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Grand unified inflation confronts WMAP

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Abstract: In a class of realistic four and five dimensional supersymmetric grand unified models, the scalar spectral index is found to be $n_s = 0.98(\pm 0.01)$, in excellent agreement with the values determined by several previous experiments and most recently by the Wilkinson Microwave Anisotropy Probe (WMAP). The models predict $dn_s/d\ln k \sim 10^{-3}$ and a negligible tensor-to-scalar ratio $r \sim 10^{-8}$. A new five dimensional supersymmetric SO(10) model along these is presented in which inflation is associated with the breaking of SO(10) to SU(5) at scale M, with $\delta T/T \propto (M/M_{\rm Planck})^2$, so that $M \simeq 10^{16}\,$GeV. The inflaton decay leads to the observed baryon asymmetry via leptogenesis. We also discuss how the monopole problem is solved without the use of non-renormalizable terms.

Keywords: Field Theories in Higher Dimensions, Supersymmetric Effective Theories, Cosmology of Theories beyond the SM.

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Supersymmetric grand unified theories (GUTs) provide an especially attractive framework for physics beyond the standard model (and MSSM), and it is therefore natural to ask if there exists in this framework a compelling, perhaps even an intimate connection with inflation. In ref. [1] one possible approach to this question was presented. In its simplest realization, inflation is associated with the breaking at scale M of a grand unified gauge group G to H. Indeed, inflation is 'driven' by quantum corrections which arise from the breaking of supersymmetry by the vacuum energy density in the early universe. The density fluctuations, it turns out, are proportional to $(M/M_{\rm Planck})^2$, where $M_{\rm Planck} \simeq 1.2 \times 10^{19}$ GeV denotes the Planck mass. From the variety of $\delta T/T$ measurements, especially by the Wilkinson Microwave Anisotropy Probe (WMAP) [3], the symmetry breaking scale M is of order 10^{16} GeV, essentially identical to the scale of supersymmetric grand unification.

Because of the logarithmic radiative corrections that drive inflation, the spectrum of scalar density fluctuations turns out to be essentially flat. For the simplest models, the scalar spectral index was found to be $n_s = 0.98(\pm 0.01)$ [1], in excellent agreement with a variety of observations [4] including the recent WMAP data. The variation $dn_s/d\ln k$ of the spectral index is found to be small ($\sim 10^{-3}$).

In some recent papers [5, 6] it was shown how the above scheme can be extended to five dimensional supersymmetric models. There are good reasons for discussing such models. Consider, for instance, the case of $G = \mathrm{SO}(10)$ (or SU(5)) in four dimensions. The presence of dimension five baryon number violating operators mediated through Higgsino exchange implies in the 'minimal' scheme a proton life time $\tau_{p\to K^+\bar\nu} \sim 10^{30\pm 2}$ yrs. This may be in conflict with the recent lower bounds ($\tau_p > 1.9 \times 10^{33}$ yrs) for $p \to K^+\bar\nu$ determined by the Superkamiokande experiment [7]. There are other serious issues such as the notorious doublet-triplet (DT) splitting problem, which have led people to investigate five (and higher) dimensional theories compactified on suitable orbifolds that provide a relatively painless way of implementing the DT splitting. Furthermore, dimension five proton decay can be easily eliminated which is an attractive feature of the five dimensional framework.

In this paper we present a realistic model of inflation based on five dimensional supersymmetric SO(10) compactified on an orbifold $S^1/(Z_2 \times Z_2')$. There are two fixed points (branes) where the gauge symmetries are SO(10) and $\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$, respectively [8, 5]. Through the spontaneous breaking of SO(10) to SU(5), the effective low energy symmetry corresponds to the MSSM gauge group. The inflationary scenario will be associated with the symmetry breaking $\mathrm{SO}(10) \to \mathrm{SU}(5)$. In its simplest realization the scalar spectral index $n_s = 0.98 \pm 0.01$. The variation of n_s with respect to the wave number k is small but in principle measurable ($dn_s/d\ln k \sim 10^{-3}$), which will be tested by ongoing and future observations. The WMAP data combined with other observations appears to prefer, but does not require, a far more significant running, $dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$. Our model predicts a negligible tensor-to-scalar ratio $r \sim 10^{-8}$. After inflation is over, the inflaton (which belongs to $\mathbf{16}$, $\overline{\mathbf{16}}$ of SO(10)) decays into right-handed neutrinos whose out of equilibrium leads to the observed baryon asymmetry via leptogenesis [9, 10, 5]. The symmetry breaking scale M is estimated from inflation to be of order 10^{16} GeV, which leads to righ-handed neutrino masses of the correct magnitude, of order 10^{14} GeV or less, that can yield a mass spectrum for the light neutrinos suitable for neutrino oscillations [5].

