Hindawi
Advances in Mathematical Physics
Volume 2022, Article ID 7243750, 11 pages
https://doi.org/10.1155/2022/7243750

Research Article

A Well-Behaved Anisotropic Strange Star Model

Amos V. Mathias and Jefta M. Sunzu

Department of Mathematics and Statistics, University of Dodoma, P.O. Box 338, Dodoma, Tanzania

Correspondence should be addressed to Jefta M. Sunzu; jefta@aims.ac.za

Received 6 May 2022; Revised 17 October 2022; Accepted 31 October 2022; Published 18 November 2022

Academic Editor: Claudio Dappiaggi

We obtain a new nonsingular exact model for compact stellar objects by using the Einstein field equations. The model is consistent with stellar star with anisotropic quark matter in the absence of electric field. Our treatment considers spacetime geometry which is static and spherically symmetric. Ansatz of a rational form of one of the gravitational potentials is made to generate physically admissible results. The balance of gravitational, hydrostatic, and anisotropic forces within the stellar star is tested by analysing the Tolman-Oppenheimer-Volkoff (TOV) equation. Several stellar objects with masses and radii comparable with observations found in the past are generated. Our model obeys different stability tests and energy conditions. The profiles for the potentials, matter variables, stability, and energy conditions are well behaved.

1. Introduction

The studies on the structure and behaviour of compact relativistic stellar spheres have been possible through investigation of solutions for field equations. Neutral and charged spheres have been investigated under specified spacetime geometries. Charged stellar models under static and spherically symmetric spacetime include the performance by [1–10]. Uncharged stellar models include recent works performed by [11–15]. The studies by Ruderman [16] and Canuto [17] indicate that radial and transverse pressures within the stellar bodies may not be equal. The quantity defining this difference is called the pressure anisotropy. Different phenomena explain the indicators of this imbalance of pressures within the stellar object. Some of these phenomena include existence of condensate states such as pion and kaon condensations as indicated by Kippenhahn and Weigert [18] which exist when the stellar core has solid matter as observed by Sawyer [19]. This can also happen when the stellar matter passes through several phase transitions as indicated by Sokolov [20]. Bowers and Liang [21] asserted that no compact stellar sphere is composed wholly of perfect fluid. Ultrahigh density and gravitational pull in these objects result to enormous pressure anisotropy. Several studies have recognized the significance of pressure anisotropy in stellar models including recent performance by [6, 7, 12, 22–25]. Imposition of equation of state for stellar matter in modelling relativistic stellar objects is very significant. Various studies have adopted different equations defining the state of stellar fluid to obtain well-behaved stellar models. We observe that [23, 26–30] obtained well-behaved charged stellar models by applying linear equation of state. The treatment by [11, 31–35] applied quadratic equation of state to generate stellar models with astrophysical significance. The works by [13, 36–39] generated physically significant stellar models with viable results in astrophysics and astronomy using Chaplygin equation of state. The recent relativistic models by [4, 40–42] were generated by imposing polytropic equation of state. On the other hand, [43, 44] applied van der Waals equation of state to obtain astrophysically significant stellar models. The use of linear equation of state in modelling self-gravitating stellar objects is evident in various studies. Models consistent with strange stars composed of quark matter have been found with this equation of state. The simplified form of linear equation of state has the form $p_r = 1/3(\rho - 4B)$ as indicated by Witten [45], where ρ and B represent energy density and bag constant, respectively. We are interested to investigate the geometry and physical characteristics of strange stars with quark matter by introducing linear form of equation of state along with a new form of one of the gravitational potentials missing in the previous studies to obtain a well-behaved anisotropic strange star model. Additionally, we undertake several physical tests which are missing in most of the models generated in the past. This article is organised in seven sections. The basic stellar equations are presented in Section 2 followed by the transformations in Section 3. The model and its physical properties are introduced in Sections 4 and 5, respectively. Discussion of findings is presented in Section 6, and the closing remarks are provided in Section 7.

2. Basic Stellar Equations

We generate a new exact solution describing the interior of the strange star in general relativity. The geometry of spacetime is considered to be static and spherically symmetric. The line element of the star interior is considered to have the form

$$\mathrm{ds}^2 = -e^{2\nu(r)}\mathrm{dt}^2 + e^{2\lambda(r)}\mathrm{dr}^2 + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right), \quad (1)$$

with $\nu(r)$ and $\lambda(r)$ being the gravitational functions. The exterior of the strange star is considered to conform to Schwarzschild exterior spacetime given by the line element

$$\mathrm{ds}^2 = -\left(1 - \frac{2M}{r}\right)\mathrm{dt}^2 + \left(1 - \frac{2M}{r}\right)^{-1}\mathrm{dr}^2 + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right), \quad (2)$$

where M is the mass of the star. The energy momentum tensor for the stellar star in the absence of electric field is given by

$$T_{\mathrm{ij}} = \mathrm{diag}\left(-\rho, p_r, p_t, p_t\right), \quad (3)$$

where ρ, p_r, and p_t are the energy density, radial pressure, and tangential pressure, respectively. These matter variables are determined relative to a comoving unit timelike fluid four-velocity u^a. The value $8\pi G/c^4$ representing the coupling constant and the speed of light c is considered to be united.

The Einstein field equations which govern neutral stellar stars can be represented as

$$\frac{1}{r^2}\left(1 - e^{-2\lambda}\right) + \frac{2\lambda'}{r}e^{-2\lambda} = \rho, \quad (4a)$$

$$-\frac{1}{r^2}\left(1 - e^{-2\lambda}\right) + \frac{2\nu'}{r}e^{-2\lambda} = p_r, \quad (4b)$$

$$e^{-2\lambda}\left(\nu'' + \nu'^2 - \nu'\lambda' + \frac{\nu'}{r} - \frac{\lambda'}{r}\right) = p_t. \quad (4c)$$

The primes ($'$) in the field equations represent the derivatives of the gravitational functions with respect to the radial distance r. The function representing the mass of the neutral stellar star is given by

$$M(r) = \frac{1}{2}\int_0^r \omega^2\rho(\omega)d\omega. \quad (5)$$

The stellar star is considered to compose quark matter which admit the linear equation of state of the form

$$p_r = \frac{1}{3}(\rho - 4B), \quad (6)$$

where B is the bag constant.

3. Transformations

To ease the integrability of the field equations in systems (4a), (4b), and (4c), we embrace Durgapal and Bannerji's [46] transformations given by

$$\begin{aligned} x &= \mathrm{C}r^2, \\ Z(x) &= e^{-2\lambda(r)}, \\ A^2y^2(x) &= e^{2\nu(r)}, \end{aligned} \quad (7)$$

where A and C are arbitrary real constants. When we subject system (2) to these transformations, we obtain

$$\frac{1 - Z}{x} - 2\dot{Z} = \frac{\rho}{C}, \quad (8a)$$

$$4Z\frac{\dot{y}}{y} + \frac{Z - 1}{x} = \frac{p_r}{C}, \quad (8b)$$

$$4\mathrm{x}Z\frac{\ddot{y}}{y} + \left(4Z + 2\mathrm{x}\dot{Z}\right)\frac{\dot{y}}{y} + \dot{Z} = \frac{p_t}{C}, \quad (8c)$$

and the line element becomes

$$\mathrm{ds}^2 = -A^2y^2\mathrm{dt}^2 + \frac{1}{4\mathrm{x}CZ}\mathrm{dx}^2 + \frac{x}{C}\left(d\theta^2 + \sin^2\theta d\phi^2\right). \quad (9)$$

