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Axially Symmetric Universe Solutions with Strange Quark Matter in Creation-Field Cosmology

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Abstract— This study investigates the axially symmetric universe model in the Creation Field of Cosmological theory. Strange quark matter is assumed as matter distribution by attaching a string cloud. The proportion of shear scalar σ^2 and expansion scalar θ have been used for the purpose of the study, and a relationship between scale factors $A(t)$ and $B(t)$ has been attained as $A = B^k$. The modified Einstein field equations have been solved using the constant deceleration parameter $q = m - 1$. Besides, the solutions have been achieved at special conditions, such as the exponential expansion model of deceleration parameter $q = -1$. It has been drawn from the obtained results that, in the early universe, the scale factors A and the spatial volume of the universe V have a zero value at the initial time of the universe. Furthermore, these values have rapidly increased with cosmic time, confirming the expansion of the universe models. Moreover, some kinematic quantities have been investigated for the constructed models. All the results are discussed within the cosmological framework and supported by compatible studies.

Keywords — *Axially symmetric space-time, early universe model, strange quark matter, deceleration parameter*

Mathematics Subject Classification (2020) 83C05, 83C15

1. Introduction

The Big Bang cosmology, which Einstein described using field equations, was inadequate in issues like the expanding universe, primordial nucleosynthesis, and the observed uniformity of the cosmic microwave background radiation (CMBR). Einstein's Theory of Relativity (GR) is one of the leading theories that successfully explains the structure and functioning of the universe on large scales. In recent years, especially with the advancement of technology, precise Type Ia Supernova observations and CMBR have shown that the universe is expanding at an accelerating rate [1–3]. Additionally, observations of CMBR and Supernovae suggest that the present-day universe consists of approximately 4% baryonic matter, 21% dark matter, and 76% dark energy [4, 5]. Due to its repulsive effects, the dominant dark energy in today's universe is believed to be responsible for the accelerating expansion. Given this, the dynamic structure of the universe is investigated from two distinct perspectives cosmologically. The first approach involves adding a term to the Einstein field equations defining dark energy and dark matter. The cosmological constant, which Einstein later added to the field equations to obtain a static universe model, is considered to perform this role. The Einstein field

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equations (EFEs), including dark energy and dark matter, are known as the Λ-Cold Dark Matter (Λ-CDM) model. This model is one of the most successful at explaining the present-day universe. However, this model also brings about some cosmological issues, namely the horizon problem, the flatness problem, and the violation of energy conservation [6]. The second approach involves using modified and alternative gravitational theories to understand the dynamics of the universe. Over time, many modified and alternative gravitational theories have been proposed and continue to be proposed. One well-known alternative gravitational theory is the steady state theory, proposed by Bondi and Gold [7]. According to the steady state theory, the universe does not have a singular beginning or end in the cosmic time scale. The large-scale statistical properties of the universe are invariant. The theory describes a very slow but continuous creation of matter instead of the one-time infinite and explosive creation at the beginning, assuming that the mass density is constant. However, the continuous matter creation approach in the theory also violates the conservation of matter. To address this problem, Hoyle and Narlikar [8] have introduced a novel field theory framework, incorporating a massless and chargeless scalar Creation (C) field into the Einstein-Hilbert action to account for matter formation. In the C-field theory proposed by Hoyle and Narlikar, unlike the steady state theory, there is no Big Bang-type singularity. A solution to the field equations involving negative energy massless C scalar creation fields and radiation was obtained by Narlikar and Padmanabhan [9]. They have shown that the cosmological model they derived has met all observational tests and provided a viable alternative to the Big Bang model. Furthermore, they demonstrated that the cosmological model naturally addresses singularity, horizon problems, and flatness.

