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String Cloud and Domain Walls with Quark Matter in n-Dimensional Kaluza-Klein Cosmological Model

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Abstract We have obtained Kaluza-Klein cosmological solutions in n-dimensions for quark matter coupled with the string cloud and domain walls in general relativity. Some properties of the models, thus obtained, are also studied.

Keywords Kaluza-Klein theory · Cosmic strings · Domain walls · Quark matter

1 Introduction

The current trend in modern theoretical physics is to search for a theory which provides a unification of gravity with other fundamental interactions of nature. Weinberg [1] studied the unification of the fundamental forces with gravity which reveals that the space-time should be different from four. Since the concept of higher dimensional space-time is not unphysical the string theories are discussed in ten dimensions or twenty six dimensions of space-time. Because of this, studies in n-dimensions inspired many researchers to enter into such field of study to explore the hidden knowledge about the universe. Chodos and Detweller [2], Ibanez and Verdaguer [3], Gleiser and Diaz [4], Banerjee and Bhui [5], Reddy and Venkateswara Rao [6], Khadekar and Gaikwad [7] have studied the multidimensional cosmological models in Einstein's general relativity theory.

It is still a challenging problem to know the exact physical situation at very early stages of the formation of our universe. At the very early stages of evolution of the universe, it is generally assumed that during the phase transition (as the universe passes through its critical temperature) the symmetry of the universe is broken spontaneously. It can give rise to topologically stable defects such as strings, domain walls and monopoles. Of all these cosmological structures, cosmic strings and domain walls have excited the most interest. The concept of string theory was developed to describe events at the early stages of the evolution of the universe. Kibble [8] and Vilenkin [9] believed that strings can be considered as one of the sources of density perturbations that are required for the formation of large

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scale structures in the universe. The study of string cosmological models in general relativity was initiated by Vilenkin [10], Letelier [11], Krori et al. [12, 13]. Relativistic string models in the context of Bianchi Space-time have been obtained by Banerjee et al. [14], Tikekar and Patel [15], Bhattacharjee and Baruah [16], Mahanta and Mukharjee [17]. Gundalach and Ortiz [18], Barros and Romero [19], Sen and Banerjee [20], Smalley [24], Barros et al. [21], Reddy [22, 23], Rahaman et al. [25–27], Reddy et al. [28–30], Adhav et al. [31] have studied several aspects of cosmic strings in Brans and Dicke [32], Dicke [33], Saez and Ballester [34] scalar-tensor theories of gravitation and in Lyra [35] geometry. Chakraborty and Ghosh [36] studied string cosmology with Brans-Dicke theory in higher dimensional space-time.

In particular, the domain walls have become important in recent years from cosmological stand point when a new scenario of galaxy formation has been proposed by Hillet et al. [37]. According to them the formation of galaxies are due to domain walls produced during phase transitions after the time of recombination of matter and radiation. So far a considerable amount of work has been done on domain walls. Ipser and Sikivie [38], Windrow [39], Goets [40], Mukherjee [41], Wang [42], Rahman and Bera [43], Rahman [44], Reddy and Subbarao [45] are some of the authors who have investigated several aspects of domain walls.

During the phase transitions of the universe another important phase transition is Quark-Gluon Plasma (QGP) → Hadron gas which is called as quark-hadron phase transition when cosmic temperature was $T \approx 200$ MeV. Itoh [46], Bodmer [47] and Witten [48] have explored the possibility of the existence of quark matter and proposed two ways of formation of quark matter: the quark-hadron phase transition in the early universe and conversion of neutron stars into strange quark matter at ultrahigh densities. Typically, quark matter is modeled with an equation of state based on the phenomenological bag model of quark matter, in which quark confinement is described by an energy term proportional to volume. In the framework of this model the quark matter is composed of massless u, d quarks, massive s quarks and electrons. In the simplified version of the bag model, assuming that the quarks are massless and non interacting, we then have quark pressure $p_q = \rho_q/3$, where ρ_q is the quark energy density.