Applying the transformations in Equation (7) to Equation (5), the mass function becomes

$$M(x) = \frac{1}{4C^{3/2}}\int_0^x \sqrt{\omega}\rho(\omega)d\omega. \quad (10)$$

Incorporating the equation of state (6) in systems (4a), (4b), and (4c), the field equations becomes

$$\rho = \left(\frac{1 - Z}{x} - 2\dot{Z}\right)C, \quad (11a)$$

$$p_r = \frac{1}{3}(\rho - 4B), \quad (11b)$$

$$p_t = p_r + \Delta, \quad (11c)$$

$$\Delta = C\left(2x\frac{\dot{y}}{y} + \frac{5}{3}\right)\dot{Z} + C\left(4x\frac{\ddot{y}}{y} + 4\frac{\dot{y}}{y} + \frac{1}{3x}\right)Z + \frac{4}{3}B - \frac{C}{3x}, \tag{11d}$$

$$\frac{\dot{y}}{y} = \frac{1}{3Z}\left(\frac{1-Z}{x} - \frac{\dot{Z}}{2} - \frac{B}{C}\right). \tag{11e}$$

We notice that (20) can also be written as

$$y(x) = \mathrm{He}^{\int g(x)\mathrm{dx}}, \tag{12}$$

where

$$g(x) = \frac{1}{3Z}\left(\frac{1-Z}{x} - \frac{\dot{Z}}{2} - \frac{B}{C}\right), \tag{13}$$

and H is the constant of integration. The anisotropic factor Δ is defined by $\Delta = p_t - p_r$, and the force exerted due to anisotropy is given by $2\Delta/r$. The study by [47] indicated that when $\Delta > 0$, the anisotropic force acts outward and it is repulsive in nature and when $\Delta < 0$, the force acts inward with attractive behaviour. When $p_t = p_r$, it implies that $\Delta = 0$ and there is no anisotropic force and the model becomes isotropic.

4. The Model

The matter variables involved in our model include $\rho, p_r p_t$, Z, y, and Δ. Since the systems (11a), (11b), (11c), (11d), and (11e) have lesser number of equations as compared to unknown variables, we specify one of the variables in the system to simplify the integration process. We followed the method recently applied by Mathias and Sunzu [30] with a different choice of metric function. The choice is carefully made to yield physically admissible model. We specify the gravitational potential $Z(x)$ in a rational form given by

$$Z(x) = \frac{1+\psi x}{(1+\gamma x)^2}, \tag{14}$$

where ψ and γ are real constants such that $\psi \neq \gamma$ and $\gamma \neq 0$. This function is continuous and regular throughout the interior of the stellar star. This choice takes reciprocal form of the potential in [48, 49] to obtain a well-behaved strange star model. The choice of potential made by [49] had a rational form of $Z(x)$ with quadratic expression in the numerator and linear expression in the denominator. The choice in the current paper has linear expression in the numerator and quadratic expression in the denominator. Our choice of potential is a new form, and it guarantees a new strange star model that obeys various physical tests on stability, state of hydrostatic equilibrium, and energy conditions. The choice made in this study enlightens more the investigations of strange stars.

When we apply Equation (14) into Equation (12), we obtain the metric function y in the form

$$y(x) = H(1+\psi x)^{-n}\sqrt[3]{(1+\gamma x)}\exp\left[Y(x)\right], \tag{15}$$

where H is a constant of integration and the function $Y(x)$ is given by

$$Y(x) = \frac{\gamma\psi x(2C\gamma\psi - B(-2\gamma + 4\psi + \gamma\psi x))}{6C\psi^3}, \tag{16}$$

where n is given by

$$n = \frac{2B(\gamma-\psi)^2 + C\psi\left(2\gamma^2 - 4\gamma\psi + 3\psi^2\right)}{6C\psi^3}. \tag{17}$$

The exact model obtained by solving systems (4a), (4b), and (4c) can be written in the form

$$e^{2\lambda} = (1+\gamma x)^2(1+\psi x)^{-1}, \tag{18a}$$

$$e^{2\nu} = A^2H^2(1+\psi x)^{-2n}\sqrt[3]{(1+\gamma x)^2}\exp\left[2Y(x)\right], \tag{18b}$$

$$p_r = \frac{1}{3}(\rho - 4B), \tag{18c}$$

$$p_t = p_r + \Delta, \tag{18d}$$

$$\begin{aligned}\Delta = {} & \frac{1}{9(1+x\gamma)^4(1+x\psi)}(12B - 24C\gamma + 48\mathrm{Bx}\gamma \\ & - 53\mathrm{Cx}\gamma^2 + 72\mathrm{Bx}^2\gamma^2 - 12\mathrm{Cx}^2\gamma^3 + 48\mathrm{Bx}^3\gamma^3 \\ & - 3\mathrm{Cx}^3\gamma^4 + 12\mathrm{Bx}^4\gamma^4 + 18C\psi - 36\mathrm{Cn}\psi \\ & + 12\mathrm{Bx}\psi - 60\mathrm{Cnx}\gamma\psi + 48\mathrm{Bx}^2\gamma\psi \\ & - 67\mathrm{Cx}^2\gamma^2\psi - 24\mathrm{Cnx}^2\gamma^2\psi + 72\mathrm{Bx}^3\gamma^2\psi \\ & - 12\mathrm{Cx}^3\gamma^3\psi + 48\mathrm{Bx}^4\gamma^3\psi - 3\mathrm{Cx}^4\gamma^4\psi \\ & + 12\mathrm{Bx}^5\gamma^4\psi + 18\mathrm{Cx}\psi^2 - 18\mathrm{Cnx}\psi^2 \\ & + 36\mathrm{Cn}^2x\psi^2 + 24\mathrm{Cx}^2\gamma\psi^2 - 24\mathrm{Cnx}^2\gamma\psi^2 \\ & + 72\mathrm{Cn}^2x^2\gamma\psi^2 - 14\mathrm{Cx}^3\gamma^2\psi^2 - 6\mathrm{Cnx}^3\gamma^2\psi^2 \\ & + 36\mathrm{Cn}^2x^3\gamma^2\psi^2 - 6C(1+x\gamma)(1+x\psi) \\ & \cdot\left(-6 + (-7+12n)x^2\gamma\psi + x(-4\gamma - 9\psi\right. \\ & \left. + 12n\psi)\right)\dot{Y}(x) + 36\mathrm{Cx}(1+x\gamma)^2 \\ & \cdot(1+\psi)^2\dot{Y}(x)^2 + 36\mathrm{Cx}(1+x\gamma)^2 \\ & \cdot\left.(1+x\psi)^2\ddot{Y}(x)\right).\end{aligned} \tag{18e}$$

5. Physical Properties

We notice that the solution functions presented in systems (18a), (18b), (18c), (18d), and (18e) which are obtained by solving the system of field equations in systems (11a), (11b), (11c), (11d), and (11e) are in elementary form. The mass function in Equation (10) then becomes

$$M(x)=\frac{x\sqrt{x}(-3\psi+\gamma(6+x(\gamma(3+x\gamma)+\psi)))}{6\sqrt{C}(1+x\gamma)^3}, \tag{19}$$

and the line element has the form

$$\begin{aligned} ds^2 &= -H^2(1+\psi x)^{-2n}\sqrt[3]{(1+\gamma x)^2}\exp\left[2Y(x)\right]dt^2 \\ &+ \frac{(1+\gamma x)^2}{1+\psi x}dr^2 + r^2\left(d\theta^2+\sin^2\theta d\phi^2\right). \end{aligned} \tag{20}$$