The Big Bang theory predicts that the universe cooled down quickly in its early stages. Because of the universe's swift cooling, phase transitions occurred, forming matter forms known as topological defects [10]. One of these forms of matter is referred to as cosmic strings. Cosmic strings are one-dimensional objects that form during spontaneous symmetry breaking [11]. Cosmic strings hold particular significance in astrophysics. It is believed that cosmic strings play an important role in galaxy formation due to the density fluctuations they cause [12]. Cosmic strings have stress energy and interact with gravitational fields [13]. Therefore, studying the gravitational effects induced by strings is cosmologically important. Due to these properties, string cosmological models are being extensively studied to analyze the dynamic structure of the early universe. During the early epochs of the universe, a phase transition known as the quark-hadron transition occurred at a cosmic temperature of T 200 MeV, creating the Quark-Gluon Plasma [14]. It is believed that certain cosmic entities, similar to neutron stars and quark-gluon plasma, may have originated from quark matter in the early universe. [15, 16]. Usually, the quark form of matter is expressed by an equation of state involving the bag model, in which quarks can be assumed to be non-interacting and massless matter [17, 18]. In this case, the quark pressure p_q can be expressed as follows:

$$p_q = \frac{1}{3}\rho_q \tag{1.1}$$

Here, ρ_q is called quark matter energy density. Total energy density ρ is written as

$$\rho = \rho_q + B_c \tag{1.2}$$

where B_c symbolizes the bag constant. Moreover, total pressure p is provided as

$$p = p_q - B_c \tag{1.3}$$

In recent years, scientists have focused on describing the universe's expansion by investigating alternative theories of gravity, cosmic matter, and various universe models. Chaubey et al. [19] have investigated

Creation Field Cosmology (CFC) with cosmological constant Λ for the Bianchi type-I universe. Bali [20] has studied Bianchi II space-time with dust and massless scalar field in CFC theory. Aygün et al. [21] have investigated a higher dimensional Friedman-Robertson-Walker (FRW) universe filled with strange quark matter (SQM) in framework CFC. Moreover, $(n+2)$ dimensional FRW universe with domain wall (DW) matter distributions has been worked in CFC theory by Çağlar and Aygün [22]. Rezki and Zaim [23] have investigated the Bianchi-I universe with a time-varying electric field in CFC theory. Adhav et al. [24] have researched an axially symmetric universe in CFC theory for a perfect fluid. Singh and Beesham [25, 26] have studied the Locally Rotationally Symmetric (LRS) Bianchi-I universe with constant deceleration parameter (CDP) in GR theory and $f(R,T)$ gravity for a perfect fluid. Besides, Singh and Beesham [27] have worked SQM in $f(R,T)$ theory for the LRS Bianchi-I universe model. SQM with string cloud (SC) has been investigated in $f(R)$ gravity for Kaluza-Klein space-time by Sobhanbabu and Santhi [28]. Santhi and Chinnappalanaidu [29] have explored SQM attached to SC for Kantowski–Sachs universe $f(R)$ theory. Çağlar et al. [30] have DW matter with SQM in $f(R,T)$ theory for Ruban universe. In this study, SQM, proposed to have formed during the early universe, is investigated within the context of the LRS Bianchi I space-time, one of the anisotropic and homogeneous universe models that describe the geometry of the early universe by the motivation of the aforesaid studies.

The paper is organized as follows: Section 2 attains the modified Einstein field equations (MEFEs) and some kinematic quantities. Section 3 obtains the equations' solutions using two assumptions. Section 4 discusses all solutions in depth and provides essential figures. Finally, Section 5 provides a conclusion.