In this paper we also provide a new resolution of the well known monopole problem. In the class of models discussed, unless care is exercised, superheavy monopoles can be produced at the end of inflation leading to cosmological disaster. In ref. [11], the problem was circumvented by including sizable higher order (non-renormalizable) terms in the superpotential, such that the GUT symmetry is broken along an inflationary trajectory. In our new scenario we show how the problem is solved in a five dimensional framework without invoking non-renormalizable terms.

The four dimensional inflationary model is best illustrated by considering the following superpotential which allows the breaking of a gauge symmetry G down to H, keeping supersymmetry intact [1, 12]:

$$W_{\rm infl} = \kappa S(\phi\bar{\phi} - M^2)\,. \tag{1}$$

Here ϕ and $\bar{\phi}$ represent superfields whose scalar components acquire non-zero vacuum expectation values (VEVs), which break G to H. The singlet superfield S provides the scalar field that drives inflation. Note that by invoking a suitable R symmetry $U(1)_R$, the form of W is unique at the renormalizable level. For example, W and S can be assigned an R-charge of unity, while the R-charges of ϕ, $\bar{\phi}$ are zero. It is gratifying to realize that R symmetries naturally occur in (higher dimensional) supersymmetric theories and can be appropriately exploited.

From W, it is straightforward to show that the supersymmetric minimum corresponds to non-zero (and equal in magnitude) VEVs for ϕ and $\bar{\phi}$, while $\langle S\rangle = 0$. (After supersymmetry breaking *à la* $N = 1$ supergravity, $\langle S\rangle$ acquires a VEV of order $m_{3/2}$ (gravitino mass)).

An inflationary scenario is realized in the early universe with both ϕ, $\bar{\phi}$ and S displaced from their present day minima. Thus, for S values in excess of the symmetry breaking scale M, ϕ, $\bar{\phi}$ VEVs vanish, the gauge symmetry is restored, and a potential energy density proportional to M^4 dominates the universe. With supersymmetry thus broken, there are radiative corrections from the ϕ-$\bar{\phi}$ supermultiplets that provide logarithmic corrections to the potential which drives inflation. In one loop approximation [1, 13],

$$V \simeq \kappa^2 M^4 \left[1 + \frac{\kappa^2 \mathcal{N}}{32\pi^2}\left(2{\rm ln}\frac{\kappa^2|S|^2}{\Lambda^2} + (z+1)^2{\rm ln}(1+z^{-1}) + (z-1)^2{\rm ln}(1-z^{-1})\right)\right], \tag{2}$$

where $z = x^2 = |S|^2/M^2$, $\mathcal{N}$ is the dimensionality of the representations to which ϕ, $\bar{\phi}$ belong, and Λ denotes a renormalization mass scale. The logarithmic loop corrections in Eq. (2) enable the inflaton field to slowly roll down to the supersymmetric vacuum state. From eq. (2) the microwave CMB anisotropy on the Hubble scale l is found to be [1]

$$\left(\frac{\delta T}{T}\right)_l \simeq \frac{8\pi}{\sqrt{\mathcal{N}}}\left(\frac{N_l}{45}\right)^{1/2}\left(\frac{M}{M_{\rm Planck}}\right)^2 x_l^{-1} y_l^{-1} f(x_l^2)^{-1}\,. \tag{3}$$

Here, $y_l \simeq x_l(1 - 7/12x_l^2 + \cdots)$, $f(x_l^2)^{-1} \simeq 1/x_l^2$, for S_l sufficiently larger than M, and $N_l \simeq 50 - 60$ denotes the e-foldings needed to resolve the horizon and flatness problems.

Comparison of the expression for $\delta T/T$ in eq. (3) with the WMAP result shows that the gauge symmetry breaking scale M is around 10^{16} GeV [14], which is tantalizingly close to the GUT scale inferred from the evolution of the MSSM gauge couplings. Thus, it is natural to embed this kind of inflationary scenario within a GUT framework. However, in this case we must make sure that cosmological problems associated with topological defects such as monopoles do not arise. In addition, while constructing a realistic inflationary model based on supersymmetric GUT, we would also like to resolve the notorious DT splitting problem. These, as we will see, are most easily carried out in a five dimensional framework.

The scalar spectral index n_s is approximately given by

$$n_s \simeq 1 - \frac{1}{N}\,, \tag{4}$$

where N denotes the number of e-foldings experienced by the scale under consideration. For the horizon scale, in particular, $N_h \simeq 50 - 60$, so that

$$n_s^{(h)} = 0.98 \pm 0.01\,. \tag{5}$$

It should be noted that the inclusion of supergravity corrections can, in some cases, lead to a spectral index larger than unity [for a recent discusion and additional references, see ref. [14].]. The galactic scale corresponds to $N_g \simeq 40 - 50$, and given eq. (4), we conclude that the variation of n_s with k is quite tiny, $dn_s/d\ln k \sim 10^{-3} - \text{few} \times 10^{-4}$. It would be interesting to test this prediction against the ongoing and future observations.