5.1. Compactness and Redshift. The compactness factor μ for the stellar stars proposed by [50] is given by

$$\mu=\frac{2M}{R}, \tag{21}$$

where M is the total mass of the stellar star and R is the stellar radius. The critical value of compactification factor for isotropic fluid spheres $\mu_{\text{crit}} \leq 8/9$, however for anisotropic spheres μ_{crit}, may exceed this limit [51]. By applying Equation (19) to Equation (21), we obtain

$$\mu(x)=\frac{x(-3\psi+\gamma(6+x(\gamma(3+x\gamma)+\psi)))}{3(1+x\gamma)^3}. \tag{22}$$

The gravitational redshift z_s of a stellar star is given by

$$z_s=\frac{1}{\sqrt{1-\mu}}-1, \tag{23}$$

where μ is the quantity defining compactness of the stellar star. In the present model, z_s is found by substituting (22) into (23), and the resulting function has the form

$$z_s(x)=\left[1-\frac{x(-3\psi+\gamma(6+x(\gamma(3+x\gamma)+\psi)))}{3(1+x\gamma)^3}\right]^{-1/2}-1. \tag{24}$$

5.2. The TOV Equation. The Tolman-Oppenheimer-Volkoff (TOV) equation is an important tool to examine the balance of forces acting within the stellar object. When the forces are well balanced, then the stellar object is said to be in the state of hydrostatic equilibrium. The balance of forces implies that the energy within the stellar star is conserved. The TOV equation is given by

$$p_{r'}+(\rho+p_r)\nu'-\frac{2\Delta}{r}=0. \tag{25}$$

The balancing condition for a neutral anisotropic stellar star is that all forces (gravitational force F_g, hydrostatic force F_h, and anisotropic force F_a) act within the stellar fluid sum to zero. That is,

$$F_g+F_h+F_a=0, \tag{26}$$

where

$$F_g=-(\rho+p_r)\nu', \tag{27a}$$

$$F_h=-p'_r, \tag{27b}$$

$$F_a=\frac{2\Delta}{r}. \tag{27c}$$

The expressions for the forces in (27a), (27b), and (27c) are in the form

$$\begin{aligned} F_g(x) &= -\frac{4\sqrt{x}}{9\sqrt{C}(1+x\gamma)^4(1+x\psi)}\left(-2B+6C\gamma\right. \\ &- 6Bx\gamma+6Cx\gamma^2-6\beta x^2\gamma^2+2Cx^2\gamma^3 \\ &\left.- 2Bx^3\gamma^3-3C\psi-Cx\gamma\psi\right)\left(-B+6C\gamma\right. \\ &- 3Bx\gamma+3Cx\gamma^2-3Bx^2\gamma^2+Cx^2\gamma^3 \\ &\left.- Bx^3\gamma^3-3C\psi+x\gamma\psi\right), \\ F_h(x) &= \left(3\sqrt{C}(1+x\gamma)^4\right)^{-1}\left(2\gamma C^2\sqrt{x}\left(15\gamma+4x\gamma^2\right.\right. \\ &\left.\left.+ x^2\gamma^3-10\psi+2x\gamma\psi\right)\right), \\ F_a(x) &= \frac{2\sqrt{C}}{9\sqrt{x}(1+x\gamma)^4(1+x\psi)}\left(12B-24C\gamma\right. \\ &+ 48Bx\gamma-53Cx\gamma^2+72Bx^2\gamma^2-12Cx^2\gamma^3 \\ &+ 48Bx^3\gamma^3-3Cx^3\gamma^4+12Bx^4\gamma^4+18C\psi \\ &- 36Cn\psi+12Bx\psi-60Cnx\gamma\psi+48Bx^2\gamma\psi \\ &- 67Cx^2\gamma^2\psi-24Cnx^2\gamma^2\psi+72Bx^3\gamma^2\psi \\ &- 12Cx^3\gamma^3\psi+48Bx^4\gamma^3\psi-3Cx^4\gamma^4\psi \\ &+ 12Bx^5\gamma^4\psi+18Cx\psi^2-18Cnx\psi^2 \\ &+ 36Cn^2x\psi^2+24Cx^2\gamma\psi^2-24Cnx^2\gamma\psi^2 \\ &+ 72Cn^2x^2\gamma\psi^2-14Cx^3\gamma^2\psi^2-6Cnx^3\gamma^2\psi^2 \\ &+ 36Cn^2x^3\gamma^2\psi^2-6C(1+x\gamma)(1+x\psi) \\ &\cdot\left(-6+(-7+12n)x^2\gamma\psi+x(-4\gamma-9\psi\right. \\ &\left.+ 12n\psi)\right)\dot{Y}(x)+36Cx(1+x\gamma)^2 \\ &\cdot(1+\psi)^2\dot{Y}(x)^2+36Cx(1+x\gamma)^2 \\ &\left.\cdot(1+x\psi)^2\ddot{Y}(x)\right). \end{aligned} \tag{28}$$

5.3. Stability Conditions. The stability of a stellar model can be tested under different stability criteria. The nature of radial and tangential variations of equation of state parameter prompts information on model stability. The equation of state parameter in radial and transverse orientations is given by $w_r = p_r/\rho$ and $w_t = p_t/\rho$, respectively. In the present model,

$$w_r(x) = \left(3C\left(3x\gamma^2 + x^2\gamma^3 - 3\psi + \gamma(6 + x\psi)\right)\right)^{-1} \cdot \left(-4B(1 + x\gamma)^3 + C\left(3x\gamma^2 + x^2\gamma^3 - 3\psi + \gamma(6 + x\psi)\right)\right)$$
$$w_t(x) = \left(9C^2(1 + x\gamma)(1 + x\psi)\left(3x\gamma^2 + x^2\gamma^3 - 3\psi + \gamma(6 + x\psi)\right)\right)^{-1}\left(4B^2x(1 + x\gamma)^6 - 2\mathrm{BC}(1 + x\gamma)^3\left(6 + 4x^3\gamma^3 + 3x(8\gamma - \psi) + x^2\gamma(12\gamma + 7\psi)\right) + C^2\left(24x^4\gamma^5 + 4x^5\gamma^6 - 12x^2\gamma^3(-9 + x\psi) + 9\psi(-1 + x\psi) + 2x^3\gamma^4(36 + x\psi) + x\gamma^2\left(54 - 75x\psi - 5x^2\psi^2\right) + 6\gamma\left(3 - 5x\psi + 4x^2\psi^2\right)\right)\right). \tag{29}$$

The stability of the stellar model can also be examined based on the value of adiabatic index Γ given by

$$\Gamma = \left(\frac{\rho + p_r}{p_r}\right)\frac{\mathrm{d}p_r}{d\rho}. \tag{30}$$

The stability condition for Newtonian spheres can be examined based on the value of adiabatic index satisfying the inequality $\Gamma > 4/3$. However, the work by [52] indicates that the stability of stellar sphere with anisotropic fluid satisfies the inequality

$$\Gamma > \frac{4}{3} + \left[\frac{4(p_{t0} - p_{r0})}{3|p_{r0}'|} + \frac{8\pi\rho_0 p_{r0}}{3|p_{r0}'|}r\right]_{\max}, \tag{31}$$

where p_{r0}, p_{t0}, and ρ_0 represent initial radial pressure, tangential pressure, and energy density, respectively. The works by [53–55] show that the stability of anisotropic stellar spheres satisfies the inequality $\Gamma > \Gamma_c$, where Γ_c is the critical adiabatic index defined by

$$\Gamma_c = \frac{4}{3} + \frac{19}{21}\mu, \tag{32}$$

where μ is the compactification factor.

