Cosmological scenario based on the particle creation and holographic equipartition

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Abstract

We propose a cosmological scenario which describes the evolution history of the universe based on the particle creation and holographic equipartition. The model attempts to solve the inflation of the early universe and the accelerated expansion of the present universe without introducing the dark energy from the perspective of thermodynamics. Throughout the evolution of the universe, we assume that the universe always creates particles in some way and holographic equipartition is always satisfied. Further, we choose that the creation rate of particles is proportional to \( H^2 \) in the early universe and to \( H \) in the present and late universe, where \( H \) is the Hubble parameter. Then we obtain the solutions \( a(t) \propto e^{\alpha t/3} \) and \( a(t) \propto t^{1/2} \) for the early universe and the solutions \( a(t) \propto t^\delta \) and \( a(t) \propto e^{Ht} \) for the present and late universe, where \( \alpha \) and \( \delta \) are the parameters. Finally, we obtain and analyze two important thermodynamic properties for the present model.

1. Introduction

The accelerated expansion of the universe have been confirmed by the probe of Type Ia supernovae[1,2], cosmic microwave background radiation[3,4] and baryon acoustic oscillations[5,6] since the 1990s. In order to explain the phenomenon, various models such as the lambda cold dark matter (ΛCDM) model[7], Λ(\( t^\lambda \)) CDM (i.e. the dark energy varies with time \( t \)) model[8,9] and particle creation model[10,11] have been proposed. Among these models, the particle creation model has some following advantages[11,12]: (i) There exists a description of the non-equilibrium thermodynamics because the process of particle creation is an irreversible process accompanied by the entropy production[13,14]. (ii) It contains only a single free parameter, namely the particle creation rate. Such a one-parameter model is preferred by the statistical Bayesian analysis[15].

In the past 30 years, great progress has been made in the study of gravity from the viewpoint of thermodynamics. In 1995, Jacobson showed that the Einstein field equation can be derived based on the Clausius relation and entropy-area relation[16]. Then he and his collaborators investigated the properties of the non-equilibrium thermodynamics of the spacet ime by introducing the term of entropy generation[17]. On the other hand, Padmanabhan derived the important thermodynamic relation \( S = 2\beta E \) and the first law of thermodynamics[19] consistent with the usual form of thermodynamics from a similar but different thermodynamic perspective, where \( S \) is the entropy of the horizon, \( \beta = 1/(kT) \) in which \( k \) is the Boltzmann constant and \( T \) is the temperature of the horizon, and \( E \) represents the active gravitational mass. In addition, there exists a simple correspondence between the surface term \( L_{\text{surf}} \) and bulk term \( L_{\text{bulk}} \) when the Lagrangian of gravity \( L \) is decomposed into \( L = L_{\text{surf}} + L_{\text{bulk}} \) [20,21], which shows that the gravitation action is holographic because the same information is coded in the surface term and bulk term. These results indicate that there is a deep connection between gravitational dynamics and horizon thermodynamics.

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In particular, Padmanabhan proposed that the spacetime is composed of the microscopic degree of freedom and the de Sitter universe satisfies the holographic equipartition (an especial holographic principle). Further, he thought that our universe is asymptotically de Sitter and derived the evolution equations of the universe based on the difference between the number of degrees of freedom on the surface and the number of degrees of freedom in the bulk. Subsequently, this model was extensively studied. Therefore, there is a solid physical foundation to study the evolution of the universe from the perspective of holographic equipartition.

In this paper, we propose a cosmological scenario which describes the evolution history of the universe based on the particle creation and holographic equipartition. Throughout the evolution of the universe, we assume that the universe always creates particles in some way and holographic equipartition is always satisfied. In our scenario, the creation rate of the radiation is $\Gamma = \alpha H^2$ in the early universe and the creation rate of the pressureless matter is $\Gamma = \alpha H$ in the present and late universe, where $\alpha$ is a positive parameter and $H$ is the Hubble parameter. The whole evolution history of the universe may be explained as follows. The universe starts from an unstable de Sitter universe ($a(t) \propto e^{\alpha t/3}$) and evolves into a standard radiation stage ($a(t) \propto t^{1/2}$) due to the creation of radiation. With the expansion of the universe, the pressureless matter whose creation rate is $\Gamma = \alpha H$ begins to dominate the universe. The negative creation pressure of the matter accelerates the expansion of the universe and drives the present accelerated universe ($a(t) \propto t^\delta$ ($\delta > 1$)) to the de Sitter universe ($a(t) \propto e^{Ht}$).