The total energy density is

$$\rho_m = \rho_q + B_c, \tag{1}$$

but, the total pressure is

$$p_m = p_q - B_c. \tag{2}$$

The equation of state for strange quark matter [49, 50] will be

$$p_m = (\rho_m - 4B_c)/3. \tag{3}$$

Recently, in the Brook-Haven National Laboratory, Back et al. [51], Adams et al. [52] and Adcox et al. [53] have created quark-gluon plasma as a perfect fluid. Hence, we can consider the quark-gluon in the form of perfect fluid and we have the equation of state as

$$p_m = (\gamma - 1)\rho_m, \quad \text{where } 1 \le \gamma \le 2 \text{ is a constant.} \tag{4}$$

Kaluza [54] and Klein's [55] theory is most significant theory because it was one of the early possibilities of unification of gravity with electromagnetism and it has been elegantly presented in terms of geometry. In a certain sense, it is just ordinary gravity in free space described in five dimensions instead of four. Overduin and Wesson [56] have presented an excellent review of Kaluza-Klein theory and higher dimensional unified theories, in which the cosmological and astrophysical implications of extra-dimensions have been discussed. Ponce [57], Chi [58], Fukui [59] Liu and Wesson [60], Coley [61] have studied Kaluza-Klein cosmological models with different matters. Palatnik [62] constructed Schwarzschild solution for 3 space and n time dimensions in Kaluza-Klein theory.

It is possible to couple quark matter with cosmic strings and domain walls. Because, the strings are free to vibrate and different vibrational modes of the strings represent the different particle types, since different modes are seen as different masses or spins. Arakelyen et al. [63] have studied quark-gluon string model description of baryon production. Gravitons in Kaluza-Klein theory have been studied by Kumar and Suresh [64]. Burau [65] examined anisotropic flow of charged and identified hadrons in the quark-gluon string model for Au + Au collisions at 200 GeV. Filho-Boschi and Brage [66] have studied the duality between static strings and quark anti-quark configuration in the Randall-Sendrum scenarios. This motivates the authors to study quark matter coupled with the cloud of strings and domain walls in the n-dimensional Kaluza-Klein space time.

Our paper is organized as follows. In Sect. 2, the field equations and their solutions are obtained for dust quark matter coupled with the strings in the n-dimensional Kaluza-Klein space-time. Section 3 deals with the field equations and their solutions which are obtained for strange quark matter coupled with domain walls in the n-dimensional Kaluza-Klein space time. The last section is mainly concerned with the physical and kinematical properties of models.

2 Field Equations and their Solutions for Strings with Quark Matter

The line element for n-dimensional Kaluza-Klein model can be written as

$$ds^2 = -dt^2 + a^2 \sum_{i=1}^{n-2} dx_i^2 + b^2 dx_{n-1}^2, \tag{5}$$

where a and b are functions of time t only.

The energy momentum tensor for a cloud of cosmic strings source is

$$T_i^j = \rho u_i u^j - \lambda x_i x^j, \tag{6}$$

where ρ is the rest energy density of cloud of strings with particles attached to them and λ is the tension density of strings.

We consider

$$\rho = \rho_p + \lambda, \tag{7}$$

where ρ_p is the rest energy density of particles.

The string is free to vibrate and we know that different vibrational modes of the string represent the different types of particles, since different vibrational modes are seen as different masses or spins. Therefore, we will consider quarks instead of particles in the cloud of strings. Hence (7) will transform to

$$\rho = \rho_p + \lambda + B_c. \tag{8}$$

From (6) and (8), we can write the energy-momentum tensor [67] for strange quark matter attached to the cloud of strings as

$$T_i^j = (\rho_q + \lambda + B_c)u_i u^j - \lambda x_i x^j, \tag{9}$$

where u^o is timelike vector and x^i is the unit spacelike vector in the direction of anisotropy so that

$$x^i = (A^{-1}, 0, 0, 0, 0, 0, \ldots) \quad \text{and} \quad u^i = (\ldots, 0, 0, 0, 1),$$
$$u^o u_o = -1, \quad \text{otherwise zero},$$
$$x^{n-1} x_{n-1} = 1, \quad \text{otherwise zero}.$$

The Einstein's field equations in general relativity are

$$R_i^j - \frac{1}{2}R = -8\pi G T_i^j. \tag{10}$$

Here we consider geometrized units so that $8\pi G = c = 1$ and we use co-moving co-ordinates system.