As shown in refs. [11, 15, 5], a combination of the the gravitino constraint on the reheat temperature ($T_R \leq 10^{10}$ GeV [16]) as well as leptogenesis requires that the dimensionless superpotential coupling $\kappa \sim 10^{-3}$. Thus, the vacuum energy density during inflation is of order $10^{-6} M_{\rm GUT}^4$, so that the tensor-to-scalar ratio $r \sim 10^{-8}$, which could be hard to detect in any forseeable experiment.

After inflation is over the universe converts to a radiation dominated epoch through the superpotential couplings $\gamma_{ij}\bar{\phi}\bar{\phi}\mathbf{16}_i\mathbf{16}_j/M_P$, where $\mathbf{16}_i$ ($i = 1, 2, 3$) denote the three chiral families of SO(10) (with R-charge $= 1/2$), γ_{ij} is a dimensionless coupling, and M_P ($\simeq 2.4 \times 10^{18}$ GeV) is the reduced Planck mass. That is, the inflaton decay produces right-handed neutrinos whose out of equilibrium decay produces the observed baryon asymmetry via leptogenesis along the lines previously discussed in [9, 10, 5].

Next we present a realistic five dimensional SO(10) model in which the inflationary scenario described by the superpotential W in eq. (1) can be realized. We assume compactification on an orbifold $S^1/(Z_2 \times Z_2')$, such that on the two fixed points (branes) we have the gauge symmetries SO(10) and $\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ respectively. To realize the MSSM gauge group at low energies, we introduce the Higgs hypermultiplets $\mathbf{16}_H$ and $\overline{\mathbf{16}}_H$ in the bulk with $Z_2 \times Z_2'$ parities,

$$\mathbf{16}_H = (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2})_H^{++} + (\mathbf{4}, \mathbf{2}, \mathbf{1})_H^{+-}\,, \tag{6}$$

$$\mathbf{16^c}_H = (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2})_H^{c--} + (\mathbf{4}, \mathbf{2}, \mathbf{1})_H^{c-+}\,, \tag{7}$$

$$\overline{\mathbf{16}}_H = (\mathbf{4}, \mathbf{1}, \mathbf{2})_H^{++} + (\overline{\mathbf{4}}, \mathbf{2}, \mathbf{1})_H^{+-}\,, \tag{8}$$

$$\overline{\mathbf{16}}^{\mathbf{c}}{}_H = (\mathbf{4}, \mathbf{1}, \mathbf{2})_H^{c--} + (\overline{\mathbf{4}}, \mathbf{2}, \mathbf{1})_H^{c-+}\,. \tag{9}$$

The relevant superpotentials on the two branes, B1 (SO(10) brane) and B2 ($\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ brane) are:

$$
\begin{aligned}
W_{B1} &= \kappa S \left(\mathbf{16}_H \overline{\mathbf{16}}_H - M_1^2 \right) , \\
W_{B2} &= \kappa S \left(c_1 H^c \overline{H}^c + c_2 \mathbf{1}\mathbf{1}' - M_2^2 \right) + c_3 \Sigma H^c \overline{H}^c , \qquad (10)
\end{aligned}
$$

where $H^c \equiv (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2})_H^{++}$, $\overline{H}^c \equiv (\mathbf{4}, \mathbf{1}, \mathbf{2})_H^{++}$, and c_1, c_2, c_3 are dimensionless couplings. In W_{B2}, we exhibit only the chiral multiplets with $(++)$ parities of $\mathbf{16}_H$, $\overline{\mathbf{16}}_H$ which contain massless modes, since the heavy KK modes would be decoupled. Since the inflaton S is a bulk superfield, it participates in both superpotentials. In eq. (10), a pair of singlet superfields $\mathbf{1}$, $\mathbf{1}'$ and a superfield Σ in the adjoint representation $(\mathbf{15}, \mathbf{1}, \mathbf{1})$ with suitable $U(1)_R$ charges are introduced on B2.

During inflation, S and Σ develop VEVs ($\langle S \rangle > M_1, M_2$), while $\langle \mathbf{16}_H \rangle = \langle \overline{\mathbf{16}}_H \rangle = \langle H^c \rangle = \langle \overline{H}^c \rangle = \langle \mathbf{1} \rangle = \langle \mathbf{1}' \rangle = 0$. As shown in refs. [5, 6], positive vacuum energies localized on the branes could trigger exponential expansion of the three space, in the presence of a brane-localized Einstein-Hilbert term. Due to a non-zero VEV of Σ during inflation, the $\mathrm{SU}(4)_c$ factor in $\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ is spontaneously broken to $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{B-L}$, and the accompanying monopoles are inflated away.