The paper is organized as follows. In section 2, we introduce the non-equilibrium thermodynamics which describes the particle creation. In section 3, we obtain the energy of the universe enclosed by the Hubble horizon by using the laws of energy equipartition and holographic equipartition. Next we obtain the laws of evolution for the early universe and the present and late universe by choosing the suitable creation rates of particles in section 4. In section 5, we investigate the thermodynamical properties for this model. The summary is made in the last section. We use units $c = \hbar = 1$.

2. Particle creation in cosmology

As we know, the first law of thermodynamics in a close system which only does the volume work can be expressed as

$$dE = \delta Q - pdV, \quad (1)$$

where $\delta Q$ is the amount of heat exchanged by the system, $p$ is the pressure, $dE$ is the change of internal energy and $dV$ is the change of volume. When the thermodynamic process is reversible, the amount of heat exchanged by the system can be expressed as $\delta Q = TdS$ where $T$ is the temperature and $dS$ is the entropy change.

For an adiabatic open system where the particle number is not conserved due to the particle creation, the first law of thermodynamics is written as $[10]$

$$d(\rho V) + pdV = \frac{h}{n}d(nV), \quad (2)$$

where $n$ is the particle number per unit volume, $h = \rho + p$ is the enthalpy with $\rho$ being the energy density.

To calculate the creation pressure due to the particle creation, we consider the universe as a sphere with the radius $a(t)$. Thus the volume is $V = \frac{4}{3}\pi a^3(t)$ and the right term of Eq.(2) is expressed as

$$\frac{h}{n}d(nV) = (\rho + p)V \left(3H + \frac{\dot{n}}{n}\right) dt, \quad (3)$$

where $H = \frac{\dot{a}}{a}$ is the Hubble parameter. Inserting Eq.(3) and the relation $\dot{n} + 3Hn = n\Gamma$ into Eq.(2) where $\Gamma$ is the particle creation rate, we obtain

$$\dot{\rho} + 3H(\rho + p + p_c) = 0, \quad (4)$$

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where the effect of particle creation is expressed as an extra pressure

\[ p_e = -\frac{(\rho + p)\Gamma}{3H}. \]  

Thus we can deem that Eq. (4) is the modified continuity equation due to the particle creation.

Particle creation in the universe generates the entropy whose change is \(dS = s \, d(nV)\) where \(s = S/V\) \cite{10}, which provides an explanation for the origin of cosmological entropy. In addition, the negative pressure caused by the particle creation can explain the current accelerated expansion. In fact, introducing bulk viscous fluids to study the accelerated expansion of the universe is also due to the negative pressure effect of viscous fluids \cite{36, 37, 38, 39}.

3. Energy equipartition and holographic equipartition

Research in recent decades has uncovered an important fact that the spacetime can be heated up like the matter. In fact, Unruh discovered that an observer can measure a temperature \(T = \frac{\kappa}{2\pi}\) when he accelerates through the inertial vacuum with a proper acceleration \(\kappa\) in 1976 \cite{40}. Furthermore, the temperature measured by the accelerated observer in the vacuum is as real as that measured by an inertial thermometer in the ordinary matter \cite{41}. Hence, it can be concluded that the spacetime, just as the ordinary matter, is made up of the microscopic degrees of freedom. In the description of the evolution of the universe based on the emergent perspective of gravity, the energy equipartition law

\[ E = \frac{1}{2}N_{\text{bulk}}kT \]  

holds, where \(E\) is the energy in the volume \(V\), \(N_{\text{bulk}}\) is the number of degrees of freedom in the volume \(V\) and \(T\) is the local acceleration temperature.

In Ref. \cite{22}, Padmanabhan thought that our universe is asymptotically de Sitter rather than exactly de Sitter and the expansion of the universe is being driven by the difference \((N_{\text{sur}} - N_{\text{bulk}})\) where \(N_{\text{sur}}\) is the number of surface degrees of freedom on the horizon. However, we assume that the universe obeys always holographic equipartition due to the particle creation in this paper. Therefore the number of bulk degrees of freedom enclosed by the horizon is

\[ N_{\text{bulk}} = N_{\text{sur}}. \]  

In addition, the number of surface degrees of freedom can be expressed as \cite{42}

\[ N_{\text{sur}} = \frac{A}{L_p^2}, \]  

where \(A\) is the area of the horizon. So the total energy in the volume \(V\) is

\[ E = \frac{A}{2L_p^2}kT. \]  