The above field equations (10) for metric (5) with the energy momentum tensor (9) for a cloud of strings will be

$$\left(\frac{n^2-5n+6}{2}\right)\left(\frac{\dot{a}}{a}\right)^2 + (n-2)\left(\frac{\dot{a}\dot{b}}{ab}\right) = \rho, \tag{11}$$

$$(n-3)\left(\frac{\ddot{a}}{a}\right) + \left(\frac{\ddot{b}}{b}\right) + \left(\frac{n^2-7n+12}{2}\right)\left(\frac{\dot{a}}{a}\right)^2 + (n-3)\left(\frac{\dot{a}\dot{b}}{ab}\right) = 0, \tag{12}$$

$$(n-2)\left(\frac{\ddot{a}}{a}\right) + \left(\frac{n^2-5n+6}{2}\right)\left(\frac{\dot{a}}{a}\right)^2 = \lambda, \tag{13}$$

where overhead dot denotes differentiation with respect to time t.

For metric (5), the physical parameters expansion scalar θ and shear scalar σ^2 have the following expressions:

$$\theta = u^i_{;i} = (n-2)\left(\frac{\dot{a}}{a}\right) + \left(\frac{\dot{b}}{b}\right), \tag{14}$$

$$\sigma^2 = \frac{1}{2}(\sigma_{ij}\sigma^{ij}). \tag{15}$$

The equations (11)–(13) are three independent non-linear differential equations in four unknown parameters ρ, λ, a, b. Therefore, in order to obtain an exact solution of above differential equations, one relation between them is needed. In view of the anisotropy of the space time, we assume that shear expansion θ is proportional to the components of shear tensor σ^2 which also represents anisotropy of the universe [68]. Hence, we consider, a polynomial relation between the metric coefficients a and b as

$$b = \mu a^\alpha, \quad \text{where } \mu \text{ and } \alpha \text{ are constants.} \tag{16}$$

If we consider that shear viscosity is zero implying that shear scalar is zero, then from (15) we obtain a similar relation as given by (16). This is consistent with the experimental observations carried out by Back et al. [51], Adams et al. [52], Adcox et al. [53] in Brook-Haven

National Laboratory. As per results of Brook-Haven National Laboratory, the quark-gluon plasma has very small viscosity which is considered nearly to be zero shear viscosity and hence quark-gluon plasma behaves like a perfect fluid. But, in order to study the behaviour of the shear viscosity, we will not discuss above case. We will consider it otherwise.

Using relation (16), (12) will reduce to

$$\left(\frac{\ddot{a}}{a}\right)+\left(\frac{2\alpha^2-8\alpha+2\alpha n+n^2-7n+12}{2\alpha+2n-6}\right)\left(\frac{\dot{a}}{a}\right)^2=0. \tag{17}$$

Integrating, we get

$$a=K_3(K_1t+K_2)^{1/N+1},\quad \text{where } K_3=(N+1)^{1/N+1}, \tag{18}$$

$$b=K_4(K_1t+K_2)^{\alpha/N+1},\quad \text{where } K_4=\mu K_3^{\alpha},\ N\neq -1. \tag{19}$$

Here K_1, K_2, K_3 and K_4 are constants of integration.

Substituting values of a and b from (18) and (19) into (11), (13), (14) and (15), we have

$$\rho=\frac{K_1^2K_5}{((N+1)^2(K_1t+K_2)^2)},\quad \text{where } K_5=\frac{n^2-5n+2n\alpha-4\alpha+6}{2}, \tag{20}$$

$$\lambda=\frac{K_1^2K_6}{((N+1)^2(K_1t+K_2)^2)},\quad \text{where } K_6=\frac{n^2-7n+10}{2}, \tag{21}$$

$$\rho_q+B_c=\rho_p=\rho-\lambda=\frac{(n+n\alpha-2\alpha-2)K_1^2}{(N+1)^2(K_1t+K_2)^2}, \tag{22}$$

$$\theta=\frac{K_1(n-2+\alpha)}{((N+1)(K_1t+K_2))},\quad \sigma^2=\left(\frac{n+3}{18}\right)\theta^2. \tag{23}$$

For $n=5$, we get, dust quark matter solution, i.e. $\lambda=0$ and

$$\rho_q+B_c=\rho_p=\rho=\frac{3(\alpha+1)K_1^2}{(N+1)^2(K_1t+K_2)^2}.$$

For $n=5$ and $\alpha=-1$, the matter disappears and we get geometric string solution, i.e. $\rho_p=0$.

