Singularity-free non-exotic compact star in $f(R, T)$ gravity

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Abstract. In the present work, we have searched for the existence of anisotropic and non-singular compact star in the $f(R, T)$ gravity by taking into account the non-exotic equation of state (EoS). In order to obtain the solutions of the matter content of the compact object, we assume the well-known barotropic form of EoS that yields the linear relation between pressures and energy density. We propose the existence of non-exotic compact star which shows the validation of energy conditions and stability within the perspective of $f(R, T)$ extended theory of gravity. The linear material correction in the extended theory and matter content of compact star can remarkably satisfy energy condition. We discuss various physical features of the compact star and show that the proposed model of the stellar object satisfies all regularity conditions and is stable as well as singularity-free.

Keywords. Compact star; $f(R, T)$ gravity; singularity.

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1. Introduction

Harko et al [1] have proposed the extended theory of gravity, the so-called $f(R, T)$ gravity, by changing the geometrical part of the Einstein field equations instead of changing the source side by taking a generalised functional form of the argument to address galactic, extra-galactic and cosmic dynamics. In this theory, the gravitational terms of total action is defined by the functional form of $f(R)$ and $f(T)$. The main aim of this theory is to address some observational phenomena such as dark energy [2], dark matter [3] and massive pulsars [4] that were hardly explained by general relativity (GR). Among all the extended/modified theories of gravity, the $f(R, T)$ theory attracts more attention due to its unique feature of non-minimal coupling of matter and geometry [5]. In the recent past, several applications of $f(R, T)$ gravity [6–14] have been reported in the literature.

In this paper, we focus ourselves on investigating a non-exotic compact star within $f(R, T) = R + 2\xi T$ formalism where $\xi$ is an arbitrary constant. The compact star is a hypothetical dense body that may be a black hole or a degenerate star and the pressure inside it is not isotropic. In astrophysics, the structure and properties of the compact star had been studied by numerous researchers in different physical contexts [15–17]. In 2006, the most significant compact star has been observed by Rosat Surveys due to their X-ray emission [18]. This means that the gravitational energy of the compact star is radiated through X-rays. Long ago, Hewish et al [19] investigated some rapidly pulsating radio source which is in general the beam of electromagnetic radiation. This discovery inspires physicists to think about modelling compact star-like neutron star and quark star in the framework of general relativity and its extended form [20–23]. It is common understanding that one cannot analyse the structure and properties of compact star by taking into account the equation of state which relate the pressure and energy density in proportion. In refs [24–26], it has been found that the pressure of the compact star is anisotropic in nature. Recently, Momeni et al [27] have constructed a model of compact star in Horndeski theory of gravity and analysed it in modified theory of gravity. However, our model deals with the singularity-free compact star composed of non-exotic matter in $f(R, T)$ theory of gravity and its functional form $f(R, T) = R + 2\xi T$. In refs [6,28], some applications of $f(R, T)$ theory with respect to steller objects are reported. Some other relevant investigations on different functional forms of extended $f(R, T)$ theory of gravitation can be observed.
in [29,30] under different physical contexts. In 2014, Rahaman et al [31] studied the static wormhole in \( f(R) \) gravity with Lorentzian distribution which generates two models – one is derived from the power law form and the other one is based on the assumption of particular shape function which allows the reconstruction of the \( f(R) \) theory. Zubair et al [32] investigated numerical solutions for different wormhole matter content in the realm of \( f(R, T) \) gravity. Moraes [9] constructed the model of static wormhole by applying \( f(R, T) \) formalism.

In the present paper, we are concerned with the singularity-free non-exotic model of compact star with the realm of functional form of \( f(R, T) = R + 2\xi T \). It is worth mentioning that our model is derived from the well-known barotropic equation of state (EoS) in Krori and Barua (KB) space–time [33] that yield singularity-free solution. Das et al [23] have investigated a model of stellar object in the static spherically symmetric space–time which is probably singular and generates a set of solutions describing the interior of a compact star under \( f(R, T) \) theory of gravity which admits conformal motion whereas the present investigation is one with singularity-free solution. However, a common feature of both the investigations is the non-exotic matter configuration in \( f(R, T) \) gravity.

