10}$ GeV [17]. We expect the heaviest right handed neutrino to have a mass of around 10^{14} GeV, which is in the right ball park to provide via the seesaw a mass scale of about .05 eV to explain the atmospheric neutrino anomaly through oscillations. Comparing this with

$$T_r = \left(\frac{45}{2\pi^2 g^*}\right)^{\frac{1}{4}} (\Gamma_\chi\, m_P)^{\frac{1}{2}} \simeq \frac{1}{16} \frac{(m_P\, m_\chi)^{\frac{1}{2}}}{M} M_i \qquad (3)$$

(where $m_P \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck mass, M_i is the mass of the i'th family heavy right handed neutrino, and $\Gamma_\chi = (1/8\pi)(M_i^2/M^2)m_\chi$ is the decay rate of the inflaton), we see that for $m_\chi \gtrsim 10^5$ GeV, the inflaton should not decay into the heaviest right handed neutrino, otherwise T_r would be too high [7]. Thus, we require that

$$\frac{m_\chi}{2} \le M_3 \le \frac{2M^2}{m_P}\,. \qquad (4)$$

The gravitino constraint expressed by (4) requires $\kappa \lesssim 10^{-3}$ independent of the details of seesaw parameters for the SUSY hybrid inflation model [18]. However, in shifted and smooth hybrid inflation the Majorana mass of the heaviest right handed neutrino $M_3 \le 2M^2/M_S$ can remain an order of magnitude greater than the inflaton mass so that this constraint does not restrict κ or M.

In thermal leptogenesis [19] the lightest right handed Majorana neutrino N_1 washes away the previous asymmetry created by the heavier neutrinos. If, on the other hand, N_1 as well as the heavier neutrinos are out of equilibrium ($T_r < M_1$), the lepton asymmetry could predominantly result from the inflaton χ decaying into the next-to-lightest neutrino N_2. ($\chi \to N_3 N_3$ is ruled out by the gravitino constraint.) It is easier to account for the observed baryon asymmetry in this case since the asymmetry per right handed neutrino decay is in general greater than the case where the inflaton decays into the lightest neutrino, and unlike thermal leptogenesis there is no washout factor.

We have reviewed non-thermal leptogenesis in SUSY hybrid inflation models in [14]. For the simplest SUSY hybrid inflation model, sufficient lepton asymmetry can be generated provided that the dimensionless coupling constant appearing in the superpotential (1) satisfies $10^{-6} \lesssim$

$\kappa \lesssim 10^{-2}$. SUGRA correction to the potential is negligible for this range and the power spectrum is essentially scale invariant. For shifted and smooth hybrid inflation, leptogenesis with larger values of the coupling constant and the symmetry breaking scale is also possible.

Constraints from neutrino mixing could further restrict the range of κ that is allowed. We have applied the constraint of maximal (or near maximal) atmospheric mixing, as observed by Super-Kamiokande and K2K, to the case where the inflaton predominantly decays into the next-to-lightest right handed Majorana neutrino. We have numerically shown, for this case, that sufficient lepton asymmetry can still be generated with hierarchical Dirac neutrino masses imposed by the gauge symmetries. Results for SUSY hybrid inflation with $G_{LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and shifted hybrid inflation with $G_{PS} \equiv SU(4)_c \times SU(2)_L \times SU(2)_R$ are shown in Figs. 2 and 3.

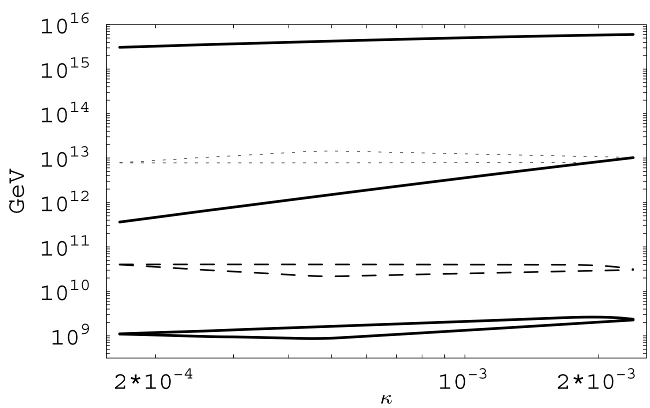

Fig. 2. From bottom to top, T_r, M_2 (dashed lines), $m_\chi/2$, M_3 (dotted lines) and M as functions of κ, for SUSY hybrid inflation with G_{LR} and hierarchical left handed Majorana neutrinos. The regions for T_r, M_2 and M_3 are bound by the baryon asymmetry and near maximal atmospheric mixing ($\sin^2 2\theta_{23} \geq 0.95$) constraints

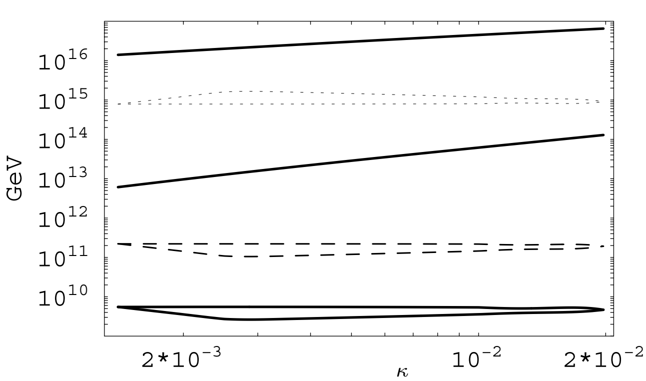

Fig. 3. Same as Fig. 2, for shifted hybrid inflation with $G = G_{PS}$ and hierarchical left handed Majorana neutrinos

4 Conclusion

Supersymmetric hybrid inflation models provide a compelling framework for the understanding of the early universe. They account for the primordial density perturbations with a GUT scale symmetry breaking yet without any dimensionless parameters that are very small. The spectral index in these models are essentially scale invariant, consistent with a variety of CMB measurements including the recent WMAP. Such models can also satisfactorily meet the gravitino and baryogenesis constraints, consistent with the observed neutrino (mass)^2 differences and near maximal atmospheric neutrino mixing.

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