In this brane model, $\mathbf{16}_H$, $\overline{\mathbf{16}}_H$ on B1, and $\mathbf{1}$, $\mathbf{1}'$ on B2 play the role of ϕ, $\bar{\phi}$ in eq. (1). With the (localized) VEVs of the scalar components of $\mathbf{16}_H$, $\overline{\mathbf{16}}_H$ along the SU(5) singlet direction (i.e. $\langle \nu_H^c \rangle$, $\langle \overline{\nu}_H^c \rangle$) at B1 after inflation, the SO(10) gauge symmetry breaks to SU(5). On the other hand, at B2 only the singlets $\mathbf{1}$, $\mathbf{1}'$ rather than H^c, $\overline{H}^c$ develop VEVs at the minimum of the potential. Since Σ becomes heavy by VEVs of $\mathbf{16}_H$, $\overline{\mathbf{16}}_H$ on B1, the VEV $\langle \Sigma \rangle$ vanishes after inflation, and so the symmetry $\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ on B2 is restored. Consequently, the effective low energy theory after inflation is the desired MSSM ($= \{\mathrm{SU}(5)\} \cap \{\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R\}$). We note that the symmetry breaking process $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{B-L} \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \to \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ does not create any unwanted topological defects such as monopoles, and so we have formulated a realistic 5D model in which the monopole problem is solved without introducing non-renormalizable terms.

While the Goldsotne fields $(\overline{\mathbf{3}}, \mathbf{1})_{-2/3}^{++}$, $(\mathbf{1}, \mathbf{1})_{-1}^{++}$ (also $(\mathbf{3}, \mathbf{1})_{2/3}^{++}$, $(\mathbf{1}, \mathbf{1})_{1}^{++}$) of H^c ($\overline{H}^c$) are absorbed by the appropriate gauge bosons, the superhiggs mechanism leaves intact the massless supermultiplets $(\overline{\mathbf{3}}, \mathbf{1})_{1/3}$, $(\mathbf{3}, \mathbf{1})_{-1/3}$, which can acquire masses of order $m_{3/2}$ from their couplings to $\langle S \rangle$ after supersymmetry breaking. To eliminate this pair from the low energy theory, we can introduce on B1 a 10-plet with couplings $\mathbf{16}_H \mathbf{16}_H \mathbf{10}$ and $\overline{\mathbf{16}}_H \overline{\mathbf{16}}_H \mathbf{10}$ (thus, $\mathbf{10}$ has an R-charge of unity), and/or a $(\mathbf{6}, \mathbf{1}, \mathbf{1})$ field ($\equiv D$) on B2 with couplings $H^c H^c D$ and $\overline{H}^c \overline{H}^c D$. Then, the pair acquires superheavy masses proportional to $\langle \nu_H^c \rangle$ or $\langle \overline{\nu}_H^c \rangle$, and the low energy spectrum is precisely the MSSM one.

Note that we introduced the Higgs 16-plets in the bulk rather than on the SO(10) brane B1 in order to avoid unwanted states associated with the pseudo-Goldstone symmetry of the superpotential. Recall that the orbifold compactification breaks SO(10) down to $\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$.

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To resolve the DT splitting problem, the Higgs 10-plet (or $(\mathbf{1},\mathbf{2},\mathbf{2})$) should be introduced in the bulk (on B2). By suitable $Z_2 \times Z_2'$ parity assignments, the MSSM Higgs doublets are kept light, while the color triplets become superheavy.

In summary, we have taken the approach that a satisfactory inflationary scenario should:

(i) resolve the flatness and horizon problem;

(ii) resolve cosmological problems associated with topological defects;

(iii) give rise to the observed $\delta T/T$ fluctuations;

(iv) provide a satisfactory explanation of the origin of the observed baryon asymmetry;

(v) be well grounded in particle physics.

While four dimensional SO(10) models of inflation are hard to construct, especially if a resolution of DT splitting problem is also desired, things are much easier if we consider five dimensional SO(10). In the model we have discussed, the gauge symmetry during inflation is broken to $\mathrm{SU}(3)_c \times \mathrm{U}(1)_{B-L} \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ so that monopoles are inflated away. When inflation ends, the unbroken gauge symmetry turns out to be $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$. The scalar spectral index n_s is very close (or even equal [14]) to unity, $dn_s/d\ln k \sim 10^{-3}$, and the tensor-to-scalar ratio $r \sim 10^{-8}$. The observed baryon asymmetry naturally follows from leptogenesis.

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