Chapter 7

Summary

We finally close our discussions with summary and some concluding remarks. In the introductory chapter, we have mentioned several phase transitions which are predicted to have occurred during the expansion history of the universe. The consequences of these phase transitions are manifold. For example, depending on the specific details of the unified models, the phase transition associated with GUT symmetry breaking may lead to the formation of topological defects, e.g., domain walls, strings or monopoles. The presence of such defects in the early universe could crucially affect the evolution of the universe in several ways. Among these, cosmic strings are the most fascinating and most throughly studied defects because of it's various important cosmological and astrophysical consequences. It was believed earlier that the cosmic string generated fluctuations can be the seed of the structure formations. However, the density fluctuations from the cosmic strings and other topological defects are not consistent with the latest WMAP data. Of course, even with present models of cosmic string network evolution, it is not completely ruled out that cosmic strings may contribute to some part in the structure formation in the universe.

In this thesis, we have discussed cosmic string induced density fluctuations from a different point of view. Our main motivations for these discussion rely on the fact that these density fluctuations could affect the dynamics of phase transitions in important ways. We have introduced a model [14], where it was proposed, that the quark-hadron phase transition in the presence of cosmic string induced density fluctuations can lead to the formation of baryon inhomogeneities with large amplitude. It was also suggested that, these baryon inhomogeneities may survive various dissipative processes until the stage of the nucleosynthesis and can affect the outcome of primordial abundances of light elements. However, as we know that, one of the successful stories of the standard model of cosmology is to reproduce the primordial abundances correctly. In SBBN theory, the distribution of baryons were assumed to be homogeneous at the onset of the nucleosynthesis. Therefore, any deviation from baryon homogeneities at the onset of the nucleosynthesis could spoil the seemingly successful SBBN calculations of primordial abundances. Though several modifications to SBBN are still being considered to better account for the abundances of light elements. One such possibility discussed extensively in the literature is the so called inhomogeneous big bang nucleosynthesis (IBBN) [22, 23], where nucleosynthesis takes place in the presence of baryon number inhomogeneities. So the natural question is that, without disturbing significantly the abundance of elements which are consistent within SBBN calculations, how much inhomogeneities till can be accommodated at the onset of the nucleosynthesis. These constraints on baryon inhomogeneities motivated us to determine the amplitude and the length scale of baryon inhomogeneities which can be generated in the model of ref.[14]. The results thus obtained can be used to constrain the parameters of that particular model which are responsible for the generation of baryon fluctuations in the early universe.

We have found out that, if the quark-hadron phase transition occurs in the presence of cosmic string induced density fluctuations, then the baryon inhomogeneities can be generated with large magnitude. The length scale and the magnitude are such that, they could indeed survive until the stage of nucleosynthesis. Analyzing our results with the IBBN model developed by Kainulainen et al. [22], we found out that these baryon inhomogeneities can affect the calculations of abundances of light elements significantly. We have discussed that, such inhomogeneities can be avoided if the cosmic string formation scale is some what smaller than about 10^{14} GeV. Alternatively, some other input in our calculation can also be constrained. For example, the average string velocity can be sufficiently small so that significant density perturbations are never produced at the QCD scale, or strings may move ultra-relativistically so that resulting wakes are very thin, and trap a negligible amount of baryon number.

In this thesis, we have discussed another consequence of quark-hadron phase transition, namely, the trapping of axions by cosmic string wakes which could eventually form axionic inhomogeneities. Although there are several sources [89] from which axions can be generated, we focussed only on those axions which are generated from the oscillations of axionic strings. The dynamics of axions during quark-hadron phase transition has been studied previously by Hindmarsh [29], as we have mentioned in this thesis. It was proposed that during the quark-hadron phase transition, the low momentum axions are expected to get trapped initially inside the shrinking bubbles of quark phases. This happens because of the fact that the mass of the axions is relatively larger in the hadronic phase compared to that in the quark phase. As the transition further proceeds, the axions gradually pick up momentum from the walls of the shrinking QGP bubbles and can escape from the quark phases. These axions which are left behind as the QGP bubbles collapse can form isocurvature fluctuations.

In this thesis, we have considered the trapping of the axions in the presence of cosmic string wakes. We have shown, that the geometry of the collapsing interfaces in our model is of sheet like planar structure in contrast to the spherical geometry as was discussed in ref.[29]. Thus, the geometry of the over dense regions of axions in our model is also of sheet like structure unlike the spherical clumps as studied by Hindmarsh [29]. The amplitude of the isocurvature fluctuations as we have found out is quite large, which is of the order of $(\frac{\delta\rho}{\rho})_{axion} \sim 10^5$. These over dense axions will be concentrated within a planar sheet like region of thickness few cm. The sheet can extend upto a distance scale of order of a km at QCD scale. We have mentioned the possible implications of these fluctuations, especially on small scale

CMBR anisotropies.

