

Inflatonic Q-ball evaporation: A new paradigm for reheating the Universe

Anupam Mazumdar

*The Abdus Salam International Centre for Theoretical Physics,
Strada Costiera-11, 34100, Trieste, Italy*

and

*Physics Department, McGill University,
3600-University Road,
Montreal, H3A 2T8, Canada*

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We show that the inflaton condensate associated with a global symmetry can fragment into quasi stable Q balls after the end of inflation, provided the inflaton oscillations give rise to an effective equation of state with negative pressure. We argue that chaotic inflation with a running inflaton mass may give rise to the desired scenario where the process of fragmentation into inflatonic Q balls can actually take place even though there is total zero charge. We show that such inflatonic Q balls will reheat the Universe to a sufficiently low temperature via surface evaporation.

I. INTRODUCTION

Inflation, as the early Universe paradigm, inflates away all spatial inhomogeneities except the quantum fluctuations which is observationally bounded by one part in 10^5 , see [1]. The creation of matter and entropy generation takes place only when the inflaton, as a condensate, breaks-up and decays into the Standard Model degrees of freedom. This may either happen via perturbative decay of the condensate [2, 3] or via non-perturbative processes dubbed as preheating [4, 5]. Preheating typically involves an amplification in some of the fluctuation modes as well as the fragmentation of the inflaton condensate. Reheating dynamics depends very much on the form assumed for the inflaton potential, and for some choices, the inflaton condensate may also form Q -balls, see [6–8]. The Q -balls do not decay throughout their volume, but evaporates only via surface interaction [9], see a review [10] on Q -balls and their cosmological consequences.

II. REHEATING AS A SURFACE EFFECT

Usually the process of reheating is taken to be entirely a volume effect. This can be problematic, however, especially if the scale of inflation is high, i.e. $H_{inf} \sim 10^{15} - 10^{16}$ GeV, as it is sometimes assumed in order to provide the right magnitude for the density perturbations, and also for reasons that have to do with non-thermal heavy dark matter production or exciting right-handed Majorana neutrinos for leptogenesis, etc., (see for alternative low scale non-thermal leptogenesis [11])

As it is well known, the entropy thus dumped into the Universe may pose a problem for big bang nucleosynthesis by overproducing gravitinos from a thermal bath; an often quoted bound on the reheat temperature is $T_{rh} \leq 10^9$ GeV [12]. Note that gravitino can also be produced non-thermally [13], and there are other supersymmetric relics such as inflatino

[14]. Though, it was recently pointed out that inflatino production is not dangerous for the big bang nucleosynthesis [15]. Nevertheless, Obtaining such a low reheat temperature is a challenge for high scale inflation models especially if the inflaton sector and the Standard Model sector are strongly coupled. One way to solve the gravitino problem is to dilute them via a brief period of late thermal inflation [16], or assuming that the inflaton sector is a hidden sector while matter along with density perturbations are created from the observable sector Minimal supersymmetric Standard Model flat directions, see [17]. Low scale inflation can also solve the gravitino problem [18].

A novel way to avoid the gravitino problem is reheating via the surface evaporation of an inflatonic soliton. Compared with the volume driven inflaton decay, the surface evaporation naturally suppresses the decay rate by a factor

$$\frac{area}{volume} \propto L^{-1}, \quad (1)$$

where L is the effective size of an object whose surface is evaporating. The larger the size, the smaller is the evaporation rate, and therefore the smaller is the reheat temperature.

Reheating as a surface phenomenon has been considered [6, 7] in a class of chaotic inflation models where the inflaton field is not real but complex. As the inflaton should have coupling to other fields, the inflaton mass should in general receive radiative corrections [1], resulting in a running inflaton mass and in the simplest case in the inflaton potential that can be written as

$$V = m^2 |\Phi|^2 \left[1 + K \log \left(\frac{|\Phi|^2}{M^2} \right) \right], \quad (2)$$

where the coefficient K could be negative or positive, and m is the bare mass of the inflaton. The logarithmic correction to the mass of the inflaton is something one would expect because of the possible Yukawa and/or gauge couplings to other fields. Though it is not pertinent, we note that the potential Eq. (2) can be generated in a supersymmetric theory if the inflaton has a gauge coupling [19–21] where $K \sim -(\alpha/8\pi)(m_{1/2}^2/m_{\tilde{\ell}}^2)$, where $m_{1/2}$ is the gaugino mass and $m_{\tilde{\ell}}$ denotes the slepton mass and α is a gauge coupling constant. It is also possible to obtain the potential Eq. (2) in a non-supersymmetric (or in a broken supersymmetry) theory, provided the fermions live in a larger representation than the bosons. In this latter situation the value of K is determined by the Yukawa coupling h with $K = -C(h^2/16\pi^2)$, where C is some number.