Now let us consider an universe enclosed by the Hubble horizon which is a sphere with the radius \(H^{-1}\). Thus, the volume, the temperature and the area of the Hubble horizon can be written as \(V = \frac{4\pi}{3H^3}\), \(kT = \frac{H}{2\pi}\) and \(A = \frac{4\pi}{H^2}\), respectively. Inserting these physical quantities into Eq. (9), we obtain

\[ E = \frac{1}{4H^2L_p^2}. \]  

This is an explicit relation between the energy enclosed by the Hubble horizon and the Hubble parameter. The relation (10) implies that the universe enclosed by the Hubble horizon has a negative specific heat since \(E \propto T^{-1}\). This is also the expected result even in Newtonian gravitating systems \cite{43}.

There are two relevant important energy contents in the flat universe, namely the Misner-Sharp energy and Komar energy. Thus a question naturally arises as to whether the energy \(E\) in the energy equipartition law is the Misner-Sharp energy or Komar energy. Now let us investigate the two energy conditions.
3.1 Misner-Sharp Energy

The Misner-Sharp energy is
\[ E = \int T_{\mu\nu}u^\mu u^\nu dV, \]  
(11)

where \( u^\mu = \delta^\mu_0 \) is the four velocity and \( T_{\mu\nu} = (\rho, p + p_e, p + p_e, p + p_e) \) is the energy-momentum tensor. Then the energy inside the Hubble horizon is
\[ E = \int_0^{H^{-1}} 4\pi r^2 \rho dr = \frac{4\pi \rho}{3H^3}, \]  
(12)

where we have assumed that the energy density \( \rho \) is homogeneous. Comparing Eq.(10) with Eq.(12), we get
\[ \rho = \frac{3H^2}{4\pi L_p^2}. \]  
(13)

Thus we obtain one of the evolution equation of the universe from the energy equipartition law. The equipartition law is an equation of state while Eq.(13) can be deemed as a dynamic evolution equation of the universe. So the evolution of the universe can be derived from an equation of state, namely the equipartition law.

3.2 Komar Energy

The Komar energy is defined as
\[ E = \int (2T_{\mu\nu} - T g_{\mu\nu})u^\mu u^\nu dV, \]  
(14)

where \( T \) is the trace of the energy-momentum source \( T_{\mu\nu} \). Then the energy inside the Hubble horizon can be reduced to
\[ E = \int_0^{H^{-1}} 4\pi r^2 |\rho + 3(p + p_e)| dr = \frac{4\pi}{3H^3} |\rho + 3(p + p_e)|, \]  
(15)

Thus Eq.(10) changes to
\[ |\rho + 3(p + p_e)| = \frac{3H^2}{4\pi L_p^2}. \]  
(16)

This shows that the change of Hubble parameter is related to the creation pressure of particles when the Komar energy is chosen. It is also interesting to note that Padmanabhan thought that the Komar energy is the active gravitational mass-energy[15] and derived the standard Friedmann equation when the Komar energy is taken[22, 23]. Therefore, we will study the evolution of the universe by using the Komar energy as the energy of the universe enclosed by Hubble horizon in this paper. Of course, we can also use the Misner-Sharp energy as the energy of the universe and obtain the evolution laws of the universe consistent with astronomical observations. But we will not discuss it here.

As usual, the cosmic fluid is deemed as the ideal fluid whose equation of state is
\[ p = \omega\rho, \]  
(17)

where \( \omega \) is a constant.

