COSMOLOGY OF $\mathrm{B}-\mathrm{L}$ COSMIC STRINGS

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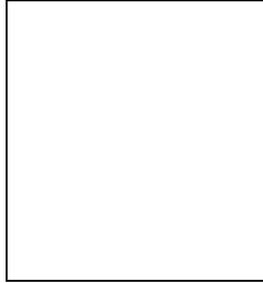
$\mathrm{B}-\mathrm{L}$ cosmic strings form in a wide class of theories beyond the Standard Model which contain a $\mathrm{U}(1)_{\mathrm{B-L}}$ gauge symmetry. They can form at the end of hybrid inflation and explain, together with inflation, the Cosmic Microwave Background anisotropies and the formation of large scale structure. They can produce Cold Dark Matter in the form of the Lightest SuperParticle and they can be at the origin of the baryon asymmetry of our universe. One major advantage of these mechanisms is that they are non-thermal.

1 Motivations

Theories beyond the Standard Model based on gauge groups G which contain a $\mathrm{U}(1)_{\mathrm{B-L}}$ gauge symmetry (B and L are respectively baryon and lepton numbers) are very interesting for both particle physics and cosmology. First of all, they predict the existence of right-handed neutrinos and the left-handed neutrinos can acquire very small masses according to the see-saw mechanism[1]; the neutrino oscillations discovered by the SuperKamiokande[2] are predicted. Next, if the theory is supersymmetric, the Lightest SuperParticle (LSP) can remain stable down to low energies and becomes a good Cold Dark Matter (CDM) candidate. This is due to the fact that $\mathrm{U}(1)_{\mathrm{B-L}}$ contains a Z_2 discrete symmetry which can be left unbroken down to low energies if Higgs in *safe* representations of G are used to break G down to low energies. This plays the role of R-parity[3] and in such theories the LSP can be automatically stable. The third main interesting point for cosmology is that inflation emerges *naturally*, i.e. no field nor any symmetry other than the ones used to build the theory itself are needed for inflation to arise; and natural values of the parameters are obtain when constraints from the Cosmic Microwave Background Explorer (COBE) data are applied[5]. If the existence of a unified gauge group G is assumed, it must somehow be broken down to the Standard Model gauge group. It can either break directly or via one or more intermediate gauge symmetry $\mathrm{G} \to ...?... \to \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y = \mathrm{G_{SM}}$.

Therefore, if in the very early Universe symmetries between particles were described by a gauge group larger than G_{SM}, the Universe must have undergone a series of phase transitions associated with spontaneous symmetry breakings. These symmetry breakings may have lead to non-trivial topologies of the vacuum manifold and topological defects may have formed according to the Kibble mechanism[4]. It is well known that all unified theories lead to the formation of topological monopoles which are topologically stable down to low energies and are in conflict with observations - this is true as soon as the $U(1)_Y$ gauge symmetry of the Standard Model is embedded in a non-abelian group which does not contain U(1) factor. Hence some mechanism has to be invoked to disperse these monopoles. The standard scenario for solving the monopole problem is inflation. Inflation also solves many of the cosmological problems such as the horizon problem and predicts the formation of the large scale structure. Inflation is always confronted with fine-tuning problems unless supersymmetry is invoked. The standard scenario for inflation in supersymmetric theories is the so-called F-term hybrid scenario[6] and it can be implemented in theories which contain $U(1)_{\text{B–L}}$ [5]. In the simplest model of F-term inflation topological defects form at the end of inflation, and hence an intermediate symmetry is needed to solve the monopole problem. In this case, the general symmetry breaking pattern will thus have to be of the form $G \rightarrow H \rightarrow G_{SM}$, with H chosen in such a way that monopoles form when G breaks down to H, then inflation takes place driven by some scalar field associated with the breaking of H, and at the end of inflation H spontaneously breaks down to G_{SM} and no unwanted defects must be formed. It is not easy to find an adequate H. One possibility, is to chose H such that $B - L$ strings form when H breaks down to G_{SM}.