The paper is structured as follows: The basics of \( f(R, T) = f(R) + 2\xi T \) formalism are presented in §2. Section 3 deals with the KB metric, solution of field equations and physical behaviour of the model. In §4, we provide the boundary conditions, which are essential for finding the values of constants. In §5, we demonstrate the validity of energy conditions, stability and mass–radius relation to show the physical acceptance of the model. In §6, we match the model parameters with observation data sets. In §6, we give our results and discuss the future perspectives of the study.

2. The \( f(R, T) = f(R) + 2\xi T \) formalism

The total action for the \( f(R, T) \) theory of gravitation [1] reads as

\[
S = \frac{1}{4\pi} \int d^4 x f(R, T) \sqrt{-g} + \int d^4 x L_m \sqrt{-g},
\]

where \( R \) is the Ricci scalar, \( T \) is the trace of energy–momentum tensor \( T^i_j \), \( g \) is the metric determinant and \( L_m \) is the matter Lagrangian density.

By varying the total action \( S \) with respect to metric \( g_{ij} \), we obtain

\[
R_{ij} f'(R, T) - \frac{1}{2} f(R, T) g_{ij} + \left( g_{ij} \nabla^i \nabla_i - \nabla_i \nabla_j \right) f'(R, T) = 8\pi T_{ij} - \dot{f}(R, T) \theta_{ij} - \dot{f}(R, T) T_{ij}. \tag{2}
\]

Here, \( f'(R, T) = \frac{\partial f}{\partial R} \), \( \dot{f}(R, T) = \frac{\partial f}{\partial T} \) and \( \theta_{ij} \) reads as

\[
\theta_{ij} = g^{ij} \frac{\partial T_{ij}}{\partial g^{ij}}. \tag{3}
\]

In this paper, we take the more generic form of matter Lagrangian as \( L_m = -\rho \) [6]. Hence eq. (3) leads to

\[
\theta_{ij} = -2T_{ij} - \rho g_{ij}. \tag{4}
\]

Following the proposition of ref. [1], we assume the functional form of \( f(R, T) = f(R) + 2\xi T \) where \( \xi \) is a constant. In the literature, this functional form is commonly used to obtain cosmological solution in \( f(R, T) \) theory of gravitation [7–9].

Equations (2) and (4) lead to

\[
G_{ij} = (8\pi + 2\xi) T_{ij} + \xi (2\rho + T) g_{ij}, \tag{5}
\]

where \( G_{ij} \) is the Einstein’s tensor.

3. The KB metric and field equations

The Krori and Barua space–time [33,34] reads as

\[
ds^2 = -e^{\nu(r)}dt^2 + e^{\lambda(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2) \tag{6}
\]

with \( \lambda(r) = Ar^2 \) and \( \nu(r) = Br^2 + C \) where \( A, B \) and \( C \) are constants.

In this paper, we take an anisotropic fluid satisfying the matter content of the stellar object as

\[
T_{ij} = \text{diag}(-\rho, p_r, p_t, p_t), \tag{7}
\]

where \( \rho, p_r \) and \( p_t \) are the energy density, radial pressure and tangential pressure respectively. Thus, the trace of energy momentum tensor may be expressed as \( T = -\rho + p_r + 2p_t \).

Metric (6) and field equation (5) along with eq. (7) give the following equations:

\[
e^{-\lambda} \left( \frac{\lambda'}{r} - \frac{1}{r^2} \right) + \frac{1}{r^2} = (8\pi + \xi) \rho - \xi (p_r + 2p_t) \tag{8}
\]

\[
e^{-\lambda} \left( \frac{\nu'}{r} + \frac{1}{r^2} \right) - \frac{1}{r^2} = \xi \rho + (8\pi + 3\xi) p_r + 2\xi p_t \tag{9}
\]
\[
e^{-\lambda} \left( \frac{\nu'^2 - \lambda' \nu'}{2} + \frac{\nu' - \lambda'}{r} + \nu'' \right) = \zeta \rho + \zeta p_r + (8\pi + 4\zeta) p_t.
\]

(10)

3.1 Solution of field equations and physical parameters

To solve the above set of equations for the matter content of the compact star, it is useful to invoke the equation of state (EoS) which gives the relation between energy density and pressure. The most common barotropic forms of EoS [35] are

\[
p_r = \alpha \rho, \quad (11)
\]
\[
p_t = \beta \rho, \quad (12)
\]

where \(\alpha\) and \(\beta\) are constants having values in the range \((0, 1)\).

