The Peccei–Quinn Field as Curvaton
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A simple extension of the minimal supersymmetric standard model which naturally and simultaneously solves the strong CP and $\mu$ problems via a Peccei-Quinn and a continuous R symmetry is considered. This model is supplemented with hybrid inflation and leptogenesis, but without taking the specific details of these scenarios. It is shown that the Peccei-Quinn field can successfully act as a curvaton generating the total curvature perturbation in the universe in accord with the cosmic background explorer measurements. A crucial phenomenon, which assists us to achieve this, is the ‘tachyonic amplification’ of the perturbation acquired by this field during inflation if the field, in its subsequent evolution, happens to be stabilized for a while near a maximum of the potential. In this case, the contribution of the field to the total energy density is also enhanced (‘tachyonic effect’), which helps too. The cold dark matter in the universe consists, in this model, mainly of axions which carry an isocurvature perturbation uncorrelated with the total curvature perturbation. There are also lightest sparticles (neutralinos) which, like the baryons, originate from the inflationary reheating and, thus, acquire an isocurvature perturbation fully correlated with the curvature perturbation. So, the overall isocurvature perturbation has a mixed correlation with the adiabatic one. It is shown that the presently available bound on such an isocurvature perturbation from cosmic microwave background radiation and other data is satisfied. Also, the constraint on the non-Gaussianity of the curvature perturbation obtained from the recent Wilkinson microwave anisotropy probe data is fulfilled thanks to the ‘tachyonic effect’.

Cosmology of Theories beyond the SM, Cosmological Phase Transitions, Physics of the Early Universe

Introduction sect:introduction
The recent data wmap on the acoustic peaks of the angular power spectrum of the cosmic microwave background radiation (CMBR) strongly favor the idea of inflation, which offers the most elegant solution to the outstanding problems of standard big bang cosmology and exterminates unwanted relics such as monopoles. Moreover, inflation is now generally accepted as the most likely origin of the primordial density perturbations which are needed for explaining the structure formation in the universe llbook. The usual assumption is llbook,lectures that these perturbations come solely from the slowly rolling inflaton field. In this case, the observed density perturbations are expected to be purely adiabatic, since fluctuations in the inflaton cannot cause an isocurvature perturbation. Also, significant non-Gaussianity is not encountered onefield in the usual one-field inflationary models, while the non-Gaussianity which is possible multifield in multifield models requires extreme fine-tuning of the initial conditions. However, although adiabatic and Gaussian perturbations are perfectly consistent with the present data, appreciable non-Gaussianity nongauss or the presence of a significant isocurvature density perturbation trd,agws cannot be excluded by observations.

An alternative possibility curv, which has recently attracted attention curv1,luw02,curv2,dimo,curv3,gl, curv4,prep, is that the adiabatic density perturbations originate from the vacuum perturbations during inflation of some light ‘curvaton’ field different from the inflaton. In the curvaton scenario, significant non-Gaussianity may easily appear because the curvaton density is proportional to the square of the curvaton field amplitude. Also, the curvaton density perturbations can lead, after curvaton decay, to isocurvature perturbations in the densities of the various components of the cosmic fluid. In the simplest case, the residual isocurvature perturbations are either fully correlated or fully anti-correlated with the adiabatic density perturbation, with a calculable and generally significant relative magnitude. In the presence of axions, however, the correlation is, in general, mixed. It is important to be noted that the curvaton hypothesis makes dimo the task of constructing viable models of inflation much easier, since it liberates us from the very restrictive requirement that the inflaton is responsible for the curvature perturbations.

The most compelling extension of the standard model (SM) of particle physics is its supersymmetric (SUSY) version, the so-called minimal supersymmetric standard model (MSSM). It is, however, clear that
even the MSSM must be part of a larger scheme since it leaves a number of fundamental questions unanswered. For instance, the strong CP and $\mu$ problems cannot be solved in MSSM. Also, it is not easy to generate in MSSM the observed baryon asymmetry of the universe by electroweak sphaleron processes or to realize inflation.

The strong CP problem can be elegantly resolved by including a Peccei-Quinn (PQ) symmetry broken spontaneously at an intermediate mass scale, which can be easily generated within the supergravity (SUGRA) extension of MSSM. The PQ field, which breaks the PQ symmetry, corresponds, in this case, to a flat direction in field space lifted by non-renormalizable interactions. Moreover, the $\mu$ parameter of MSSM can be generated from the PQ scale. A minimal extension of MSSM, which solves the strong CP and $\mu$ problems along these lines, has been constructed in Ref. [98]. A key ingredient was a global $U(1)$ symmetry obeyed by the superpotential. This model has been further extended to simple SUSY grand unified theory (GUT) models leading to hybrid inflation and yielding successful baryogenesis via a primordial leptogenesis in accord with the data on neutrino masses and mixing. Also, the R symmetry implies exact baryon number conservation, thereby explaining proton stability.