1.1 $B - L$ *cosmic strings*

Cosmic strings form according to the Kibble mechanism during the phase transition associated with the spontaneous symmetry breaking of a gauge group H down to a subgroup K of H if the first homotopy group of the vacuum manifold $\frac{H}{K}$ is non trivial. $B - L$ cosmic strings form when a gauge group H which contains $U(1)_{\text{B–L}}$ breaks down to a subgroup K of H which does not contain $U(1)_{\text{B–L}}$ if $\pi_1(\frac{H}{K}) \neq I$. The Higgs field which forms the string is a Higgs field in a complex representation of H which breaks H and local $B - L$ symmetry when acquiring a non-vanishing vacuum expectation value; we call it $\phi_{\text{B–L}}$. In supersymmetric theories, the superpotential has to be holomorphic and two Higgs superfields $\Phi_{\text{B–L}}$ and $\overline{\Phi}_{\text{B–L}}$ in complex conjugate representations are needed to break $B - L$; $B - L$ cosmic strings are then made of two Higgs fields (the scalar components of $\Phi_{\text{B–L}}$ and $\overline{\Phi}_{\text{B–L}}$) which wind around the string in opposite directions. The simplest model in which $B - L$ strings are formed is during the symmetry breaking $SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{\text{B–L}} \rightarrow G_{SM}$.

2 $B - L$ **Strings and Inflation**

2.1 *Hybrid inflation*

As mentioned in the introduction, $B - L$ cosmic strings can form at the end of F-term hybrid inflation. This is the case when the superpotential in the sector which breaks H and $B - L$ is given by:

$$W_{\text{B–L}} = \alpha S \overline{\Phi}_{\text{B–L}} \Phi_{\text{B–L}} - \mu^2 S \tag{1}$$

where S is a superfield singlet under H, μ and α are two constants which are taken to be positive and $\frac{\mu}{\sqrt{\alpha}}$ sets the $B - L$ breaking scale. In such models, the strings together with inflation generate the cosmological perturbations, and the strings contribution to the CMB is non-negligible but model dependent[5]. Both the strings and the inflation perturbations are proportional to $\frac{\mu}{\sqrt{\alpha}}$ and COBE data gives the constraint $\frac{\mu}{\sqrt{\alpha}} \simeq 4.7 \times 10^{15}$ GeV. The mass-per-unit length of the

strings is $\propto \frac{\mu^2}{\alpha}$. The parameter α is determined such as to solve the horizon problem and values of order $10^{-2} - 10^{-3}$ can be found. A realistic model based on SO(10) has been built[7].

Numerical work based on a toy U(1) model has shown that a mixed scenario with inflation and strings soften the oscillations in the CMB power spectrum predicted by inflation alone and may well better fit the data[8]. If this is confirmed by new experimental data and by improved simulations - using a realistic model and taking into account the fact that the strings form at the end of inflation i.e. may have a specific distribution - the motivation for studying such models would be even stronger.

2.2 Thermal inflation

If a superpotential containing only non-renormalisable terms is used to break $\mathrm{B-L}$, such as

$$W_{\mathrm{B-L}} = \lambda \frac{(\overline{\Phi}_{\mathrm{B-L}} \Phi_{\mathrm{B-L}})^2}{M} \tag{2}$$

where λ is constant taken to be positive and M is a superheavy scale beyond which quantum gravity takes place, a period of thermal inflation takes place[9]. This can solve the monopole problem if the $\mathrm{B-L}$ breaking scale is $\sim 10^{11}$ GeV. But it cannot be at the origin of the large scale structure nor solve the horizon problem. At the end of this low energy inflationary period fat $\mathrm{B-L}$ cosmic strings formed. We would like to point out that it is not easy to build such a realistic model.

Thermal inflation dilutes the monopoles previously formed but it also dilutes any baryon asymmetry which might have been previously generated; and it is in general very difficult to produce the observed baryon asymmetry after thermal inflation. However, here, baryogenesis via leptogenesis can take place at the end of inflation through the decay of the right-handed neutrinos released by decaying $\mathrm{B-L}$ cosmic string loops[10]. This scenario is independent of the reheat temperature of the universe after the inflationary era.

