INFLATION AND THE $B - L$ BREAKING SCALE

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Inflation arises in supersymmetric grand unified theories (susy GUTs) without fine
tuning and cosmic strings usually form at the end of inflation. Hence both strings
and inflation contribute to the density perturbations in the very early universe
which lead to structure formation and to CMB anisotropies. This may give us a
hint as to the $B - L$ breaking scale.

1 Inflation and cosmic strings in susy GUTs

Inflation requires that there was a period in the early universe when the vacuum
energy density was non zero so that the cosmic scale factor grew exponentially.
In susy theories, the scalar potential is the sum of F-terms and D-terms. Hence
inflation can either come from the non vanishing vev of a F-term or by that
of a D-term. Inflation can also either come from the visible sector or from
the hidden sector which breaks susy at low energy and communicates with the
visible sector only via gravitational interaction. For a given GUT G, the full
superpotential can formally be written as:

$$W = W_{\text{GUT}}(A_i) + W_{\text{infl}}(S, \Phi, \overline{\Phi}) + W_{\text{ew}}(H_1, H_2) + W'_{\text{hidden}}(B_i),$$

where $W_{\text{GUT}}$ implements the breaking of G down
to the 3$c^2$L
1
$Y$ except from the breaking which is done in the inflaton sector
when inflation comes from the visible sector; $W_{\text{infl}}$ leads to a period of inflation,
$S$ is a scalar singlet under G and plays the role of the inflaton, and when
inflation comes from the visible sector $\Phi$ and $\overline{\Phi}$ are Higgs superfields which
transform non trivially under G; $W_{\text{ew}}$ breaks 3$c^2$L
1
$Y$ down to 3$c^1Q$;
$W'_{\text{hidden}}$ makes the breaking in the hidden sector, except from the part which is done
in the inflaton sector when inflation comes from the hidden sector.

The simplest superpotential for F-term inflation is given by:

$$W_{\text{infl}}^F = \alpha S\Phi\overline{\Phi} - \mu^2 S$$

and the scalar potential

$$V_{\text{infl}}^F = \alpha^2|S|^2(|\Phi|^2 + |\overline{\Phi}|^2) + |\alpha S\Phi - \mu^2|^2,$$

$\alpha, \beta \geq 0$. This potential reduces the rank of G by one unit and leads to in-
flation. Setting chaotic initial conditions, the fields quickly settle down to the
local minimum of the potential at $|S| > \frac{\mu}{\sqrt{\alpha}} = S_c$ and $\langle|\Phi|\rangle = \langle|\overline{\Phi}|\rangle = 0$; there
is a non-vanishing vacuum energy density $V = \mu^4$, susy is broken, and inflation
starts. Quantum corrections to the effective potential help the inflaton
to slowly roll down the potential. When $S$ falls below $S_c$, inflation stops, the
fields settle down to the global minimum of the potential at $\langle|\Phi|\rangle = \langle|\overline{\Phi}|\rangle = \frac{\mu}{\sqrt{\alpha}}$
and $S = 0$, susy is restored and the SSB associated with the vevs of $\Phi$ and $\overline{\Phi}$
takes place. It is easy to see that the above potential has got cosmic strings solutions, therefore cosmic strings form at the end of inflation.

The simplest superpotential for D-term inflation is given by \( W_{\text{D-infl}} = \alpha S \Phi_x \Phi_x \) and the scalar potential is \( V_{\text{D-infl}} = \alpha^2 |S|^2 (|\Phi_x|^2 + |\Phi_x|^2) + \alpha^2 |\Phi_x|^2 + \alpha^2 \left( |\Phi_x|^2 - |\Phi_x|^2 + \xi_x^2 \right) \), we now assume the presence of a Fayet-Iliopoulos D-term \( \xi_x \) which can only exist is \( G \) contains a \( U(1)_x \) factor. The evolution of the fields is very similar to the previous case. The local minimum is at \( |S| > \frac{\alpha}{\delta^2} \), \( \langle \Phi_x \rangle = \langle \Phi_x \rangle = 0 \) and the global susy minimum at \( \langle S \rangle = \langle \Phi \rangle = 0, \langle |\Phi| \rangle = \xi_x^2 \).

Hence in both types of scenarios cosmic strings form at the end of inflation, both strings and inflation will contribute to the CMB anisotropies.