Now, from metric (6), one may obtain \(\lambda' = 2Ar, \quad \nu' = 2Br\) and \(e^{-\lambda} = e^{-Ar^2}\). Putting these values in eqs (8)–(10) along with the barotropic EoS (11) and (12), we obtain

\[
\rho = \frac{1}{[8\pi + \zeta - \zeta(\alpha + 2\beta)]} \times \left[ \exp(-Ar^2) \left( 2A - \frac{1}{r^2} \right) + \frac{1}{r^2} \right],
\]

(13)

\[
p_r = \frac{[8\pi + \zeta - \zeta(\alpha + 2\beta)]}{\alpha} \times \left[ \exp(-Ar^2) \left( 2A - \frac{1}{r^2} \right) + \frac{1}{r^2} \right],
\]

(14)

\[
p_t = \frac{[8\pi + \zeta - \zeta(\alpha + 2\beta)]}{\beta} \times \left[ \exp(-Ar^2) \left( 2A - \frac{1}{r^2} \right) + \frac{1}{r^2} \right].
\]

(15)

We observe that the barotropic EoS (11) and (12) are identically satisfied with solutions (13)–(15). Also we note that the energy density \(\rho\), radial pressure \(p_r\) and tangential pressure \(p_t\) decrease with \(r\) and finally approach small positive values. The behaviour of \(\rho, p_r\) and \(p_t\) is plotted in figure 2 for physically acceptable values of problem parameters. Figure 1 depicts the variation of \(\lambda\) against \(r\).

It is worth noting that \(d\rho/dr\) and \(dp_r/dr\) are negative leading to the following requirements for our model to be physically acceptable:

(i) The energy density is positive and its first derivative is negative.

(ii) The radial pressure is positive and radial pressure gradient is negative.

We also note that at \(r = 0\), the second derivative of energy density as well as radial pressure are negative which shows that the energy density and radial pressure are maximum at the centre of the wormhole.

The anisotropic parameter \((\Delta)\) is computed as

\[
\Delta = \frac{2(\beta - \alpha)}{r[8\pi + \zeta - \zeta(\alpha + 2\beta)]} \times \left[ \exp(-Ar^2) \left( 2A - \frac{1}{r^2} \right) + \frac{1}{r^2} \right].
\]

(16)

The anisotropic parameter is equivalent to the force due to the local anisotropy which is directed inward if radial pressure is greater than the tangential pressure and outward when radial pressure is less than tangential pressure. From eq. (16), we observe that the nature of \(\Delta\) depends on the free parameters \(\alpha\) and \(\beta\). These parameters are positive constant having values between 0 and 1 but \((\beta - \alpha)\) may be positive or negative depending upon the choice of values of these parameters. Thus, the repulsive anisotropic force \((\Delta > 0)\) will appear when \(\beta > \alpha\). Under this specification, the compact star allows the construction of more massive distribution [34]. That is why we have taken \(\beta > \alpha\) throughout the graphical analysis of the model. Figure 3 shows the variation of \(\Delta\) with respect to \(r\) for different values of \(\alpha\) and \(\beta\).

4. Boundary conditions

The central density is obtained by putting \(r = 0\) in eq. (13), i.e.

\[
\rho_c = \rho(r = 0) = \frac{3A}{8\pi + \zeta(1 - \alpha - 2\beta)}.
\]

(17)

The radial pressure and tangential pressure at the centre are given by

\[
p_{rc} = p_r(r = 0) = \frac{3A\alpha}{8\pi + \zeta(1 - \alpha - 2\beta)}.
\]

(18)
At the centre, anisotropy is zero which leads to $\alpha = \beta$. It is also required that the physical fluids must obey the Zeldovich’s criterion, i.e. $(p_r/c) \leq 1$. This implies that $\alpha = \beta \leq 1$. This shows the physical constraints on $\alpha$ and $\beta$.