2. C-Field Theory and Modified Einstein Field Equations

In this work, EFEs have been attained in the framework of CFC suggested by Harko and Narlıkar [8]. MEFEs are written in the following form:

$$R_{ij} - \frac{1}{2}Rg_{ij} = -(T_{ij}^M + T_{ij}^C) \tag{2.1}$$

Here, R and R_{ij} are called Ricci scalar and Ricci tensor. Moreover, T_{ij}^M and T_{ij}^C symbolize the matter tensor of Einstein's theory and C-Field, respectively, and the matter tensor of C-Field is written as [24, 31]:

$$T_{ij}^C = -f(C_iC_j - \frac{1}{2}g_{ij}C^kC_k) \tag{2.2}$$

Here, $f > 0$ and $C_i = \frac{\partial C}{\partial x^i}$ [32]. In this study, the SC matter with SQM is assumed as matter distribution, and it is given as follows:

$$T_{ij}^M = \rho u_i u_j - \rho_s x_i x_j \tag{2.3}$$

where u_i symbolizes 4-velocity of the particle and x_i determines the string direction [33]. Moreover, ρ_s is the string energy density, and ρ is named the rest energy density, which can written in the form including quark matter density ρ_q and bag constant B_c [34]:

$$\rho = \rho_q + \rho_s + B_c \tag{2.4}$$

By using (2.3) and (2.4), as in [35], the energy momentum tensor is rewritten as follows:

$$T_{ij}^M = (\rho_q + \rho_s + B_c)u_i u_j - \rho_s x_i x_j \tag{2.5}$$

In this work, axially symmetric universe models have been investigate,d and the line element of the universe model is given as

$$ds^2 = dt^2 - A(t)^2dx^2 - B(t)^2(dy^2 + dz^2) \tag{2.6}$$

where $A(t)$ and $B(t)$ represent the scale factors of the axially symmetric universe [36]. Additionally, various kinematic quantities, including spatial volume (V), Hubble parameter (H), shear scalar (σ^2), expansion scalar (θ), anisotropy parameter (AP), and deceleration parameter (q) for the universe model are provided as follows, respectively:

$$V = a^3 = AB^2 \tag{2.7}$$

$$H = \frac{\dot{a}}{a} = \frac{\dot{A}}{3A} + \frac{2\dot{B}}{3B} \tag{2.8}$$

$$\sigma^2 = \frac{1}{3}\left[\frac{\dot{A}}{A} - \frac{\dot{B}}{B}\right]^2 \tag{2.9}$$

$$\theta = \frac{\dot{A}}{3A} + \frac{2\dot{B}}{B} \tag{2.10}$$

$$AP = \frac{6(\dot{B}A - \ddot{A}B)^2}{(2\dot{B}A + \dot{A}B)^2} \tag{2.11}$$

and

$$q = \frac{d}{dt}\left(\frac{1}{H}\right) - 1 = \frac{2(A\dot{B} - \dot{A}B)^2 - 3AB(\ddot{A}B + 2A\ddot{B})}{(2A\dot{B} + \dot{A}B)^2} \tag{2.12}$$

From this point onward, the upper dot (.) denotes differentiation concerning cosmic time t. Besides, a provided in (2.7) and (2.8) symbolizes the average scale factor [37]. The MEFEs of the axially symmetric universe for string cloud coupled with SQM have been obtained in CFC theory by using (2.1), (2.2), (2.5), and (2.6) as follows:

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} = \frac{1}{2}f\dot{C}^2 \tag{2.13}$$

$$\frac{2\ddot{B}}{B} + \frac{\dot{B}^2}{B^2} = \frac{1}{2}f\dot{C}^2 + \rho_s \tag{2.14}$$

and

$$\frac{2\dot{A}\dot{B}}{AB} + \frac{\dot{B}^2}{B^2} = -\frac{1}{2}f\dot{C}^2 + \rho_s + \rho_q - B_c \tag{2.15}$$