Here we would like to argue the validity of Eq.(8) from the viewpoint of gravitational dynamics. If the gravity can be quantized and has a minimum quantum of area with the order of \( L_p^2 \)[42], then the horizon with the area \( A \) can be divided into \( N = \frac{4}{c_1 L_p^2} \) cells where \( c_1 \) is a numerical factor. Then we assume that there are \( c_2 \) microscopic states for the every cell, that is, every cell has \( c_2 \) degrees of freedom. According to the energy equipartition law (6), we obtain the total energy
\[ E' = \frac{c_2}{2} N kT = \frac{c_2}{c_1} A \frac{1}{2L_p^2} kT. \]  
(18)
From Eq.(18), we find that Eq.(9) can be recovered when the relation $\frac{c_2}{c_1} = 1$ is chosen. On the other hand, Eq.(18) can be reduced to $\rho = \frac{3H^2}{4\pi L_p^2}$ which is the standard Friedmann equation for the flat FRW spacetime if we choose $\frac{c_2}{c_1} = \frac{1}{2}$ and the Misner-Sharp energy (12). That is, the energy equipartition law and Einstein equation are equivalent to some extent when we take the Misner-Sharp energy as the energy of the universe and choose $\frac{c_2}{c_1} = \frac{1}{2}$. Thus, the Misner-Sharp energy seems to be a good choice for the energy of the universe. But we use the Komar energy as the energy of the universe in this paper. The reasons are as follows. Firstly, the Komar energy is really the gravitational energy as shown by Padmanabhan. Secondly, the accelerated expansion of the present universe can not be described by the Einstein equation without a cosmological constant, but can be explained by a modified gravitational field equation. On the other hand, Eq.(16) can be derived by a modified gravitational field equation. Thirdly, Eq.(8) rather than the Einstein equation is the ansatz from the perspective of thermodynamics. The above discussions are only to show the validity of Eq.(8) from the viewpoint of gravitational dynamics and do not mean that only the Misner-Sharp energy can explain the validity of Eq.(8). The reason we use the Misner-Sharp energy to argue the validity of Eq.(8) is that it is convenient to compare with the standard evolution equation derived from the general relativity. Indeed, the modified Friedmann equation can be obtained when the Komar energy is chosen.

4. Physical process of the evolution of the universe

In this section, we will give two specific cases to illustrate the validity of the present model. Furthermore, we will analyze the specific physical process of the evolution of the universe from the two cases.

Assuming that the rate of particle creation has the following formula

$$\Gamma = \gamma \left( \frac{H}{H_0} \right)^{n-1} H = \alpha H^n, \quad (19)$$

where $\gamma$ is a positive constant of the order 1, $n$ is a non-negative integer, $H_0$ is a quantity with the same dimension as $H$ and $\alpha = \frac{\gamma}{H_0^{n-1}}$. The purpose of introducing $H_0$ is to ensure that the dimension of $\Gamma$ is consistent with that of $H$. Combining Eq.(4), Eq.(5) and Eq.(17), we obtain the specific modified continuity equation

$$\dot{\rho} + 3(1 + \omega)H \rho \left( 1 - \frac{\alpha}{3} H^{n-1} \right) = 0. \quad (20)$$

Besides, the dynamic evolution equation of the universe (16) can be reduced to

$$| \alpha (1 + \omega) H^{n-1} - (1 + 3\omega) | \rho = \frac{3H^2}{4\pi L_p^2}. \quad (21)$$

Thus Eq.(20) and Eq.(21) constitute the fundamental equations of the evolution of the universe. As long as the two equations are combined, some basic physical quantities of the evolution of the universe, such as the scale factor $a(t)$ and energy density $\rho$, can be solved.

4.1 Case of $\Gamma/H = \alpha H$: evolution of the early universe

A natural choice is $n = 2$, namely $\Gamma/H = \alpha H$. According to the astronomical observations and cosmological theories, we know that the Hubble parameter $H$ has been decreasing since the very early stage of the universe except for the period of inflation. In this case, the particle creation rate is very high in the early universe and decreases rapidly over time, so choosing such a particle creation rate to study the evolution of the early universe is reasonable. In this subsection, $\omega$ is taken as $\frac{1}{3}$ because the early universe is dominated by the radiation.

Under the above choice, Eq.(20) and Eq.(21) are reduced to

$$\dot{\rho} + 4H \rho - \frac{4\alpha}{3} H^2 \rho = 0 \quad (22)$$
and

\[ | \frac{4\alpha}{3} H - 2 | \rho = \frac{3H^2}{4\pi L_p^2}. \]  

(23)

Combining the above equations, we obtain the result

\[ (\alpha H - 3)(-6H^3 + 4\alpha H^4 - 3H \dot{H}) = 0. \]  

(24)

This equation has two solutions

\[ H = \alpha/3 \]  

(25)

and

\[ t = \frac{\alpha}{3} \ln \left| \frac{4\alpha H - 6 \dot{H}}{H} \right| + \frac{1}{2H}, \]  

(26)

where the integration constant is chosen as 0.