The surface density is obtained by putting $r = R$ in eq. (13), i.e.,

$$
\rho(r = R) = \frac{(1 - \frac{2M}{R}) \left(2A - \frac{1}{R^2}\right) + \frac{1}{R^2}}{8\pi + \zeta(1 - \alpha - 2\beta)}.
$$

(20)

To obtain the boundary condition, we shall compare the interior metric to the Schwarzschild exterior at the boundary $r = R$ which leads to the following equations:

$$
1 - \frac{2M}{R} = e^{BR^2 + C}
$$

(21)

$$
e^{AR^2} \left(1 - \frac{2M}{R}\right) = 1
$$

(22)

$$
\frac{M}{R^3} = Be^{BR^2 + C}.
$$

(23)
The values of constants $A$ and $B$ are evaluated by choosing the boundary conditions such that $p_r = 0$ at $r = R$ and $\rho = a = \text{constant at } r = 0$. Thus, solving eqs (13), (14) and (21)–(23) along with boundary conditions, we obtain

$$A = \frac{[8\pi + \zeta(1 - \alpha - 2\beta)]a}{3}$$
$$= \frac{1}{R^2} \ln \left[ 1 - \frac{2M}{R} \right]^{-1}$$

(24)

$$B = \frac{1}{2R^2} \left[ e^{\frac{[8\pi + \zeta(1 - \alpha - 2\beta)]aR^2}{3} - 1} \right]$$
$$= \frac{M}{R^3} \left( 1 - \frac{2M}{R} \right)^{-1}.$$  

(25)

From eq. (24), it is evident that $A$ is a positive constant and its numerical value can be constrained by the specific choice of other free parameters, namely $\zeta$, $\alpha$ and $\beta$. Buchdahl [36] showed that the maximum allowable compactness for a fluid sphere is $(2M/R) < 8/9$.

In table 1, we have presented the numerical values of model parameters $A$, $B$, central density and radial pressure for different strange star candidates. In this paper, we have chosen $A = 0.00541$ for graphical analysis. Applying Buchdahl criteria for compactness in eq. (24), the chosen value of $A$ gives $R = 9.3749$ (see table 2) which is very close to the observed value of $R$ [37].

| Sl. No. | Stars          | $A$   | $B$   | $\rho(r = 0)$ (g/cm$^3$) | $p(r = 0)$ (dyne/cm$^2$) |
|--------|----------------|-------|-------|--------------------------|---------------------------|
| 1      | PSRJ 1614-2230 | 0.00213 | 0.00128 | $0.361232 \times 10^{15}$ | $2.682920 \times 10^{35}$ |
| 2      | PSRJ 1903+327  | 0.00489 | 0.00306 | $0.815675 \times 10^{15}$ | $6.058156 \times 10^{35}$ |
| 3      | 4U 1820-30     | 0.00515 | 0.00321 | $0.859045 \times 10^{15}$ | $6.380260 \times 10^{35}$ |
| 4      | VelaX-1        | 0.00506 | 0.00322 | $0.841611 \times 10^{15}$ | $6.250785 \times 10^{35}$ |
| 5      | 4U 1608-51     | 0.00541 | 0.00345 | $0.899825 \times 10^{15}$ | $6.683146 \times 10^{35}$ |

From figure 4, we observe that all the energy conditions are valid for radial pressure as well as tangential pressure with certain range of $D$. So the compact star presented in this paper is composed of non-exotic matter. Moraes and Sahoo [6] have also constructed the model of wormholes composed of non-exotic matter in the trace of energy momentum-tensor squared gravity. Further it is interesting to note that we may avoid the presence of exotic matter in the framework of $f(R, T)$ gravity and hence no candidate of dark energy/matter is required to explain the accelerating feature of the Universe as reported in refs [5,6].

The value of $A$ is constrained by employing the energy condition at the centre, i.e.