In the present model, the expression for Γ is given by

$$\Gamma(x) = \frac{1}{3}\left(1 + \left(\left(-4B(1 + x\gamma)^3 + C\left(3x\gamma^2 + x^2\gamma^3 - 3\psi + \gamma(6 + x\psi)\right)\right)^{-1}\left(3C\left(3x\gamma^2 + x^2\gamma^3 - 3\psi + \gamma(6 + x\psi)\right)\right)\right)\right). \tag{33}$$

The proposition by [56] provides another stability criterion for stellar spheres termed as cracking of a star. For stable stellar configurations,

$$\left|v_r^2 - v_t^2\right| < 1. \tag{34}$$

This condition is essential to prevent stellar star from overturning. The variables v_r^2 and v_t^2 are given by $v_r^2 = \mathrm{d}p_r/d\rho$ and $v_t^2 = \mathrm{d}p_t/d\rho$, respectively. In the current model,

$$v_r^2 - v_t^2 = \frac{1}{3} + \left(\left(\left(9\gamma(1 + x\gamma)(C + \mathrm{C}x\psi)^2\left(4x\gamma^2 + x^2\gamma^3 - 10\psi + \gamma(15 + 2x\psi)\right)\right)\right)^{-1} \cdot \left(2\left(2B^2(1 + x\gamma)^6\left(1 + 3x\gamma + 2x^2\gamma\psi\right) - \mathrm{BC}(1 + x\gamma)^3\left(-9\psi + x\gamma^2(24 - 5x\psi) + 4x^3\gamma^4(2 + x\psi) + 8x^2\gamma^3(3 + x\psi) + 2\gamma\left(9 + x\psi + 5x^2\psi^2\right)\right) + C^2\left(2x^5\gamma^7 + 9\psi^2 + 2x^4\gamma^6(5 - 2x\psi) + 5x^3\gamma^4\psi(-16 + 3x\psi) - x^3\gamma^5\left(-12 + 36x\psi + x^2\psi^2\right) - 3\gamma\psi\left(2 - 11x\psi + 2x^2\psi^2\right)\psi + x\gamma^3\left(27 + 3x + 103x^2\psi^2 + 5x^3\psi^3\right) - \gamma^2\left(9 + 75x\psi + 9x^2\psi^2 + 41x^3\psi^3\right)\right)\right)\right)\right). \tag{35}$$

5.4. Energy Conditions. The physically admissible models for stellar objects with anisotropic matter distribution should satisfy different energy conditions. The works by [57–59] indicate different kinds of energy conditions including null energy condition (NEC), weak energy condition (WEC), dominant energy condition (DEC), and strong energy conditions (SEC). These conditions satisfy the following inequalities:

$$\begin{aligned} &\mathrm{NEC} =: \rho + p_r \geq 0 \text{ and } \rho + p_t \geq 0, \\ &\mathrm{WEC} =: \rho \geq 0, \rho + p_r \geq 0 \text{ and } \rho + p_t \geq 0, \\ &\mathrm{DEC} =: \rho \geq 0, \rho - p_r \geq 0 \text{ and } \rho - p_t \geq 0, \\ &\mathrm{SEC} =: \rho + p_r \geq 0, \rho + p_t \geq 0 \text{ and } \rho + p_r + 2p_t \geq 0. \end{aligned} \tag{36}$$

We examine the viability of current stellar model graphically by testing these conditions.

5.5. Boundary Conditions. We match the interior solution to exterior Schwarzschild solution at the boundary of the stellar star. The conditions for continuity of metric coefficients from the line elements (1) and (2) at the boundary $(r = R)$ are given by

$$e^{2\nu(R)} = 1 - \frac{2M}{R}, \tag{37}$$

$$e^{2\lambda(R)} = \left(1 - \frac{2M}{R}\right)^{-1}. \tag{38}$$

The radial pressure p_r vanishes at $r = R$. This implies that

$$p_r(r = R) = 0. \tag{39}$$

Substituting the expressions for $e^{2\nu(R)}$, $e^{2\lambda(R)}$, M, and p_r $(r = R)$ from Equations (18a), (18b), and (19), respectively, into Equations (37), (38), and (39), we obtain

$$\begin{aligned} 0 = 1 &- \left(3\left(1 + \mathrm{CR}^2\gamma\right)^3\right)^{-1} \left(\mathrm{CR}\left(3CR^2\gamma^2 + C^2R^4\gamma^3\right.\right. \\ &\left.\left.- 3\psi + \gamma\left(6 + CR^2\right)\right)\right) - A^2H^2\left(1 + CR^2\psi\right)^{-2n} \\ &\cdot \sqrt[3]{\left(\left(1 + CR^2\gamma\right)^2\right)} \exp\left[2Y(R)\right], \end{aligned} \tag{40a}$$

$$\begin{aligned} 0 = &\left(\left(\left(3\left(1 + \mathrm{CR}^2\gamma\right)^3\right)^{-1}\left(1 + \mathrm{CR}^2\psi\right)\right)\right) \\ &\cdot R\left(3C^5R^9\gamma^5 + \mathrm{CR}(6\gamma - 3\psi)\right. \\ &+ 3C^2R^3\gamma(7\gamma - 3\psi) - 3\mathrm{CR}^2(2\gamma - \psi) \\ &- 6C^2R^4\gamma(2\gamma - \psi) + 9C^3R^5\gamma^2(3\gamma - \psi) \\ &+ 3C^4R^7\gamma^3(5\gamma - \psi) - C^5R^9\gamma^3 \\ &\cdot \left(5\gamma + CR^2\gamma^2 + \psi\right) - C^3R^5\gamma\left(6\gamma^2\right. \\ &\left.\left.- 3\gamma(-1 + \psi) + \psi\right) - C^4R^7\gamma^2(7\gamma + 2\psi)\right), \end{aligned} \tag{40b}$$

$$\begin{aligned} 0 = &\left(3\left(1 + \mathrm{CR}^2\gamma\right)^3\right)^{-1}\left(-4B + 6C\gamma - 12\mathrm{BCR}^2\gamma\right. \\ &+ 3C^2R^2\gamma^2 - 12\mathrm{BC}^2R^4\gamma^2 + C^3R^4\gamma^3 \\ &\left.- 4\mathrm{BC}^3R^6\gamma^3 - 3C\psi + C^2R^2\gamma\psi\right), \end{aligned} \tag{40c}$$

where

$$Y(R) = \frac{\gamma\psi\mathrm{CR}^2\left(2C\gamma\psi - B\left(-2\gamma + 4\psi + \gamma\psi\mathrm{CR}^2\right)\right)}{6C\psi^3}. \tag{41}$$

We observe that systems (40a), (40b), and (40c) have seven parameters (i.e., C, R, γ, ψ, A, H, and B) in the three equations. The system has sufficient free parameters for matching conditions.

6. Discussion

In this section, we describe the structure and behaviour of the model generated in Section 4, relative to acceptable behaviour of stellar models in general relativity. Mathematical computations have been performed with *Mathematica* software while plots have been generated by using *Python* programming language. All the plots are generated against the radial distance r, and the values for the parameters used are $\psi = 3.4$, $\gamma = 3.1$, $B = \pm 2.73 \times 10^{-3}$, $C = 8.0 \times 10^{-3}$, and $H = 0.26$.