In this paper, we examine whether, in the above models, the PQ field, which possesses an almost flat potential, can also play the role of the curvaton generating the adiabatic curvature perturbations with a possibly significant non-Gaussian component, while accompanied also by an isocurvature density perturbation. An important requirement is that the PQ field is effectively massless during inflation. In view of the quasi-flatness of the potential, one would imagine that this condition could be easily fulfilled by just ensuring that the value of the PQ field during inflation is not too large. However, as it is well-known crisis, large SUGRA corrections during inflation can destroy the quasi-flatness of the PQ potential and, thus, invalidate the possibility of using the PQ field as curvaton. Therefore, it is crucial to assume that some mechanism is employed to keep these corrections under control.

After the end of inflation, the inflaton starts performing coherent damped oscillations and eventually decays reheating the universe. We assume that the SUSY breaking corrections to the PQ potential which arise from the finite energy density of the oscillating inflaton field are also relatively small. Under these circumstances, the PQ field remains overdamped and, thus, undergoes a slow evolution for quite some time after the termination of inflation. At later cosmic times, however, it settles into coherent damped harmonic oscillations about zero or the PQ vacua, depending on its value at the end of inflation. Actually, we find that the values of the PQ field at the end of inflation fall into well-defined alternating bands which lead to the trivial (false) vacuum or the PQ vacua in turn. Of course, bands leading to the trivial vacuum must be excluded.

The perturbation acquired by the (light) PQ field during inflation evolves at subsequent times and, when the system settles into damped quadratic oscillations about the PQ vacua, yields a stable perturbation in the energy density of the oscillating field. After the PQ field decays, this perturbation is transferred to the radiation dominated plasma, thereby generating the total curvature perturbation. We find that, if the PQ field, as it evolves, happens to stay near a maximum of the potential for some time, its primordial perturbation from inflation is drastically enhanced and, thus, the resulting energy density perturbation of the oscillating field can be quite sizeable. Also, the contribution of the oscillating field to the total energy density comes out, in this case, larger due to the delay in the onset of the field oscillations caused by the temporary rest of the field near a maximum. Thus, the final curvature perturbation can be adequate to meet the cosmic background explorer (COBE) results. This ‘tachyonic amplification’ of the inflationary perturbation of the PQ field as well as the enhancement of its contribution to the energy density, which occur well after the end of inflation, are crucial for the viability of our scheme.

The cold dark matter (CDM) of the universe, in our case, consists of axions and lightest neutralinos. The latter originate from the late decay of the gravitinos which are generated during the reheating process which follows inflation. In accordance to the curvaton hypothesis, the inflaton and, thus, the radiation which emerges from its decay at reheating possess practically no partial curvature perturbation. Therefore, the baryons, which originate from a primordial leptogenesis taking place at reheating, as well as the neutralinos carry negligible partial curvature perturbation. Then, at curvaton decay, where its curvature perturbation is transferred to the radiation, the baryons and the neutralinos acquire an isocurvature perturbation, which is fully correlated with the total curvature perturbation. The axions, which come into play at the QCD phase transition, also acquire isocurvature perturbation which is, though, uncorrelated with
the total curvature perturbation. So, we finally obtain an isocurvature perturbation of mixed correlation with the curvature perturbation. We apply the most stringent available restriction on such isocurvature perturbations. This restriction results from the set of the CMBR and other data used in Ref. gl.

In our scheme, the curvaton decays somewhat before dominating the energy density of the universe. This can generate appreciable non-Gaussianity in the curvature perturbation. We consider the bound nongauss on the possible non-Gaussian component of the curvature perturbation from the recent CMBR data which were obtained by the Wilkinson microwave anisotropy probe (WMAP) satellite. The ‘tachyonic effect’, i.e. the possible rest of the field near a maximum of the potential for a period of time, is essential also for the fulfillment of the non-Gaussianity requirement.

The paper is organized as follows. In section sect:solution, we summarize the minimal extension of MSSM which solves the strong CP and \( \mu \) problems via a PQ and a R symmetry. We also indicate the salient features of the simple SUSY GUTs which further extend this model and yield hybrid inflation and successful baryogenesis. In section sect:evolution, we outline the evolution of the PQ system during inflation, the subsequent inflaton oscillations and the period after reheating. In section sect:curvaton, we discuss the conditions under which the PQ field can successfully act as a curvaton. In particular, we consider the constraints on the total curvature and isocurvature perturbation from the COBE results and other data. The requirements from the CDM in the universe are also taken into account. Section sect:analysis is devoted to the detailed numerical analysis of the evolution of the PQ field and its perturbations which originate from inflation. The various requirements of section sect:curvaton and the constraints from the non-Gaussianity of the curvature perturbation are numerically studied. Finally, in section sect:conclusion, we summarize our main conclusions.

A simultaneous solution of the strong CP and \( \mu \) problems sect:solution

It is well-known that, in the context of the SUGRA extension of MSSM, appropriate flat directions in field space can generate an intermediate scale equation \( M_I \sim (m_3/2m_P)^{12} \sim 10^{11} - 10^{12} \text{GeV} \).