3 $\mathrm{B-L}$ cosmic strings produce CDM

One of the major problem faced by the standard cosmology is to explain the dark matter component of the Universe. In supersymmetric theories with conserved R-parity, the LSP is stable and is a good CDM candidate. As mentioned in the introduction, in theories which predict $\mathrm{B-L}$ cosmic strings, the LSP can be automatically stable[3]. When a network of strings is formed, infinite strings and loops are initially formed. More loops are formed by the intercommuting of the long strings. String loops rapidly decay by emitting elementary particles and gravitational radiation. The main decay channel of $\mathrm{B-L}$ cosmic strings loops is into right-handed neutrinos and sneutrinos. If the LSP is Higgsino, then these will directly decay into the LSP and if the LSP is bino as is usually the case in left-right models, subsequent decay will produce the LSP. A scaling network of $\mathrm{B-L}$ cosmic strings can thus produce LSPs and these in non-negligible quantities[11]. This mechanism of LSP production, as is the leptogenesis mechanism, is non-thermal. We find that the LSP number density today released by decaying cosmic string loops is given by:

$$Y_{LSP}^{nonth} = \frac{n_{LSP}^{nonth}}{s} = \frac{6.75}{\pi} \epsilon \nu \lambda^2 \Gamma_{loops}^{-2} g_{*T_{\mathrm{B-L}}}^{\frac{-9}{4}} g_{*T_\chi}^{\frac{3}{4}} M_{pl}^2 \frac{T_\chi^4}{T_{\mathrm{B-L}}^6} \, , \tag{3}$$

where ϵ denotes the branching ratio of the right-handed neutrinos into LSP, λ is the the Higgs self coupling and $\Gamma_{loops} \simeq 10 - 20$ is a numerical string parameter. $g_{*T_{\mathrm{B-L}}}$ and g_{*T_χ} count the number of massless degrees of freedom at the critical temperature $T_c = T_{\mathrm{B-L}}$ at which the strings form and at the LSP freeze-out temperature T_χ respectively. M_{pl} is the Planck mass. In
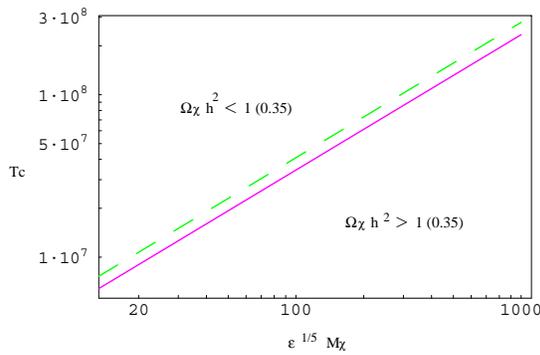
Figure 1: The critical temperature T_c as a function of the branching ratio and the LSP mass for $\Omega_\chi h^2 = 1$ (solid line) and $\Omega_\chi h^2 = 0.35$ (dashed line). The region above the curves corresponds to $\Omega_\chi h^2 < 1$ ($\Omega_\chi h^2 < 0.35$ respectively) and the region below corresponds to $\Omega_\chi h^2 > 1$ ($\Omega_\chi h^2 > 0.35$). The latter is excluded by observations.

Fig.1 we plot T_c a function of the LSP mass M_χ. The region above each curves corresponds to $\Omega_\chi h^2 < 1$ ($\Omega_\chi h^2 < 0.35$ respectively), and the region below to $\Omega_\chi h^2 > 1$ ($\Omega_\chi h^2 > 0.35$ respectively); this region is excluded by observations.

4 Conclusions

$B - L$ cosmic strings can form in all unified theories based on gauge groups with rank greater than five. They are very interesting cosmologically because they can explain the matter-antimatter asymmetry of the Universe, they can form at the end of inflation and modify the CMB power spectrum, and they can produce CDM in non-negligible quantities.

Acknowledgments

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