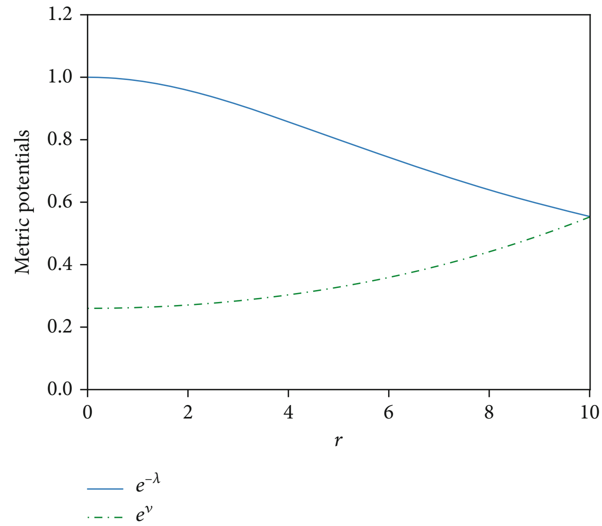

Figure 1: The metric potentials ($e^{-\lambda}$ and e^{ν}) against the radial distance r.

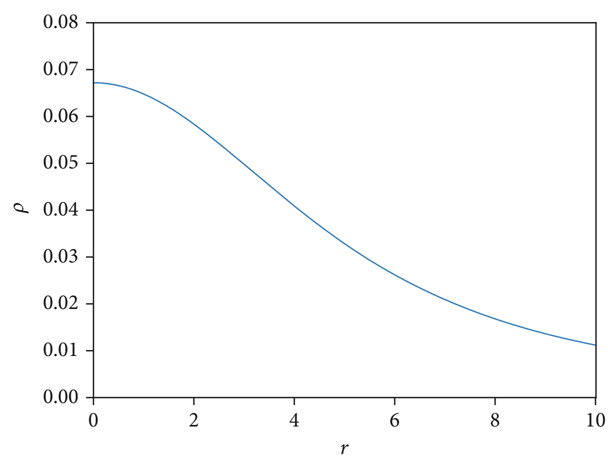

Figure 2: Energy density ρ against the radial distance r.

We observe that the profiles for the gravitational potentials presented in Figure 1 show finite, regular, and continuous behaviour throughout the stellar interior. The plots coincide at the surface of the stellar star. We also observe that these potentials are positive increasing functions at each interior point of the stellar star. Figures 2 and 3 show that the energy density ρ, radial pressure p_r, and tangential pressure p_t are monotonically decreasing functions as radius increases with negative gradient, i.e., $\rho' < 0$, $p'_r < 0$, and $p'_t < 0$. Figure 3 also indicates that the radial and tangential pressures have the same maximum value at the centre. Similar decreasing profiles are evident in recent studies by [5, 14, 60, 61]. The anisotropic factor in Figure 4 has zero value at the centre and then increases to the maximum value away from the centre and then slightly decreases as it approaches the stellar surface. This feature can also be observed in the works by [28, 29, 34]. We notice that $\Delta > 0$ at each point within the stellar interior. This implies that the force due

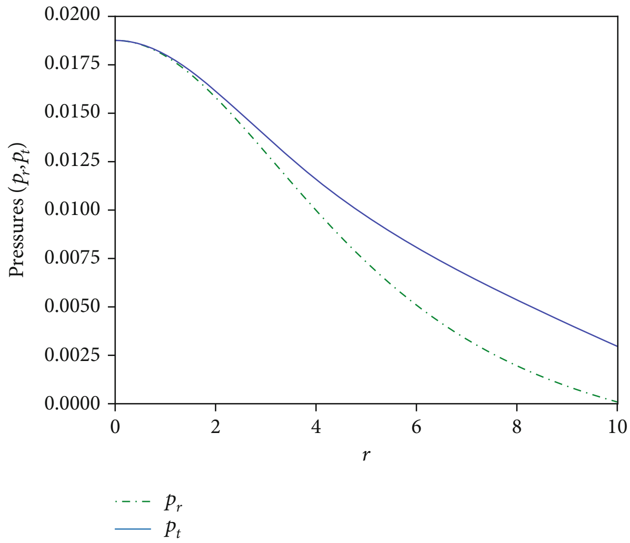

Figure 3: Radial pressure (p_r) and tangential pressure (p_t) against radial distance r.

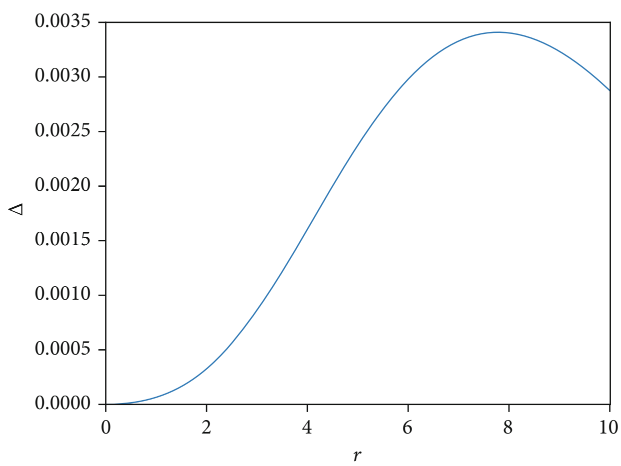

Figure 4: Measure of anisotropy Δ against radial distance r.

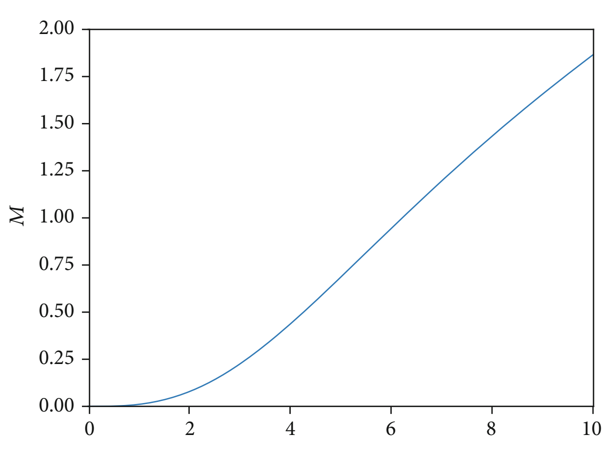

Figure 5: Mass M against radial distance r.

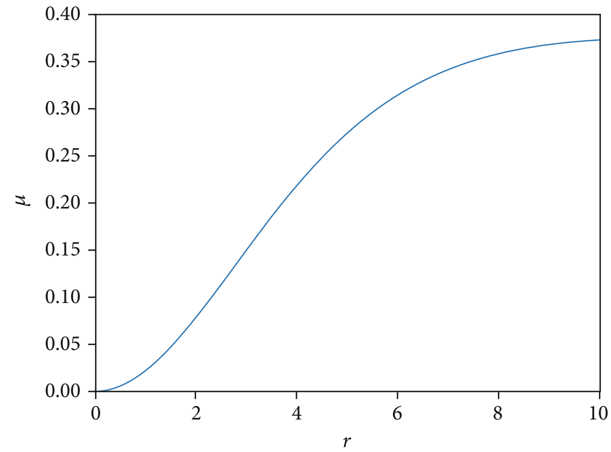

Figure 6: Compactification μ against radial distance r.

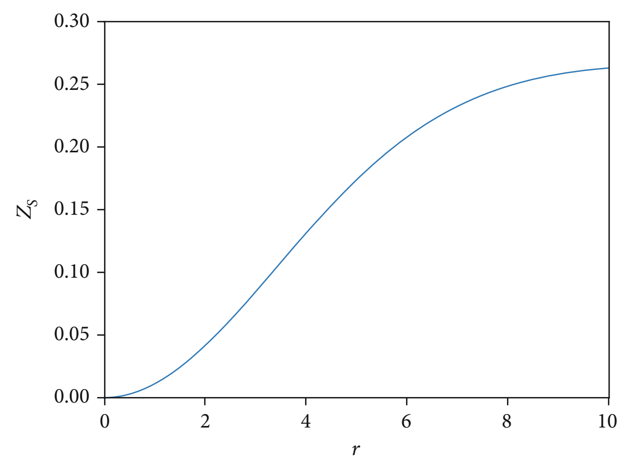

Figure 7: Surface redshift against radial distance r.