The solution (25) implies that there exists an inflation solution \( a(t) \propto e^{\alpha t} \) in the early universe. On the other hand, the evolution law of the universe is \( H = \frac{1}{2t} \) when \( t \) is large from Eq.(26), which can be reduced to the standard evolution law \( a(t) \propto t^{1/2} \) in the radiation dominated stage. These solutions can be explained as follows. The universe starts from an unstable de Sitter space (\( a(t) \propto e^{\alpha t} \)), then evolves to the standard radiation phase (\( a(t) \propto t^{1/2} \)). During the evolution of the early universe, the creation rate of the radiation is always \( \Gamma = \alpha H^2 \).

4.2 Case of \( \Gamma/H = \alpha \): evolution of the present and late universe

Another natural choice is \( n = 1 \), namely \( \Gamma/H = \alpha \). Under this choice, Eq.(20) and Eq.(21) are reduced to

\[ \dot{\rho} + (1 + \omega)(3 - \alpha) H \rho = 0 \]  

(27)

and

\[ \left| (\alpha - 1) + (\alpha - 3) \omega \right| \rho = \frac{3H^2}{4\pi L_p^2}. \]  

(28)

From Eq.(27) and Eq.(28), we obtain the results that \( \rho = \text{constant} \) and \( H^2 = 8\pi L_p^2 \rho / 3 \) if the parameter \( \omega \) is taken as \(-1\). The results are consistent with the evolution laws of the universe when the universe is dominated by the vacuum energy in the general relativity. On the other hand, the same results are obtained if \( \alpha = 3 \). The fact implies that the evolution law of the universe is \( a(t) \propto e^{\alpha t} \) and independent of the nature of matter when the particle creation rate \( \Gamma \) equals \( 3H \). Therefore, we can describe the exponentially expanding de Sitter universe without introducing the vacuum energy which is equivalent to the negative pressure matter when \( \alpha = 3 \).

When \( \omega \neq -1 \) and \( \alpha \neq 3 \), combining Eq.(27) and Eq.(28), we obtain

\[ H = \frac{1}{\delta} H^2. \]  

(29)

Further, we obtain

\[ a(t) = t^\delta, \]  

(30)

where \( \delta = \frac{2}{(1+\omega)(3-\alpha)} \). The parameter \( \delta \) satisfies the inequality \( \delta > 1 \) because the expansion of the universe is speeding up according to the astronomical observations. If the universe is dominated by the pressureless matter at present, namely \( \omega = 0 \), then we can get the range of the parameter \( \alpha \) which is \( 1 < \alpha < 3 \). From this result, we can describe the accelerated expansion of the universe without introducing the dark energy. For example, the authors of Ref.[47] pointed out that the rate of expansion which is consistent with supernova observations is \( a(t) = t^2 \) at present. Such a rate of expansion can be obtained when \( \alpha = 2 \) for the present universe dominated by the pressureless matter. Hence, we can describe the accelerated expansion of the current universe and the evolution of the de Sitter universe at a late time under this choice.
So far we have analyzed the specific physical processes of the evolution history of the universe from the cases of $\Gamma/H = \alpha H$ and $\Gamma/H = \alpha$ based on the particle creation and holographic equipartition. These results are consistent with the conclusions of the analysis of $\Lambda$ dark energy model which is generally accepted. Therefore, the current model can well explain the whole evolution history of the universe without introducing dark energy.

5. Thermodynamical properties based on the holographic equipartition

Now we start to investigate the thermodynamical properties of the universe based on the holographic equipartition in this model. In order to see the energy equipartition, we calculate the physical quantity

$$\frac{1}{2} \beta E = \frac{1}{2} \frac{2\pi}{kH} \frac{1}{H L_p^2} = \frac{\pi}{H^2 L_p^2}.$$  (31)

So the relation

$$S = \frac{1}{2} \beta E$$  (32)

holds in this model since $S = \frac{A}{4 L_p} = \frac{\pi}{H L_p^2}$. This is an important relation of thermodynamics which has been shown by Padmanabhan in the cases of the static spacetime in the general relativity\[18] and a wider class of gravity theories like the Lanczos-Lovelock gravity\[48]. This relation is indeed the energy equipartition law in the bulk when the holographic equipartition $N_{\text{sur}} = N_{\text{bulk}}$ is satisfied since $E = \frac{1}{\beta} S = \frac{aT A}{2 L_p^2} = \frac{1}{2} N_{\text{sur}} kT = \frac{1}{2} N_{\text{bulk}} kT$. So the ansatz that the holographic equipartition is always satisfied throughout the evolution of the universe is consistent with the conclusion that the relation $S = \frac{1}{2} \beta E$ is the energy equipartition in the static spacetime. Moreover, the application of the energy equipartition law is generalized to the dynamic spacetime. In return, the validity of relation (32) also means that it is a reasonable ansatz that the universe obeys always the holographic equipartition.