3. Solutions of the CFC Theory Field Equations

Five unknown quantities such as A, B, C, ρ_q and ρ_s can be solved from these three MEFEs (2.13)-(2.15) with the help of two approximations. The relationship between the scale factors can be derived by considering the ratio of the shear scalar in (2.9) to the expansion scalar in (2.10) and given as follows:

$$A = B^k \tag{3.1}$$

where k is an arbitrary constant [38,39]. Moreover, a constant form of deceleration parameter can be used to solve the MEFEs and is given in the following form:

$$q = m - 1 \tag{3.2}$$

Here, m is an arbitrary constant. Deceleration parameter q defines the fate of the universe model as follows [40,41]:

i. Super-exponential expansion: $q < -1$ when $m < 0$

ii. Exponential expansion: $q = -1$ when $m = 0$

iii. Accelerating power law expansion: $-1 < q < 0$ when $0 < m < 1$

iv. Constant expansion: $q = 0$ when $m = 1$

v. Decelerating expansion: $q > 0$ when $m > 1$

3.1. MEFEs Solutions for Model I ($q = m - 1$)

By using (3.2) with (2.12), the scale factor B for constant model has been calculated as

$$B_I = (mt(k+2))^{\frac{3}{m(k+2)}} \tag{3.3}$$

Then, by adding (3.3) to (3.1), the scale factor A has been attained as

$$A_I = (mt(k+2))^{\frac{3k}{m(k+2)}} \tag{3.4}$$

C-field function C, the string energy density ρ_s, and the SQM energy density ρ_q have been calculated from the MEFEs (2.13)–(2.15) with (3.3) and (3.4) as follows, respectively:

$$C_I = \frac{\sqrt{6f\left((3-m)k^2 - 3k(m-3) - 2m + 3\right)}ln(t)}{(k+2)fm} + c_1 \tag{3.5}$$

$$\rho_s^I = \frac{3(m-3)(k-1)}{(k+2)m^2t^2} \tag{3.6}$$

and

$$\rho_q^I = \frac{6k(3-m)}{(k+2)m^2t^2} + B_c \tag{3.7}$$

Thus, the SQM pressure p_q is obtained by using (1.1) with (3.7) as follows:

$$p_q^I = \frac{2k(3-m)}{(k+2)m^2t^2} + \frac{1}{3}B_c \tag{3.8}$$

Besides, total energy density ρ has been attained by using (1.2) with (3.7) as

$$\rho^I = \frac{6k(3-m)}{(k+2)m^2t^2} + 2B_c \tag{3.9}$$

It is possible to calculated total pressure p from (1.3) with (3.8) as

$$p^I = \frac{2k(3-m)}{(k+2)m^2t^2} - \frac{2}{3}B_c \tag{3.10}$$

Furthermore, kinematic quantities for the constructed Model I are calculated by using (3.3) and (3.4) in (2.7)–(2.11) as follows:

$$V_I = [mt(k+2)]^{\frac{1}{m}} \tag{3.11}$$

$$H_I = \frac{1}{mt}$$

$$\sigma_I^2 = \frac{5k^2 + 2k + 11}{(k+2)m^2t^2} \tag{3.12}$$

$$\theta_I = \frac{3}{mt} \tag{3.13}$$

and

$$AP_I = \frac{6(k-1)^2}{(k+2)^2} \tag{3.14}$$

3.2. MEFEs Solutions for Model II ($q = -1$)

By assuming $m = 0$ and using (2.12) with (3.2), the scale factor B for exponential expansion model has been calculated as

$$B_{II} = e^{st} \tag{3.15}$$

Then, by adding (3.15) to (3.1), the scale factor A has been attained as

$$A_{II} = e^{kst} \tag{3.16}$$

C-field function C, the string energy density ρ_s, and the SQM energy density ρ_q have been calculated from the MEFEs (2.13)–(2.15) with (3.15) and (3.16) as follows, respectively:

$$C_{II} = \frac{\sqrt{2f\,(k^2+k+1)}st}{f} + c_2 \tag{3.17}$$

$$\rho_s^{II} = (k+2)(1-k)s^2 \tag{3.18}$$

and

$$\rho_q^{II} = 2(k+2)ks^2 + B_c \tag{3.19}$$

Thus, the SQM pressure p_q is obtained by using (1.1) with (3.19) as

$$p_q^{II} = \frac{1}{3}[2(k+2)ks^2 + B_c] \tag{3.20}$$

Furthermore, total energy density ρ has been attained by using (1.2) with (3.19) as