3 Field Equations and their Solutions for Domain Walls with Quark Matter

The energy-momentum tensor ${}^DT_i^j$ of domain walls [69] is given by

$${}^DT_i^j=\rho U_iU^j-p(g_i^j+U_iU^j), \tag{24}$$

where U^o is time-like vector and $U^i=(\dots,0,0,0,1)$ so that $U^oU_o=-1$ otherwise zero. Here also we use co-moving co-ordinate system. This perfect fluid form of the domain walls includes quark matter [70] described by $\rho_m=\rho_q+B_c$ and $p_m=p_q-B_c$ as well as domain walls tension σ_w given by $\rho=\rho_m+\sigma_w$ and $p=p_m-\sigma_w$ which are related by the bag model equation of state (equation (3)) and equation of state (equation (4)).

Using the line element (5), the field equations (10) take the form for (24) as

$$\left(\frac{n^2-5n+6}{2}\right)\left(\frac{\dot{a}}{a}\right)^2+(n-2)\left(\frac{\dot{a}\dot{b}}{ab}\right)=\rho, \tag{25}$$

$$(n-3)\left(\frac{\ddot{a}}{a}\right)+\left(\frac{\ddot{b}}{b}\right)+\left(\frac{n^2-7n+12}{2}\right)\left(\frac{\dot{a}}{a}\right)^2+(n-3)\left(\frac{\dot{a}\dot{b}}{ab}\right)=-p, \tag{26}$$

$$(n-2)\left(\frac{\ddot{a}}{a}\right)+\left(\frac{n^2-5n+6}{2}\right)\left(\frac{\dot{a}}{a}\right)^2=-p, \tag{27}$$

where overhead dot denotes derivative with respect to time t.

The equations (25)–(27) are three independent non-linear differential equations in four unknown parameters ρ, p, a, b. Therefore, in order to obtain an exact solution of above differential equations, one relation between them is required. In view of the anisotropy of the space time, we assume that shear expansion θ is proportional to the components of shear tensor σ^2 which also represents anisotropy of the universe [68]. Hence, we consider, again same polynomial relation between the metric coefficients a and b as

$$b=\mu a^{\alpha}, \quad \text{where } \mu \text{ and } \alpha \text{ are constants.} \tag{28}$$

Using relation (28), (27)–(26) will give

$$\left(\frac{\ddot{a}}{a}\right)+\left(\frac{\alpha^2-4\alpha+n\alpha-n+3}{\alpha-1}\right)\left(\frac{\dot{a}}{a}\right)^2=0. \tag{29}$$

Integrating, we get

$$a=L_3(L_1t+L_2)^{1/M+1}, \quad \text{where } L_3=(M+1)^{1/M+1}, \tag{30}$$

$$b=L_4(L_1t+L_2)^{\alpha/M+1}, \quad \text{where } L_4=\mu L_3^{\alpha}, M\neq -1, \tag{31}$$

where L_1, L_2, L_3 and L_4 are constants of integration.

Now substituting (30) and (31) into (25)–(27), (14) and (15), we get the following expressions for dynamical and kinematical quantities as

$$\rho=\rho_m+\sigma_w=\frac{L_1^2L_5}{((M+1)^2(L_1t+L_2)^2)}, \quad \text{where } L_5=\frac{n^2-5n+2n\alpha-4\alpha+6}{2}, \tag{32}$$

$$p=p_m-\sigma_w=\frac{L_1^2L_6}{((M+1)^2(L_1t+L_2)^2)}, \quad \text{where } L_6=\frac{-n^2+3n-2}{2}, \tag{33}$$

$$\theta=\frac{(n+\alpha-2)L_1}{((M+1)(L_1t+L_2))}, \quad \sigma^2=\left(\frac{n+3}{18}\right)\theta^2. \tag{34}$$

Observing expressions for (equations (32) and (33)) density and pressure of domain walls, we have stiff domain wall solutions.