We have also mentioned another mechanism through which axionic inhomogeneities can be generated. As we know, for collisionless particles, moving cosmic string can produce density fluctuations with magnitude of order unity and angle of the wakes being equal to the deficit angle, $8\pi G\mu$. Since, the axions are almost collisionless, axionic inhomogeneities can be generated by above mechanism also. These over dense axions could be concentrated within very thin sheet like region of thickness $8\pi G\mu\ d_H \sim 1$ cm. However, the magnitude of these inhomogeneities is very small (of order unity) compared to the case where axionic inhomogeneities is produced by the collapsing interfaces, as mentioned above. Essentially, these thin sheet like regions will be trapped initially inside the wake of larger thickness which is produced by the formation of shock by moving string through relativistic fluid. Ultimately, these over-dense axions will also escape from this thin wake and contribute in producing overall isocurvature fluctuations.

In this thesis, we presented our study on Skyrmion formation via the kibble mechanism by incorporating a bias term in the effective potential for the linear sigma model. Such a bias term is necessary, when one has to deal with physical phenomenon where formation of defects is favored over the anti-defects (or vice-versa), for example, flux tube formation in superconductors in the presence of external magnetic field. This bias term not only has effects on defect density, it may also affect defect-anti-defect correlations.

A similar situation arises in the context of Skyrmion picture of baryon formation. When one wants to study baryon formation during chiral phase transition in relativistic heavy-ion collisions, then one has to deal with the situation of non-zero baryon excess over antibaryons. This requires that the basic mechanism of Skyrmion formation should be able to incorporate an intrinsic bias in favor of Skyrmions over anti-Skyrmions (depending on the sign of the chemical potential).

To initiate investigation in this direction we restricted ourselves to 1+1 dimensions only. We have shown that incorporation of a chemical potential term in the effective potential leads to a domain structure where order parameter is spatially varying. We have done analytical calculation as well as numerical simulation to study the formation of Skyrmion/anti-Skyrmion for two domains case. Here, we have seen that even in two domain case, Skyrmion can be produced due to the bias term in the effective potential (with positive chemical potential term) in contrast to the result obtained from standard mechanism of defects and anti-defects formations. In case of three domains, we have done numerical simulation and show that probability of formation of Skyrmion over anti-Skyrmion is highly enhanced with positive chemical potential terms. Also the probability of anti-Skyrmion drops to zero after certain value of chemical potential. We have discussed the interesting possible relationship of this kind of behavior with the critical value of chemical potential μ_c in the QCD phase diagram at $T = 0$.

Before ending the thesis, let us make few comments on our model based on which calculations have been done. Firstly, while determining the inhomogeneities of baryons and axions, we have used rather simple picture of cosmic string wakes. We have considered the cosmic string wakes to be parallel. We have mentioned, however, the number of long strings per horizon is about 15. Thus, there is every possibility of overlap of the wakes produced by these strings. This fact should be taken into account while determining the detailed amplitudes and length scales of the inhomogeneities.

We also mention here that, we have not considered the effects of density fluctuations produced by string loops. These will also lead to baryon number inhomogeneities via the effects discussed in this thesis. However, these structures will be on a more localized scale. It is more complicated to calculate the effects of density fluctuations by oscillating loops (especially when time scales are of crucial importance). Still, a more complete investigation of the effects of cosmic strings on quark-hadron transition should include this contribution also.

Lastly, our study on the effects of a bias term in the theory of defect formation has so far been investigated in 1+1 dimensions. In this study, we have ignored the issues of boundary conditions by assuming the one dimensional physical space to be compact, i.e., S^1. We further assumed that the size of the circle to be sufficiently small so that it can accommodate only a couple of correlation domains which are sufficient to form one Skyrmion in the whole circle. This way the issue of boundary condition becomes irrelevant. However, when one needs to investigate the formation of Skyrmions in a one-dimensional space of large extent, then the issues of boundary conditions will play a significant role in determining the net defect density. For 2 and 3 dimensions one needs to work out the exact nature of spatial variation of the chiral order parameter within a domain as well as for inter-domain regions. Then the program which is described in this thesis can be easily extended for these dimensions as well.