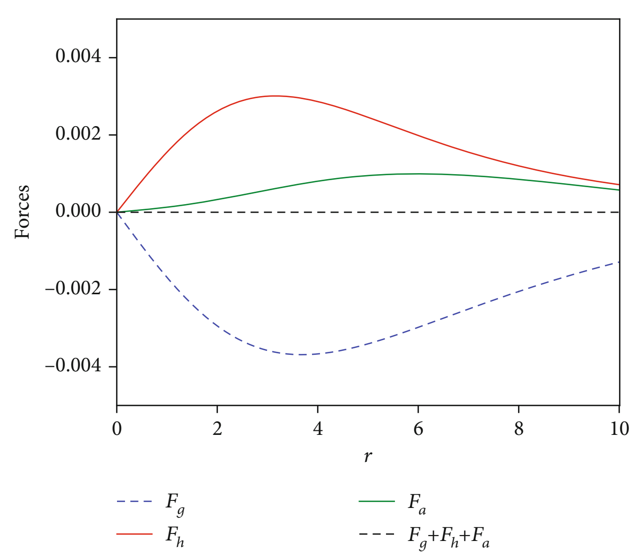

Figure 8: Variation of forces in TOV equation against radial distance r.

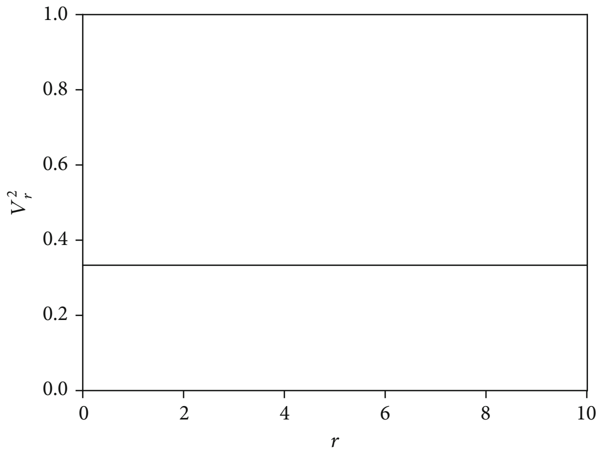

FIGURE 9: Speed of sound v against radial distance r.

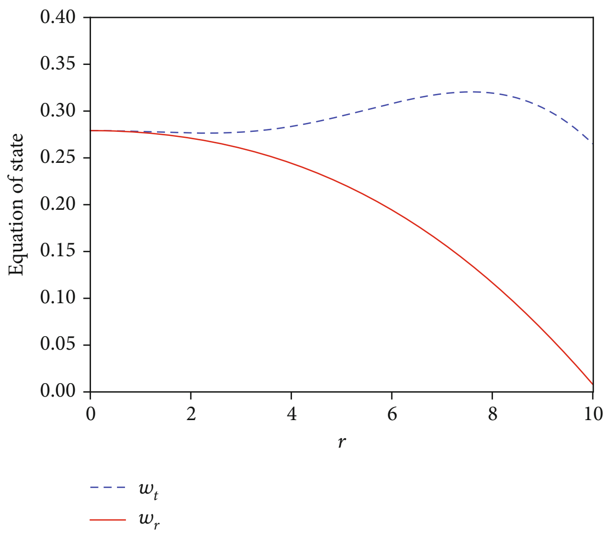

FIGURE 10: Equation of state against radial distance r.

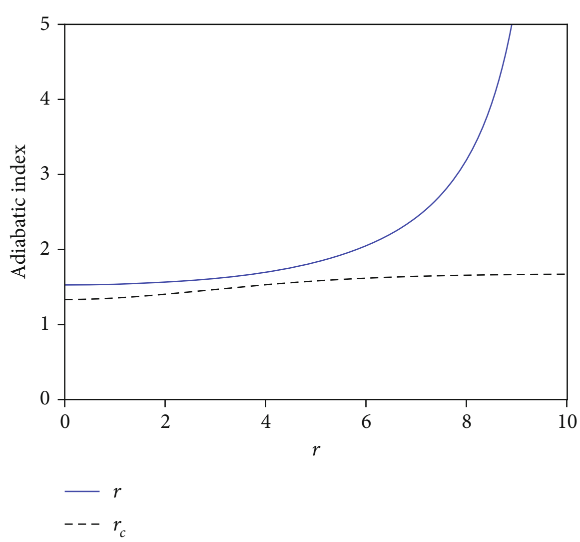

FIGURE 11: Adiabatic index Γ against radial distance r.

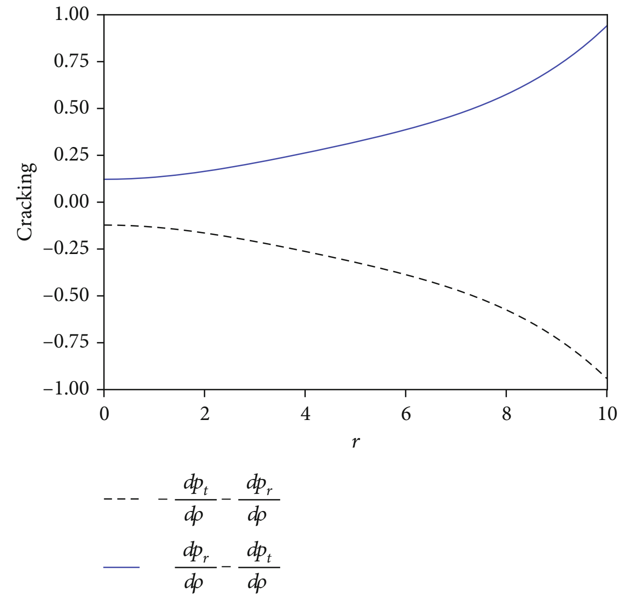

FIGURE 12: Herrera cracking $|v_r^2 - v_t^2|$ against radial distance r.

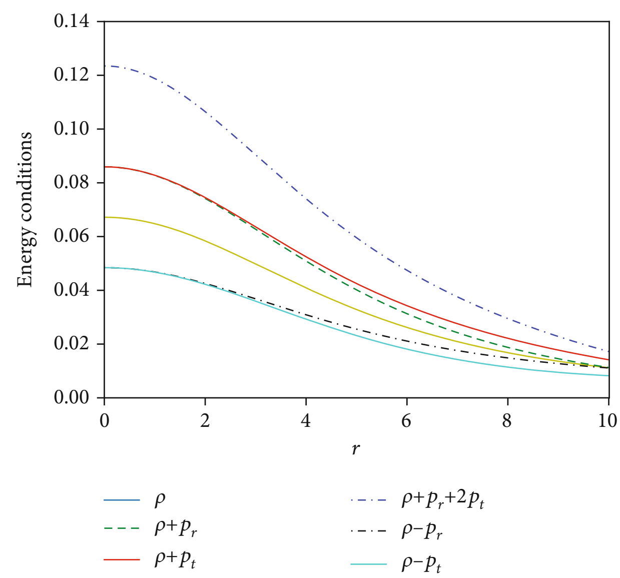

FIGURE 13: Energy conditions against radial distance r.

to anisotropy acts outward and it is repulsive in nature based on the observation by [47]. In Figure 5, we clearly observe that the mass function increases monotonically with radial distance to the surface. This is a necessary condition for well-behaved stellar models. In Figure 6, the compactification factor (μ) of the stellar star is in acceptable range for anisotropic spheres. This profile also shows that the compactness factor increases with the increase in radial distance. The upper bound for the surface redshift indicated in Figure 7 for the current model is found to be $z_s \leq 0.263$. This value conforms to [50] limit, $z_s \leq 2$ for realistic compact stars. The variations of forces in TOV equation are indicated in Figure 8. We observe that the gravitational F_g, hydrostatic

Table 1: Relativistic stellar masses and radii consistent with observations.