$$\rho^{II} = 2(k+2)ks^2 + 2B_c \tag{3.21}$$

It is possible to calculated total pressure p from (1.3) with (3.20) as

$$p^{II} = \frac{2(k+2)ks^2}{3} - \frac{2}{3}B_c \tag{3.22}$$

Moreover, kinematic quantities for the constructed Model II are calculated by using (3.15) and (3.16) in (2.7)–(2.11) as follows:

$$V_{II} = e^{\frac{(k+2)st}{3}} \tag{3.23}$$

$$H_{II} = \frac{(k+2)s}{3}$$

$$\theta_{II} = (k+2)s$$

$$\sigma^2_{II} = \frac{(5k^2+2k+11)s^2}{9}$$

and

$$AP_{II} = \frac{6(k-1)^2}{(k+2)^2} \tag{3.24}$$

4. Results and Discussion

In this work, LRS Bianchi type-I space-time has been investigated in CFC for SQM with SC. Shear scalar σ^2, expansion scalar θ, and constant deceleration parameter have been used to solve the MEFEs. Two solutions for the constructed model have been obtained depending on the value of the deceleration parameter, which is $q = m - 1$ and $q = -1$. The first solution provides the constant expanding universe model, and the new line element of the axially symmetric metric can be rewritten by using (3.3) and

(3.4) in (2.6) as follows:

$$ds_I^2 = dt^2 - (mt(k+2))^{\frac{6k}{m(k+2)}} dx^2 - (mt(k+2))^{\frac{6}{m(k+2)}} (dy^2 + dz^2) \tag{4.1}$$

It can be observed from (4.1) that m and k are essential constants. It must be that $m \neq 0$ and $k \neq -2$ to define a physical meaningful line element. The m is assumed as $m = 0.5$. Using the average deceleration parameter value obtained in the study of Maruya [31]. In the graphs, the k value was accepted as $k = 0.9$, considering the $-2 < k < 1$ condition. When $t = 0$, the constructed universe starts and ends when $m = 0$ and/or $k = -2$. Additionally, new line elements for the exponential expansion model ($q = -1$) are obtained by using (3.15) and (3.16) in (2.6) as follows:

$$ds_{II}^2 = dt^2 - e^{2kst} dx^2 - (e^{2st}(dy^2 + dz^2) \tag{4.2}$$

It can be observed that the anisotropic universe model becomes a static model when arbitrary constant $s = 0$ in (4.2). Two deceleration models have been investigated, namely the constant expanding and exponential expanding models. The different scale factors for both models are given by (3.3), (3.4), (3.15), and (3.16), and it is shown in Figure 1 for scale factor $A(t)$. The scale factor values obtained under these exponential and constant expansion conditions are also seen in the graph. While the A_I curve presents the constant expanding universe model, the A_{II} curve clearly shows the exponential expansion. In addition, the attained values of the volume parameters (3.11) and (3.23) for both models clearly define the type of expansion as expected, and this is shown in Figure 2. Moreover, these expansion types of constructed universe models agree with some studies [36, 42, 43].

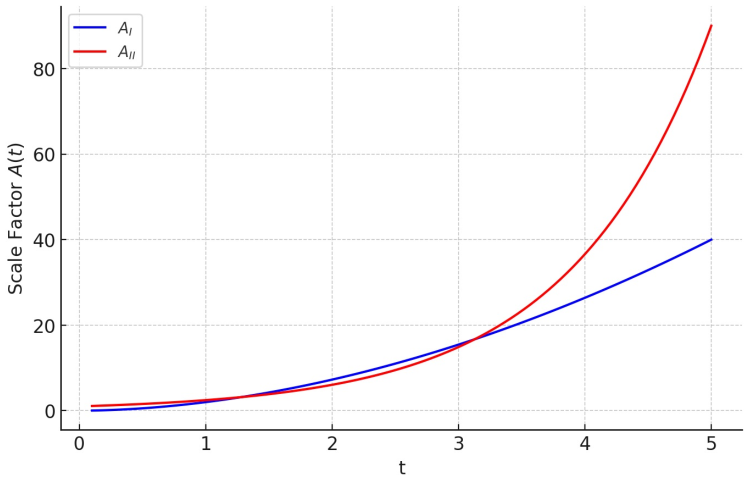

Figure 1. Graph of the scale factor A against time for $m = 0.5$, $k = 0.9$, and $s = 1$

