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Is emergent universe a consequence of particle creation process?

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ABSTRACT

A model of an emergent universe is formulated using the mechanism of particle creation. Here the universe is considered as a non-equilibrium thermodynamical system with dissipation due to particle creation mechanism. The universe is chosen as spatially flat FRW space–time and the cosmic substratum is chosen as perfect fluid with barotropic equation of state. Both first and second order deviations from equilibrium prescription are considered and it is found that the scenario of emergent universe is possible in both the cases.

1. Introduction

To overcome the initial singularity (big bang) of standard cosmology, there are various proposed cosmological scenarios which can be classified as bouncing universes or the emergent universes. Here we shall focus on the second choice which arises due to the search for singularity free inflationary models in the context of classical general relativity. In fact, an emergent universe is a model universe in which there is no time-like singularity, ever existing and having almost static behavior in the infinite past ($t \to -\infty$). Eventually the model evolves into an inflationary stage. Also the emergent universe scenario can be said to be a modern version and extension of the original Lemaitre–Eddington universe.

Harrison [1] in 1967 obtained a model of the closed universe with only radiation and showed that asymptotically (as $t \to -\infty$) it approaches the state of an Einstein static model. Then after a long gap, Ellis and Maartens [2], Ellis et al. [3] in recent past were able to formulate closed universes with a minimally coupled scalar field ϕ with a special form for the self-interacting potential and possibly some ordinary matter with equation of state $p = \omega\rho(-\frac{1}{3} \leqslant \omega \leqslant 1)$. However, exact analytic solutions were not presented in their work, only the asymptotic behavior agrees with emergent universe scenario. Subsequently, Mukherjee et al. [4] obtained solutions for Starobinsky model with features of an emergent universe. Also Mukherjee et al. [5] formulated a general framework for an emergent universe model using an ad hoc equation of state which has exotic behavior in some cases. Afterwords, a lot of works [6–13] have been done to model emergent universe for different gravity theories as well as for various type of matter. Very recently, the idea of quantum tunneling has been used to model emergent universe [14]. Here the initial static state is characterized by a scalar field in a false vacuum and then it decays to a state of true vacuum through quantum tunneling.

From the thermodynamical aspect it has been proposed that entropy consideration favors the Einstein static state as the initial state for our universe [15,16]. Also, recently, Pavon et al. [17,18] have examined the validity of the generalized second law of thermodynamics in the transition from a generic initial Einstein static phase to the inflationary phase and also from the end of the inflation to the conventional thermal radiation dominated era. In this context, the present work is quite different. Here universe is considered as a non-equilibrium thermodynamical system with dissipative phenomena due to particle creation. Both first and second order deviations from equilibrium configuration are taken into account and emergent universe solutions are possible in both the cases. The paper is organized as follows: Section 2 describes the particle creation in cosmology from the perspective of non-equilibrium thermodynamics. Emergent universe scenario has been presented both for first and second order non-equilibrium thermodynamics in Sections 3 and 4 respectively. Finally, summary of the present work has been presented in Section 5.

2. Particle creation in cosmology: Non-equilibrium thermodynamics

Suppose there are N particles in a closed thermodynamical system having internal energy E. Then the first law of thermodynamics is essentially the conservation of internal energy as [19]

$$dE = dQ - p\,dV \tag{1}$$

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where as usual p is the thermodynamic pressure, V is any comoving volume and dQ represents the heat received by the system in time dt. By introducing, the energy density $\rho = \frac{E}{V}$, the particle number density $n = \frac{N}{V}$ and heat per unit particle $dq = \frac{dQ}{N}$, the above conservation equation can be rewritten as

$$T\,ds = dq = d\left(\frac{\rho}{n}\right) + p\,d\left(\frac{1}{n}\right) \tag{2}$$

This is referred to as Gibbs equation with s, the entropy per particle. This equation is also true when the particle number is not conserved, i.e. the system is not a closed system [20].

Thus for an open thermodynamical system, the non-conservation of fluid particles ($N^{\mu}_{;\mu} \neq 0$) is expressed mathematically as

$$\dot{n} + \Theta n = n\Gamma \tag{3}$$

where $N^{\mu} = nu^{\mu}$ is the particle flow vector, u^{μ} is the particle four velocity, $\Theta = u^{\mu}_{;\mu}$ is the fluid expansion, Γ is termed as the rate of change of the particle number in a comoving volume V and by notation $\dot{n} = n_{,\mu}u^{\mu}$. The positivity of the parameter Γ indicates creation of particles while there is annihilation of particles for $\Gamma < 0$. Any non-zero Γ will behave as an effective bulk pressure of the thermodynamical fluid and non-equilibrium thermodynamics should come into picture [21].