As long as $|K| \ll 1$, during inflation the dominant contribution to the potential comes from $m^2 |\Phi|^2$ term, and inflationary slow roll conditions are satisfied as in the case of the standard chaotic model. COBE normalization then implies $m \sim 10^{13}$ GeV [6, 7]. If $K < 0$, the inflaton condensate feels a negative pressure (see, [10] for the discussion on negative pressure of the MSSM condensate) and it is bound to fragment into lumps of inflatonic matter. Moreover, since the inflation potential Eq. (2) respects a global $U(1)$ symmetry and since for a negative K it is shallower than $m^2 |\Phi|^2$, it admits a Q -ball solution [10]. Comparing with Q -balls along the MSSM flat directions, here the major difference is that the inflatonic condensate has no classical motion along the imaginary direction as usually required for a Q -ball solution.

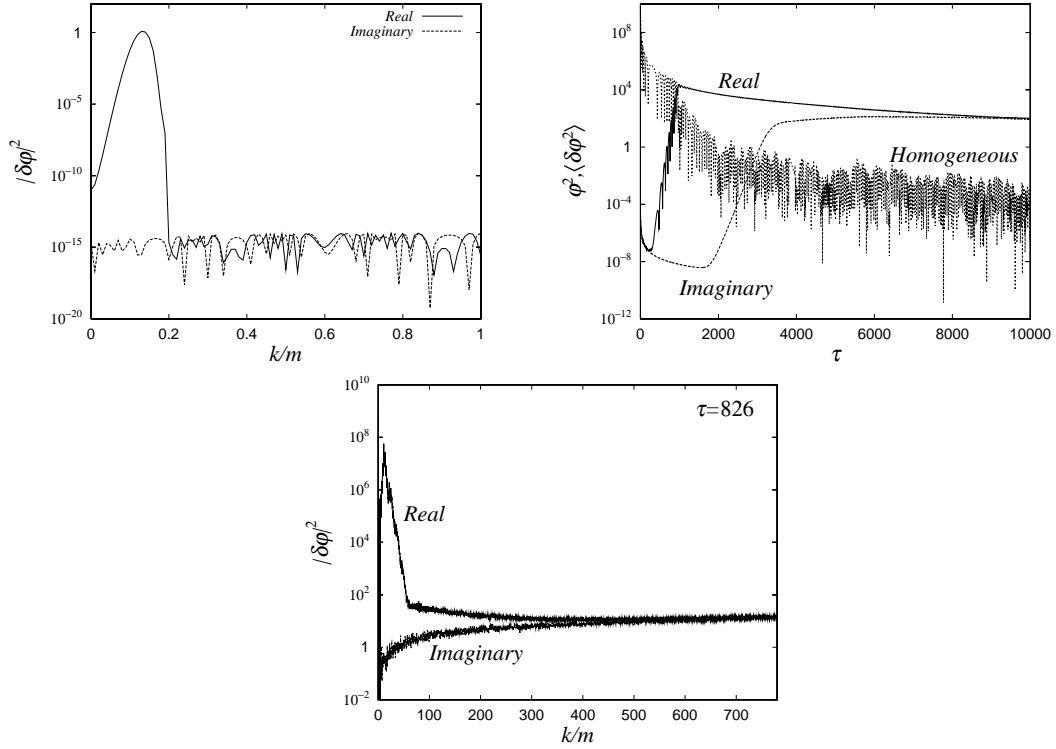


FIG. 1: The first plot from left shows the instability bands of the homogeneous mode of the inflaton along the real (solid) and imaginary (dotted) directions. The second plot shows the result of lattice simulation in the real and imaginary directions, together with the evolution of the homogeneous mode. The third plot shows the power spectra of fluctuations at late times. All plots assume $K = -0.02$.

III. Q-BALLS FROM THE INFLATON CONDENSATE

There are quantum fluctuations along both the real and imaginary directions which may act as the initial seed that triggers on the condensate motion in a whole complex plane [6, 7]. The fluctuations in the real direction grow and drag the imaginary direction along via mode-mode interactions, as illustrated by 2 dimensional lattice simulation in [7], see Figs. (1). The first plot shows the linear fluctuations without rescattering effects; scattering effects are accounted for in the second plot. The late time formation of inflatonic solitons is shown in Fig. (2). Q -balls were observed to form with both positive and negative charges, as can be seen in the first plot of Fig. (2), while keeping the net global charge conserved. Inflatonic Q -balls are of same size because the running mass potential resembles the MSSM flat direction potential in the gravity mediated case, where the Q -ball radius is independent of the charge.