Hubble has proposed that the universe was initially infinitely hot and dense during its early evolutionary phases [44]. Furthermore, all the universe's mass and energy were compressed into a singular point, meaning the universe's volume was effectively zero at the beginning. Hawking [45, 46] has described how the universe began expanding due to an explosion from this hot, dense state and has continued to expand ever since. The Planck satellite, which studied the radiation from the early universe, measured the Hubble constant as approximately $H_0 = 67.4 km/s/Mpc$ [47]. Using this value, $m \approx 1.1046x10^{39}$ can be obtained from the H_I for the $q = m - 1$ model, and $q \approx -1$ is attained, which indicates that the universe is accelerating. Over an infinite period, the universe's volume would become infinite while its density would approach zero. The investigated models agree with this idea, as shown in Figure 2. The shear scalar in (3.12) and the expansion scalar in (3.13) for the first model are infinitely large at $t = 0$ and vanish as $t \to \infty$. Furthermore, it is essential to note that the anisotropy parameter, given by (3.14) and (3.24), remains constant and equal for both expansion models.

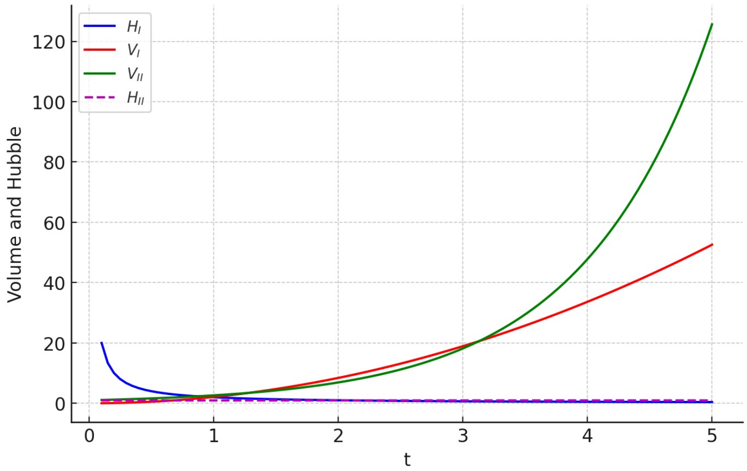

Figure 2. Graph of the volume and Hubble parameter against time for $m = 0.5$, $k = 0.9$, and $s = 1$

The C-Field function C_I for the first model (3.5) is a logarithmic function of time. This implies that the rate of matter creation decreases over time. In the early universe, the creation rate is relatively high; however, as time progresses, the amount of matter being created gradually declines. As can be seen from (3.6)-(3.10), the string energy density, SQM energy density, and matter pressure values decrease rapidly, as expected for the $q = m - 1$ model. It indicates the Big Bang singularity at the initial epoch, where the rest energy density $\rho_I \to \infty$ is $t \to 0$ and approaches zero as $t \to \infty$. These are shown in Figure 3. This solutions agree with some studies, such as Çağlar and Aygün [18], Adhav et al. [24], Sahoo et al. [42], and Yılmaz [48]. Moreover, arbitrary constant k must be $-2 < k < 1$ to get the pa positive value of string energy density $\rho_s > 0$.