(i) NEC: $\rho_0 \geq 0 \Rightarrow A \geq 0$

(ii) WEC: $\rho + p_r \geq 0$ and $\rho + p_t \geq 0$

(iii) DEC: $\rho - p_r \geq 0$ and $\rho - p_t \geq 0$

(iv) SEC: $\rho + p_r \geq 0$ and $\rho + p_r + 2p_t \geq 0$.

In general theory of relativity, the stellar objects with violations of energy conditions are common. So, there are variety of toy models of stellar objects in which the matter source is in the form of Chaplygin gas [39]. But in this paper, we have constructed the model of compact star within the $f(R, T)$ formalism that validate all energy conditions and thus represents a viable model of compact star. The value of $A$ is restricted by eq. (24).

5.2 Stability

For a physically acceptable model, the velocity of sound should be less than the velocity of light, i.e. $0 \leq v_s \leq 1$.

$$v^2_{sr} = \frac{dp_r}{d\rho} = \alpha$$

(26)
Figure 4. Validation of energy conditions of singularity-free compact star.
Both $\alpha$ and $\beta$ lie between 0 and 1 ($0 \leq \alpha \leq 1; 0 \leq \beta \leq 1$) which implies that the velocity of sound is less than 1. Thus, our solution validates the existence of physically viable compact star within the specification of alternative theory of gravity.

Equations (26) and (27) lead to

$$|v_{st}^2 - v_{sr}^2| = |\beta - \alpha| \leq 1. \quad (28)$$

From eq. (28), the stability of compact star depends upon the free parameters $\alpha$ and $\beta$. According to Herrera [40], the region of stellar object in which the radial speed of sound is greater than the transverse speed of sound, is a potentially stable region. Thus, by imposing restriction on the values of $\alpha$ and $\beta$, one may check the stability of the derived model.

5.3 Adiabatic index

The adiabatic index is

$$\Gamma = \left( \frac{\rho + p_r}{p_r} \right) \frac{dp_r}{d\rho} = 1 + \alpha. \quad (29)$$

For stable configuration $\Gamma$ should be greater than 1.33 within the isotropic stellar system. Note that $\Gamma = 1.33$ is the critical value reported in refs [41,42]. Equation (29) gives a clue to choose the value of free parameter $\alpha$. For stable configuration, we have to choose $\alpha \geq 0.33$. That is why in this paper, we have chosen $\alpha = 0.4$ for graphical (see figure 6) and numerical analysis of the model.

5.4 Mass–radius relation

In our model, the gravitational mass $m(r)$ in terms of radius $r$ is expressed as

$$m(r) = \int_0^r 4\pi r^2 \rho \, dr$$

The profile of mass function $m(r)$ with respect to radius $r$ for different values of $\zeta$ is shown in figure 5.

At $r = R$, the gravitational mass is

$$m(r= R) = \frac{4\pi R [\exp(-Ar^2)(2Ar^2 - 1) + 1]}{8\pi + \zeta - \zeta(\alpha + 2\beta)} \quad (30)$$

5.5 Compactness and red-shift

The compactness of star $(u(r))$ is

$$u(r) = \frac{m(r)}{r} = \frac{4\pi \exp(-Ar^2)(2Ar^2 - 1) + 1}{8\pi + \zeta - \zeta(\alpha + 2\beta)}. \quad (32)$$
Table 2. Comparison of estimated values of model parameters with observed data sets.

| Sl. No. | Compact star           | $M_{\text{Obs}}$ ($M_\odot$) | Radii ($r_\odot$) | $\zeta$ | $M_{\text{Esti}}$ | $Z_{\text{Obs}}$ | $Z_{\text{Esti}}$ |
|--------|------------------------|-------------------------------|-------------------|--------|------------------|-----------------|-----------------|
| 1      | PSRJ1614-2230          | 1.970 ± 0.04 [43]            | 13 ± 2            | 6      | 1.973            | 0.344793        | 0.345475        |
| 2      | PSRJ1903+327           | 1.667 ± 0.02 [45]            | 9.438 ± 0.03      | 4      | 1.686            | 0.444945        | 0.407709        |
| 3      | 4U1820-30              | 1.580 ± 0.06 [44]            | 9.1 ± 0.4         | 4      | 1.592            | 0.431786        | 0.393753        |
| 4      | VelaX-1                | 1.770 ± 0.08 [45]            | 9.56 ± 0.08       | 3.65   | 1.814            | 0.484428        | 0.441777        |
| 5      | 4U1608-51              | 1.740 ± 0.14 [37]            | 9.3 ± 1.0         | 3.65   | 1.739            | 0.493929        | 0.489662        |

The profile of the compactness of the star with respect to $r$ is plotted in figure 7.