2 CMB anisotropies and COBE normalisation

It is common to expand the temperature fluctuations in the CMB in terms of spherical harmonics: \( \delta T(\theta, \phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi) \), and then work with the multipole moments \( C_l = \frac{1}{2l+1} \sum_{m=-l}^l |a_{lm}|^2 \). For a mixed scenario with inflation and cosmic strings the total \( C_l \)'s are given by

\[
C_l^{\text{tot}} = C_l^{\text{infl}} + C_l^{\text{str}} \quad \text{with} \quad C_l^{\text{infl}} \propto \delta^2_H \quad \text{and} \quad C_l^{\text{str}} \propto (G\mu)^2 \quad (1)
\]

where, \( \delta^2_H \) is the spectrum of density perturbations from inflation at horizon crossing and \( \mu \) is the string mass per unit length; they can be calculated exactly from the slow roll parameters. In the case of D-term inflation we get \( G\mu = 2\pi \left( \frac{\xi_x}{M_{\text{pl}}} \right) \) and \( \delta_H = \alpha_{60} \frac{256\pi^2 121}{75} \left( \frac{\xi_x}{M_{\text{pl}}} \right) \), where \( \alpha_{60} \approx 1 \).

Combining Eqs. \( 1 \) we get the normalisation equation for a mixed scenario with inflation and cosmic strings: \( 1 = \left( \frac{G\mu}{(G\mu)^{\text{norm}}} \right)^2 + \left( \frac{\delta_H}{(\delta_H)^{\text{norm}}} \right)^2 \). Using the normalisation to COBE for strings from \( \delta \) and that for inflation from \( \delta \), we get \( (G\mu)^{\text{norm}} = 1.05 \times 10^{-6} \) and \( (\delta_H)^{\text{norm}} = 1.94 \times 10^{-5} \); we then find that the \( U(1)_x \) SSB scale is constraint by COBE to be \( \xi_x^2 = 4.7 \times 10^{15} \) GeV, and we also find that cosmic strings can contribute to the \( C_l \)'s up to the level of 75%.

3 Application: models with an intermediate \( U(1)_{B-L} \)

We now consider the general SSB pattern

\[
G \times \text{susy} \rightarrow ... \rightarrow 3c, 2L_2, 2R_1, 1_{B-L} \times \text{susy}
\]
\[ \frac{M_R}{\rightarrow} 3c_2L_1R_{B-L} \times \text{susy} \frac{M_{B-L}}{\rightarrow} 3c_2L_1Y_Z \times \text{susy} \]

where the discrete \( Z_2 \) is a subgroup of \( U(1)_{B-L} \) and plays the role of R-parity, and susy is broken at \( \sim 10^3 \text{ GeV} \). At \( M_G \) topologically stable monopoles in contradiction with observations form; at \( M_R \) more stable monopoles form; at \( M_{B-L} \) \( B-L \) cosmic strings (the Higgs field forming the string is the same Higgs field used to break \( B - L \) form, they are good candidate for baryogenesis. To satisfy observations, a period of inflation is needed between \( M_R \) and \( M_{B-L} \). We can also consider models without the intermediate \( M_G \) or \( M_R \), the conclusion upon \( M_{B-L} \) would be the same.

If inflation comes from the GUT itself, the superpotential in the inflation sector is \( W_{\text{infl}}(S, \Phi_{B-L}, \Phi_{B-L}) \), \( \Phi_{B-L} \) and \( \Phi_{B-L} \) are Higgs used to break \( B-L \) (if \( G = \text{SO}(10) \) they would be a pair of \( 126 + \overline{126} \)-dimensional representations). In this case, COBE constraints the \( B-L \) breaking scale to be \( M_{B-L} = 4.7 \times 10^{15} \text{ GeV} \) and \( B-L \) cosmic strings form at the end of inflation.

If inflation comes from the hidden sector, then there is considerable freedom in choosing \( M_{B-L} \). However, both \( M_G \) and \( M_R \) must be greater than \( 4.7 \times 10^{15} \text{ GeV} \) for the monopoles problem to be solved, unless \( M_G, M_R < 10^{11} \text{ GeV} \). In that case, the strings which form at the of inflation only communicat to the visible sector via gravitational interactions.

The above class of models is phenomenologically very interesting, it provides both CDM and HDM in the form of the LSP and a massive neutrino respectively, baryogenesis via leptogenesis takes place at the end of inflation, and both strings and inflation must be at the origin of density perturbations in the early universe which lead to structure formation and CMB anisotropies.

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References

1. E.J. Copeland, A.R. Liddle, D.H. Lyth, E.D. Stewart and D. Wands, Phys. Rev. D 49, 6410 (1994); G. Dvali, Q. Shafi and R. Schaefer, Phys. Rev. Lett. 73, 1886 (1994).
2. P. Binetruy and G. Dvali, Phys. Lett. B 388, 241 (1996); E. Halyo, Phys. Lett. B 387, 43 (1996).
3. B. Allen, R.R. Caldwell, E.P.S. Shellard, A. Stebbins and S. Veeraghavan, Phys. Rev. Lett. 79, 2624 (1997).
4. E.F. Bunn, A.R. Liddle and M. White, Phys. Rev. D 54, 5917R (1996).