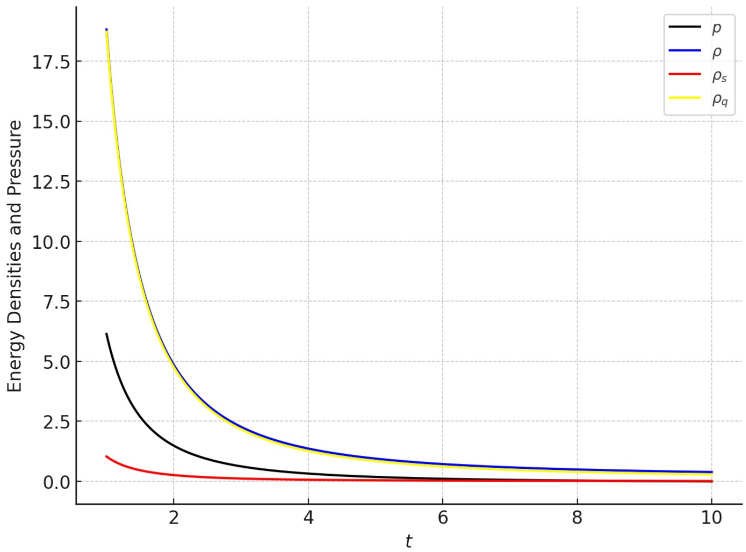

Figure 3. Graph of the energy densities and pressure of model I against time for $m = 0.5$, $k = 0.9$, and $s = 1$

The C-Field function C_{II} in (3.17) increases linearly with time ($\propto t$). This indicates that the rate of matter creation continuously increases. Such a scenario could lead to an effect similar to dark energy and may be associated with the universe's accelerated expansion. These are shown in Figure 4.

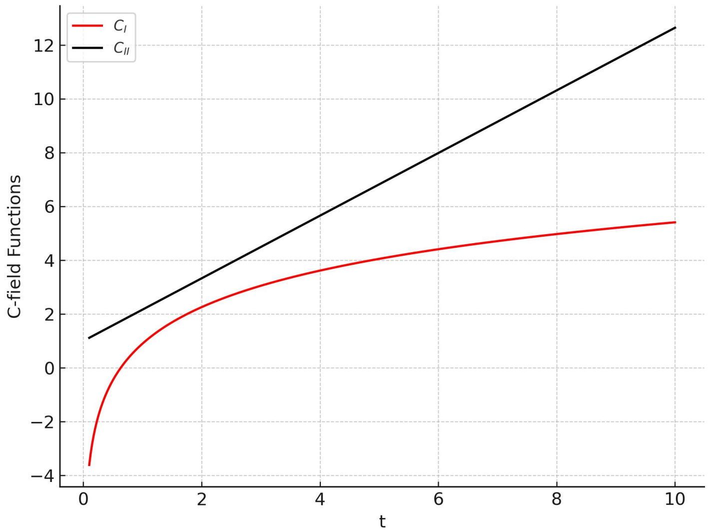

Figure 4. Graph of the C-field functions against time for $m = 0.5$, $k = 0.9$, $f = 105$, $c_1 = 0.9$, $c_2 = s = 1$

For Model II, all values of energy densities and pressures in (3.18)–(3.22) have been calculated independent of time t. In addition, the spatial volume was obtained directly proportional to time. Although the universe is expanding, its energy density does not change over time, which may indicate that dark energy (or vacuum energy) has a static component, not a dynamic one [49, 50].

5. Conclusion

This study researched the early model of the universe, focusing on the strange quark form of matter, which is suggested to have emerged during the phase transitions of the early universe. This model was analyzed within the framework of C-field theory. The constructed model supports the proposed expansion theories. In this respect, the study is compatible with alternative theories and can be an example for analyzing the early period of the universe. Based on this study's findings, future research can focus on early universe studies through various theoretical frameworks, considering investigating early universe models to explain the universe's expansion. Moreover, different models can further emphasize examining the structure of SC substances containing SQM, which are suggested to have formed in the early universe.

Author Contributions

The author read and approved the final version of the paper.

Conflicts of Interest

The author declares no conflict of interest.

Ethical Review and Approval

No approval from the Board of Ethics is required.

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