Star	ψ	γ	C	R(km)	$M(M_s)$	Reference
SAX J1808.4 -3658	0.02	11.3	1.0×10^{-2}	7.68	0.903	[65]
4U1538	0.01	5.1	2.0×10^{-1}	7.866	0.87	[66]
LMCX-4	5.4	10.1	5.0×10^{-3}	8.301	1.04	[66]
HerX-1	3.4	8.1	7.9×10^{-4}	8.1	0.85	[67]

F_h, and anisotropic F_a forces within the star are balanced such that $F_g + F_h + F_a = 0$. The gravitational force countervails the sum of hydrostatic and anisotropic forces. This condition confirms that our model satisfies the equilibrium test. Figure 9 clearly indicates that $v_r^2 = 1/3$, which is less than unity showing that the sound speed within the stellar star is less than the speed of light. This condition is necessary for stable stellar configurations. Figure 10 shows that the equation of state parameter for the current model is well behaved. We notice that w_r decreases monotonically with radial distance. This feature is also evident in the performance by [3, 62]. This is a necessary stability condition as per [63] observation. We also observe that w_t show slightly increasing behaviour to a local maximum and then slightly decreases shortly as it approaches the stellar surface but remaining positive. Figure 11 clearly shows that the adiabatic index $\Gamma > \Gamma_c$. This indicates that our model is stable [64]. In Figure 12, we can easily note that $|v_r^2 - v_t^2| \leq 1$. This agrees the Herrera [56] cracking condition for stability of the model. This model also admits several energy conditions. In Figure 13, we note that the inequalities $\rho \geq 0$, $\rho + p_r \geq 0$, $\rho + p_t \geq 0$, $\rho - p_r \geq 0$, $\rho - p_t \geq 0$, and $\rho + p_r + 2p_t \geq 0$ are all satisfied. This indicates that our model satisfies the null, weak, dominant, and strong energy conditions.

We applied the mass function (19) to obtain stellar masses compatible with the observations. We have obtained the radii and masses compatible with the compact stellar stars such as SAXJ1808.4 with $r = 7.68$ km and $M = 0.903$ M_s, 4U1538-52 with $r = 8.866$ km and $M = 0.87M_s$, LMCX-4 with $r = 8.301$ km and $M = 1.04M_s$, and HerX-1 with $r = 8.1$ km and $M = 0.85M_s$ as indicated in [65–67], respectively. Values of the parameters for these stellar masses and radii are indicated in Table 1.

7. Conclusion

In the current paper, we generated a new nonsingular exact solution of the Einstein field equations consistent with relativistic static sphere with anisotropic matter distribution. New form of one of the gravitational potentials along with a linear equation of state has been applied to obtain a strange star model consistent with stellar spheres with quark matter. All the gravitational potentials and matter variables are well behaved and are free from central singularities. The state of hydrostatic equilibrium for our model has been tested by analysing Tolman-Oppenheimer-Volkoff (TOV) equation. The profiles for gravitational potentials, matter variables, the speed of sound, compactness, redshift, hydrostatic equilibrium, stability, and energy conditions are acceptable on physical grounds. Stellar masses and radii comparable with the previous experimental observation have been generated with our model. These are compatible with relativistic compact stellar objects like SAXJ1808.4, 4U1538-52, LMCX-4, and HerX-1 observed by [65–67], respectively.

Data Availability

We have no associated data in this paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

We would like to acknowledge the University of Dodoma as our employer for providing conducive environment for research and by ensuring the availability of facilities and resources.

References

[1] J. M. Sunzu, S. D. Maharaj, and S. Ray, "Charged anisotropic models for quark stars," *Astrophysics and Space Science*, vol. 352, no. 2, pp. 719–727, 2014.

[2] S. D. Maharaj, J. M. Sunzu, and S. Ray, "Some simple models for quark stars," *The European Physical Journal Plus*, vol. 129, no. 1, p. 3, 2014.

[3] P. Bhar, F. Rahaman, A. Jawad, and S. Islam, "Anisotropic charged fluids with Chaplygin equation of state in (2 + 1) dimension," *Astrophysics and Space Science*, vol. 360, no. 1, p. 32, 2015.

[4] A. Nasim and M. Azam, "Models of charged compact objects with generalized polytropic equation of state," *European Physical Journal C: Particles and Fields*, vol. 78, p. 34, 2018.

[5] P. Mafa Takisa, S. D. Maharaj, and L. L. Leeuw, "Effect of electric charge on conformal compact stars," *European Physical Journal C: Particles and Fields*, vol. 79, no. 1, p. 8, 2019.

[6] A. S. Lighuda, S. D. Maharaj, J. M. Sunzu, and E. W. Mureithi, "A model of a three-layered relativistic star," *Astrophysics and Space Science*, vol. 366, no. 8, p. 76, 2021.

[7] A. S. Lighuda, J. M. Sunzu, S. D. Maharaj, and E. W. Mureithi, "Charged stellar model with three layers," *Research in Astronomy and Astrophysics*, vol. 21, no. 12, p. 310, 2021.

[8] J. W. Jape, S. D. Maharaj, J. M. Sunzu, and J. M. Mkenyeleye, "Generalized compact star models with conformal symmetry,"

European Physical Journal C: Particles and Fields, vol. 81, no. 12, p. 1057, 2021.

[9] M. K. Jasim, S. K. Maurya, S. Ray, D. Shee, D. Deb, and F. Rahaman, "Charged strange stellar model describing by Tolman _V_ metric," *Results in Physics*, vol. 20, article 103648, 2021.

[10] A. K. Mathias, S. D. Maharaj, J. M. Sunzu, and J. M. Mkenyeleye, "Charged anisotropic models via embedding," *Pramana*, vol. 95, no. 4, p. 178, 2021.

[11] J. M. Sunzu and T. Mashiku, "New stellar models generated using a quadratic equation of state," *Pramana*, vol. 91, no. 6, p. 75, 2018.

[12] P. Mafa Takisa, S. D. Maharaj, A. M. Manjonjo, and S. Moopanar, "Spherical conformal models for compact stars," *European Physical Journal C: Particles and Fields*, vol. 77, p. 13, 2017.

[13] P. Bhar, M. Govender, and R. Sharma, "Anisotropic stars obeying Chaplygin equation of state," *Pramana*, vol. 90, no. 1, p. 5, 2018.

[14] M. K. Jasim, D. Deb, S. Ray, Y. K. Gupta, and S. R. Chowdhury, "Anisotropic strange stars in Tolman–Kuchowicz spacetime," *European Physical Journal C: Particles and Fields*, vol. 78, no. 7, p. 603, 2018.

[15] M. K. Jasim, S. K. Maurya, K. N. Singh, and R. Nag, "Anisotropic strange star in 5D Einstein-Gauss-Bonnet gravity," *Entropy*, vol. 23, no. 8, p. 1015, 2021.