We shall consider spatially flat FRW model of the universe as an open thermodynamical system which is non-equilibrium in nature due to particle creation mechanism. Now the Einstein field equations are

$$\kappa\rho = 3H^2, \qquad \kappa(\rho + p + \Pi) = -2\dot{H} \tag{4}$$

where the cosmic fluid is characterized by the energy–momentum tensor

$$T^{\nu}_{\mu} = (\rho + p + \Pi)u_{\mu}u^{\nu} + (p + \Pi)g^{\nu}_{\mu} \tag{5}$$

The energy conservation relation $T^{\mu\nu}_{;\nu} = 0$ takes the form

$$\dot{\rho} + 3H(\rho + p + \Pi) = 0 \tag{6}$$

In the above Einstein field equations (i.e. Eq. (4)) $\kappa = 8\Pi G$ is the Einstein's gravitational constant and the pressure term Π is related to some dissipative phenomena (say bulk viscosity).

However, in the present context, the cosmic fluid may be considered as perfect fluid where the dissipative term Π is the effective bulk viscous pressure due to particle creation or equivalently the conventional dissipative fluid is not taken as cosmic substratum, rather a perfect fluid with varying particle number is considered. This equivalence can be nicely described for adiabatic (or isentropic) particle production as follows [21–23]. Now, using the conservation equations (3) and (6) the entropy variation can be obtained from the Gibbs equation (2) as

$$nT\dot{s} = -3H\Pi - \Gamma(\rho + p) \tag{7}$$

with T, the temperature of the fluid If the thermodynamical system is chosen as an adiabatic system, i.e. entropy per particle is constant (variable in dissipative process) ($\dot{s}$), then from the above relation (7) the effective bulk pressure is determined by particle creation rate as

$$\Pi = -\frac{\Gamma}{3H}(\rho + p) \tag{8}$$

Thus for isentropic thermodynamical process a perfect fluid with particle creation phenomena is equivalent to a dissipative fluid. Further, it should be noted that in the adiabatic process the entropy production is caused by the enlargement of the phase space (also due to expansion of the universe in the present model). This effective bulk pressure does not correspond to conventional non-equilibrium phase, rather a state having equilibrium properties as well (note that it is not the equilibrium era with $\Gamma = 0$).

Eliminating the effective bulk pressure from the Einstein field equations (4) using the isentropic condition (8) we have

$$\frac{\Gamma}{3H} = 1 + \frac{2}{3\gamma}\left(\frac{\dot{H}}{H^2}\right) \tag{9}$$

with γ, the adiabatic index (i.e. $p = (\gamma - 1)\rho$). Thus, if we know the cosmological evolution then from the above equation the particle creation rate can be determined or otherwise, assuming the particle creation rate as a function of the Hubble parameter one can determine the corresponding cosmological phase which we shall try in the next two sections.

3. Emergent universe in first order non-equilibrium thermodynamics

In first order theory due to Eckart [24] the entropy flow vector is defined as

$$s^{\mu}_{E} = nsu^{\mu} \tag{10}$$

So using the number conservation equation (3) and the isentropic condition (8) we obtain (suffix stands for the corresponding variable in Eckart's theory)

$$(s^{\mu}_{E})_{;\mu} = -\frac{\Pi_E}{T}\left(3H + \frac{n\mu\Gamma_E}{\Pi_E}\right) \tag{11}$$

where

$$\mu = \left(\frac{\rho + p}{n}\right) - Ts \tag{12}$$

is the chemical potential. As it has been shown above that particle production is effectively equivalent to a viscous pressure, so for the validity of the second law of thermodynamics, i.e. $(s^{\mu}_{E})_{;\mu} \geqslant 0$, it is reasonable to assume [22]

$$\Pi_E = -\zeta\left(3H + \frac{n\mu\Gamma_E}{\Pi_E}\right) \tag{13}$$

As a result, we have

$$(s^{\mu}_{E})_{;\mu} = \frac{\Pi_E^2}{T\zeta} \geqslant 0 \tag{14}$$

where ζ is termed as bulk viscous coefficient and the bulk viscous pressure satisfies the inhomogeneous quadratic relation

$$\Pi_E^2 + 3\zeta\Pi_E H = -\zeta n\mu\Gamma_E \tag{15}$$

It should be noted that the familiar linear relation for bulk viscous pressure, i.e. $\Pi_E = -3\zeta H$, may be recovered from the above quadratic relation (15) either by $\Gamma_E = 0$ or $\mu = 0$. Now using Eq. (8) in (13) to eliminate Γ_E we have

$$\Pi_E = -3\zeta_{eff}H \tag{16}$$

where $\zeta_{eff} = (\frac{nsT}{\rho + p})\zeta$.

By the second Friedmann equation in Eq. (4) and using Eq. (16) one obtains the differential equation in H as

$$2\dot{H} = -3\gamma H^2 + 3\zeta\kappa H \tag{17}$$

where for simplicity chemical potential is chosen to be zero so that $\zeta_{eff} = \zeta$. Now solving Eq. (17) the Hubble parameter can be obtained as