To determine exactly the tension σ_w of domain walls and to find density and pressure of the quark matter, we will use the equations of state given by (3) and (4) respectively.

Case 1: If we use (3) in (32) and (33), we get expressions [70] for strange quark matter coupled to the domain walls as

$$\rho_q = \frac{3}{4}\frac{(n-2)(\alpha-1)L_1^2}{((M+1)^2(L_1t+L_2)^2)}, \tag{35}$$

$$p_q = \frac{(n-2)(\alpha-1)L_1^2}{4((M+1)^2(L_1t+L_2)^2)}, \tag{36}$$

$$\sigma_w = \frac{L_1^2(2n^2-6\alpha+n\alpha-7n-2)}{4((M+1)^2(L_1t+L_2)^2)} - B_c. \tag{37}$$

In the case of domain walls with quark matter, we have stiff domain walls solutions given by (32) and (33). It is clear that in the more realistic case in which the domain walls interact with the primordial plasma, the equation of state for domain walls is expected to be more stiff than that of a radiation. So, our solutions correspond to the early stages of evolution of the universe.

In the case of strange quark matter coupled to domain walls (Case 1) i.e. from (35) and (36), we get, $p_q = \rho_q/3$ as proposed by Bodmer [47] and Witten [48]. In this case domain walls behave like invisible matter due to their negative tension. Also, if vacuum energy density B_c (called as the bag constant) is absorbed into tension of the domain walls, then these solutions correspond to $\gamma = 4/3$ case (i.e. radiation case).

Case 2: If we use (4) in (32) and (33) i.e. quark matter coupled to the domain walls, we get

$$\rho_m = \rho_q + B_c = \frac{(n-2)(\alpha-1)L_1^2}{\gamma((M+1)^2(L_1t+L_2)^2)}, \tag{38}$$

$$p_m = p_q + B_c = \left(\frac{\gamma-1}{\gamma}\right)\frac{(n-2)(\alpha-1)L_1^2}{((M+1)^2(L_1t+L_2)^2)}, \tag{39}$$

$$\sigma_w = \frac{L_1^2(n^2-2\alpha+n\alpha-4n+4-(\frac{2-\gamma}{\gamma})(n-2)(\alpha-1))}{2((M+1)^2(L_1t+L_2)^2)}. \tag{40}$$

In the case of quark matter coupled to domain walls (Case 2) i.e. when $\gamma = 1$, we get domain walls solutions with negative tension and dust quark matter. When $\gamma = 4/3$, we have domain walls solutions with negative tension and quark matter solution like radiation. When $\gamma = 2$, we have stiff quark matter solution. In this case domain walls disappear.

4 Some Physical and Kinematical Properties

For the models having string cloud with quark matter and domain walls with quark matter, we have following general properties.

For the n-dimensional model, we note that the universe starts at an initial epoch $t = -K_2/K_1$ or $-L_2/L_1$.

When $t = -K_2/K_1$ or $-L_2/L_1$, the physical parameters θ and σ^2 diverge.

As time t gradually increases, θ and σ^2 decrease, and finally they vanish when $t \to \infty$. This seems to be consistent with the results of Brook-Haven National Laboratory [51–53]. Also, as t gradually increases, all dynamical quantities decrease inversely with the square of time and finally they tend to zero when $t \to \infty$. Here, we get, $\lim(\sigma/\theta) \approx 0.61$ for our model. According to Collins et al. [71] the present upper limit of (σ/θ) is $(10)^{-5}$ obtained from indirect arguments concerning the isotropy of the primordial blackbody radiation.

For our models, this limit is considerably greater than its present value. This fact indicates that our solutions represent the early stages of evolution of the universe.

Also it may be observed that when $n = 5$, the model reduces to the model obtained by Yilmaz [72].

5 Conclusions

We have considered a spatially homogenous and anisotropic cosmological model with n-dimensions in Kaluza-Klein theory of gravitation in the presence of cloud of strings source and domain walls. The resulting cosmological model represents an inflationary n-dimensional cosmological model in Kaluza-Klein theory of gravitation which is analogues to the result obtained by Yilmaz [72] in five dimensions.

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