Q -balls of size $R \sim |K|^{-1/2}m^{-1}$ form when the fluctuations grow nonlinear [6, 7]. Since the growth rate of fluctuation is $\sim |K|m$, the Hubble parameter at the formation time can be estimated as $H_f \sim \gamma|K|m$, where γ is a numerical coefficient less than one. For $|K| \ll 1$, we can approximate the decrease in the amplitude of the oscillations by $\phi_f \sim \phi_i(H_f/H_i)$ as in the matter dominated era, where $\phi_i \simeq M_P/\sqrt{12\pi}$ denotes the amplitude at the end of inflation in the chaotic model, and $H_i \sim m$ when the oscillations begin. The

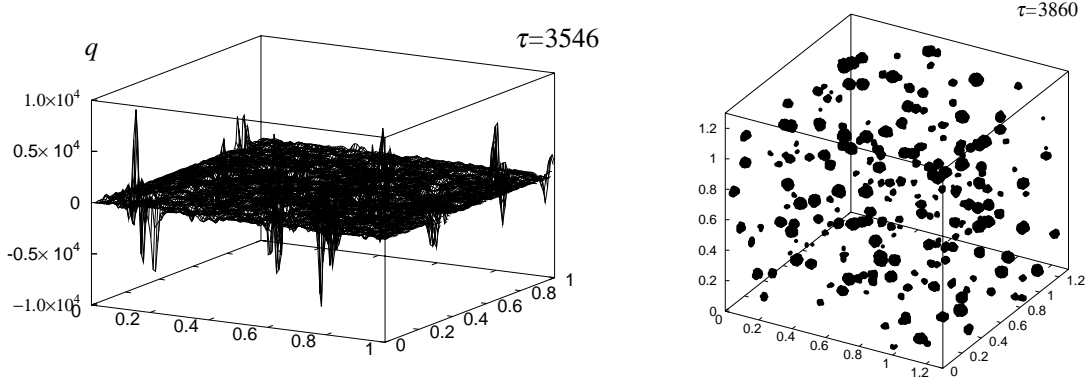


FIG. 2: The first plot shows the charge density distribution in a small sub-lattice at late times. The second plot shows inflatonic solitons forming in 3D lattice. Here $K = -0.02$

total charge of a Q -ball is given by $Q \sim (4\pi/3)R^3 n_q \sim (1/9)\beta\zeta^2\gamma^2|K|^2 R^3 m M_P^2$, where $n_q = \beta\omega\phi_0^2$, $\phi_0 \simeq \zeta\phi_f$, and $\beta \ll 1$ and $\zeta \geq 1$ are numerical factors. Note that the Q -balls have very small relative velocity and their interaction does not necessarily give rise to a violent annihilation. The Q -balls and anti- Q -balls rather merge than completely shedding their energy into free quanta, for details and relevant references, see [10].

Given an inflaton coupling to fermions of the type $h\phi\bar{\psi}\psi$ it has been shown that [6, 7] reheating is driven by surface evaporation of inflatonic Q -balls for relatively large Yukawa couplings $h \leq 1$. In general K and h are not independent quantities but are related to each other by $|K| \sim C(h^2/16\pi^2)$. If the inflaton sector does not belong to the hidden sector, it is very natural that the inflaton coupling to other matter fields is relatively large, i.e. $h \geq (m/M_P)$. In this regime the evaporation rate is saturated and given by [7]

$$\Gamma_Q = \frac{1}{Q} \frac{dQ}{dt} \simeq \frac{3}{16\pi\beta\zeta^2\gamma^2|K|^{3/2}} \left(\frac{m}{M_P}\right)^2 m. \quad (3)$$

Note that the decay rate is determined by the ratio $m/M_P \simeq 10^{-6}$, which is fixed by the anisotropies seen in the cosmic microwave background radiation. Even though we are in a relatively large coupling limit, the decay rate mimics that of a Planck suppressed interaction of the inflatonic Q -ball with matter fields. This is the most important feature of the decay rate of an inflatonic Q -ball evaporation.

Fermionic preheating [22] is not actually a problem in this case because the whole inflaton energy is never transferred during fermionic preheating because of Fermi-blocking, and the energy density stored in the fermions remains small compared to the inflaton energy density, as argued in [7]. Fermions cannot scatter inflaton quanta off the condensate [22], unlike in the case of bosonic preheating [5]. Note that inflatonic Q -ball production is reminiscent to the bosonic preheating with a self coupling interaction appearing from the running mass of the inflaton.

In conclusion, we have shown the formation of Q and anti- Q -balls from the fragmentation of the inflaton quanta. We have shown that surface evaporation of these Q -balls naturally gives rise to Planck suppressed decay rate inspite of the fact that the inflaton

coupling to the fermion is strong. We advocate here that our scenario can solve gravitino problem via decreasing the reheating temperature for high scale inflation model, see for details [6, 7].

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