Besides, differentiating Eq.(10), we obtain the change of total energy enclosed by the Hubble horizon during a time interval $dt$

$$dE = -\frac{H}{H^2 L_p^2} dt.$$  (33)

On the other hand, we obtain

$$T dS = \frac{H}{2\pi} \left( -\frac{2\pi H}{H^2 L_p^2} \right) dt = -\frac{H}{H^2 L_p^2} dt,$$  (34)

where the temperature $T = \frac{H}{2\pi}$ and the entropy-area relation $S = \frac{A}{4 L_p}$ are used. Comparing Eq.(33) with Eq.(34), we obtain the relation

$$dE = T dS.$$  (35)

This relation is actually the energy conservation relation for the universe enclosed by the Hubble horizon. However, the first law of thermodynamics is expressed as $-dE = T dS$ in Ref.\[49\] (In fact, the relation is also used in some references, for example, \[55\] [59] \[61\] [52] [53] [54]). Let us explain the difference between the notion $dE$ used in Ref.\[49\] and that used in the present paper. In Ref.\[49\], $-dE$ is the amount of heat flux crossing the horizon during time $dt$. But here $dE$ is the change of the energy inside the Hubble horizon. Moreover, $-dE$ is defined by $-dE = 4\pi R^2 T_{\mu \nu} k^\mu k^\nu dt$ where $k^\mu$ is the future directed ingoing null vector field in Ref.\[49\]. But here $dE$ is mainly composed of two parts, one of which is related to the particle creation and the other to the particles across the Hubble horizon, so the change of the entropy in this paper is mainly caused by the change of the number of particles. In addition, the energy $E$ in the bulk can be also considered as the energy on the horizon due to the holographic equipartition. Further, the entropy change on the horizon $dS$ can be expressed as $dS = dS_i + dS_e$, where $dS_i$ is the irreversible entropy change caused by the particle creation and $dS_e$ is the reversible entropy change caused by the
particles across the Hubble horizon. Therefore, the non-equilibrium thermodynamics accompanied with the entropy production can be expressed as the form (35) of the equilibrium thermodynamics on the Hubble horizon.

6. Conclusions

In this paper, we analyze the evolution history of the universe based on the particle creation and holographic equipartition. We assume that the universe always obeys the holographic equipartition $N_{\text{bulk}} = N_{\text{sur}}$ throughout the evolution of the universe due to the particle creation. This is a reasonable assumption because there exists a simple and explicit holographic correspondence between the surface term and bulk term of the Lagrange of gravity. Further, we obtain an evolution equation of the universe by using the energy equipartition and taking the Komar energy as the energy of gravity. In the early universe, we choose the creation rate of the radiation $\Gamma = \alpha H^2$ and obtain two solutions $a(t) \propto e^{\alpha t/3}$ and $a(t) \propto t^{1/2}$. In the present and late universe, we obtain two solutions $a(t) \propto t^6$ and $a(t) \propto e^{Ht}$ by choosing the creation rate of the pressureless matter $\Gamma = \alpha H$. These solutions are in good agreement with astronomical observations.

Based on the above results, we think that the evolution history of the universe can be explained as follows. The universe starts from an unstable de Sitter universe ($a(t) \propto e^{\alpha t/3}$) and evolves into a standard radiation stage ($a(t) \propto t^{1/2}$) due to the creation of radiation. Then the pressureless matter starts to dominate the evolution of the universe due to the expansion of the universe. In the present universe dominated by the pressureless matter, the universe expands as the law $a(t) \propto t^6$. So we can explain the current accelerated expansion as long as the parameter $\delta$ is greater than 1. Finally, the universe evolves to the de Sitter Universe ($a(t) \propto e^{Ht}$) in the late stage. Although the mechanisms of the transition from $a(t) \propto e^{\alpha t/3}$ to $a(t) \propto t^{1/2}$ in the early universe and the transition from $a(t) \propto t^6$ to $a(t) \propto e^{Ht}$ in the present and late universe are not clear. For completeness, we also obtain and discuss the thermodynamic relation $dE = T dS$ and conclude that the relation $S = \frac{1}{2} \beta E$ is indeed the energy equipartition law in our scenario.

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