Therefore, the red-shift function $Z(r)$ is computed as

$$Z(r) = (1 - 2u)^{-1/2} - 1$$

$$= \left[ 1 - \frac{8\pi \left( \exp(-Ar^2)(2Ar^2 - 1) + 1 \right)}{8\pi + \zeta - \zeta(\alpha + 2\beta)} \right]^{-1/2} - 1.$$  \hspace{1cm} (33)

The profile of the red-shift function with respect to $r$ is depicted in figure 8.

6. Physical validity of the model

In this subsection, we match the similarity of the physical parameters of the derived model with their observational values for certain choice of $\zeta$. By using the observational data sets for mass ($M_\odot$) and radii ($r_\odot$), we carry out a comparative study of the estimated mass ($M_{\text{Esti}}$), observed red-shift ($Z_{\text{Obs}}$) of the derived model with the observed mass and red-shift of different stars namely PSRJ1614-2230, PSRJ1903+327, 4U1820-30, VelaX-1 and 4U1608-52 and the results are listed in table 2. From table 2, we observe that the derived model is very close to 4U1608051 and PSRJ1614-2230 for $\zeta = 3.65$ and $\zeta = 6$ respectively. Note that all the figures have been plotted for $\zeta = 3.65$.

7. Result and discussion

We have constructed, in the present paper, a singularity-free anisotropic compact star in the framework of $f(R, T)$ gravity. The exact and singularity-free solution of gravitationally collapsing system is obtained by taking into account the well-known EoS which gives the relation between energy density and pressure. The energy density, radial pressure and tangential pressure are decreasing functions of $r$. At the centre of the compact star, $\rho$, $p_r$ and $p_t$ have certain fixed values which satisfy the relations $\sim (p_r)_0 = \alpha(\rho)_0$ and $(p_t)_0 = \beta(\rho)_0$. The behaviour of anisotropic parameter is plotted in figure 3 for two different choices of $\alpha$ and $\beta$. Indeed, the anisotropy in stellar object represents a force which will direct outward when $p_t > p_r$ and inward when $p_t < p_r$ which allow the construction of more or less massive distribution respectively [34]. From table 1, we observe that the estimated mass of the derived compact star is in good agreement with the observed mass data sets [37,43–45]. In general, our solution validates all the energy conditions throughout the stellar region of the compact star. The validation of energy conditions can be checked by figure 4, which is plotted by taking $A = 0.025$. Equation (28) exhibits the stability criteria of compact star which shows that the particular choice of $\alpha$ and $\beta$ will generate stable compact star. Let us now concentrate on some other models of stellar objects within $f(R, T)$ formalism, especially the work by Moraes and Sahoo [6] and Das et al [46]. Das et al [46] have proposed a unique model of stellar object in $f(R, T)$ theory of gravity and show that the gravastar is a viable alternative of black hole. It is worth noting that mechanism of obtaining the solution is entirely different from the mechanism adopted in ref. [23].

As a final comment, we note that the present study represents the model of non-exotic compact star which validate the SEC as well as other energy conditions in the stellar region of the compact star as a significance of extra term of the $f(R, T)$ theory, namely $\zeta T$. The $T$-dependence of the $f(R, T)$ theory may describe the physical facts, which is missing in general theory of relativity. In our previous work [34], we have investigated a singularity-free dark energy star which contains an anisotropic matter confined within certain radius from the centre while in the present work, we propose a model of singularity-free non-exotic compact star with the aid of $f(R, T)$ theory of gravitation. In future, one can check the viability of such solution under the specification of other valuable functional forms of $f(R, T)$ such as $f(R, T) = R + \zeta RT$ and $f(R, T) = R + \zeta R^2 + \lambda T$ where $\zeta$ and $\lambda$ are arbitrary constants.

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