[16] R. Ruderman, "Pulsars: structure and dynamics," *Annual Review of Astronomy and Astrophysics*, vol. 10, no. 1, pp. 427–476, 1972.

[17] V. Canuto, "Equation of state at ultrahigh densities," *Annual Review of Astronomy and Astrophysics*, vol. 12, no. 1, pp. 167–214, 1974.

[18] R. Kippenhahn and A. Weigert, *Stellar Structure and Evolution*, Springer, Berlin, 1990.

[19] R. F. Sawyer, "Condensed π^- phase in neutron-star matter," *Physical Review Letters*, vol. 29, p. 382, 1972.

[20] A. I. Sokolov, "Phase transformations in a superfluid neutron liquid," *Journal of Experimental and Theoretical Physics*, vol. 49, p. 1137, 1980.

[21] R. L. Bowers and E. P. T. Liang, "Anisotropic spheres in general relativity," *The Astrophysical Journal*, vol. 188, p. 657, 1974.

[22] S. K. Maurya, S. Ray, S. Ghosh, S. Manna, and T. T. Smitha, "A generalized family of anisotropic compact object in general relativity," *Annals of Physics*, vol. 395, pp. 152–169, 2018.

[23] A. T. Abdalla, J. M. Sunzu, and J. M. Mkenyeleye, "Generalised charged anisotropic quark star models," *Pramana*, vol. 95, no. 2, p. 86, 2021.

[24] R. N. Nasheeha, S. Thirukkanesh, and F. C. Ragel, "Anisotropic models for compact star with various equation of state," *The European Physical Journal Plus*, vol. 136, no. 1, p. 132, 2021.

[25] M. F. Shamir and T. Naz, "Stellar structures in $F(G)$ gravity with Tolman–Kuchowicz spacetime," *Physics of the Dark Universe*, vol. 27, article 100472, 2020.

[26] S. Banerjee, "Mathematical model of relativistic anisotropic compact stellar model admitting linear equation of state," *Communications in Theoretical Physics*, vol. 70, no. 5, p. 585, 2018.

[27] S. K. Maurya and F. Tello-Ortiz, "Generalized relativistic anisotropic compact star models by gravitational decoupling," *European Physical Journal C: Particles and Fields*, vol. 79, no. 1, p. 85, 2019.

[28] G. Panotopoulos, T. Tangphati, A. Banerjee, and M. K. Jasim, "Anisotropic quark stars in R^2 gravity," *Physics Letters B*, vol. 817, article 136330, 2021.

[29] J. M. Sunzu, A. K. Mathias, and S. D. Maharaj, "Stellar models with generalized pressure anisotropy," *Journal of Astrophysics and Astronomy*, vol. 40, no. 1, p. 8, 2019.

[30] A. V. Mathias and J. M. Sunzu, "Regular quark star model with pressure anisotropy," *Pramana*, vol. 96, no. 2, p. 2, 2022.

[31] J. M. Sunzu and A. V. Mathias, "A neutral stellar model with quadratic equation of state," *Indian Journal of Physics*, pp. 1–11, 2022.

[32] S. A. Ngubelanga, S. D. Maharaj, and S. Ray, "Compact stars with quadratic equation of state," *Astrophysics and Space Science*, vol. 357, no. 1, p. 74, 2015.

[33] S. Thirukkanesh, R. S. Bogadi, M. Govender, and S. Moyo, "Stability and improved physical characteristics of relativistic compact objects arising from the quadratic term in $p_r = \alpha\rho^2 + \beta\rho - \gamma$," *The European Physical Journal C*, vol. 81, p. 62, 2021.

[34] P. Bhar, K. N. Singh, and N. Pant, "Compact star modeling with quadratic equation of state in Tolman VII space–time," *Indian Journal of Physics*, vol. 91, no. 6, pp. 701–709, 2017.

[35] M. Malaver and H. D. Kasmaei, "Relativistic stellar models with quadratic equation of state," *International Journal of Mathematical Modelling and Computations*, vol. 10, p. 111, 2020.

[36] J. Estevez-Delgado, N. E. R. Maya, M. J. Peña, A. Cleary-Balderas, and J. M. Paulin-Fuentes, "An anisotropic charged fluids with Chaplygin equation of state," *Modern Physics Letters A*, vol. 36, no. 21, article 2150153, 2021.

[37] A. Errehymy and M. Daoud, "Model astrophysical configurations with the equation of state of Chaplygin gas," *Foundations of Physics*, vol. 49, no. 2, pp. 144–175, 2019.

[38] F. Tello-Ortiz, M. Malaver, Á. Rincón, and Y. Gomez-Leyton, "Relativistic anisotropic fluid spheres satisfying a non-linear equation of state," *European Physical Journal C: Particles and Fields*, vol. 80, no. 5, p. 371, 2020.

[39] J. M. Sunzu and A. V. Mathias, "A stellar model with anisotropic fluid and Chaplygin equation of state," *Indian Journal of Physics*, 2022.

[40] S. Thirukkanesh, R. Sharma, and S. Das, "Model of a static spherically symmetric anisotropic fluid distribution in paraboloidal spacetime admitting a polytropic equation of state," *The European Physical Journal Plus*, vol. 135, no. 8, p. 629, 2020.

[41] A. Kaisavelu, M. Govender, S. Hansraj, and D. Krupanandan, "A class of polytropic stars in Einstein–Gauss–Bonnet gravity," *The European Physical Journal Plus*, vol. 136, no. 10, p. 1029, 2021.

[42] A. Kaisavelu, S. Thirukkanesh, M. Govender, and S. D. Maharaj, "The impact of spheroidicity on the stability of polytropic spheres," *Anals of Physics*, vol. 419, article 168215, 2020.

[43] S. Thirukkanesh and F. C. Ragel, "Anisotropic compact sphere with van der Waals equation of state," *Astrophysics and Space Science*, vol. 354, no. 2, pp. 415–420, 2014.

[44] M. Malaver and H. D. Kasmaei, "Analytical models for quark stars with van der Waals modified equation of state," *International Journal of Astrophysics and Space Science*, vol. 7, no. 5, p. 58, 2019.

[45] E. Witten, “Cosmic separation of phases,” *Physical Review D*, vol. 30, no. 2, pp. 272–285, 1984.

[46] M. C. Durgapal and R. Bannerji, “New analytical stellar model in general relativity,” *Physical Review D*, vol. 27, no. 2, pp. 328–331, 1983.

[47] M. K. Gokhroo and A. L. Mehra, “Anisotropic spheres with variable energy density in general relativity,” *General Relativity and Gravitation*, vol. 26, no. 1, pp. 75–84, 1994.

[48] R. C. Tolman, “Static solutions of Einstein’s field equations for spheres of fluid,” *Physics Review*, vol. 55, no. 4, pp. 364–373, 1939.

[49] S. Thirukkanesh and F. C. Ragel, “Strange star model with Tolmann IV type potential,” *Astrophysics and Space Science*, vol. 352, no. 2, pp. 743–749, 2014.

[50] H. A. Buchdahl, “General relativistic fluid spheres,” *Physics Review*, vol. 116, no. 4, pp. 1027–1034, 1959.

[51] K. Dev and M. Gleiser, “Anisotropic stars: exact solutions,” *General Relativity and Gravitation*, vol. 34, no. 11, pp. 1793–1818, 2002.

[52] R. Chan, L. Herrera, and N. O. Santos, “Dynamical instability for radiating anisotropic collapse,” *Monthly Notices of the Royal Astronomical Society*, vol. 265, no. 3, pp. 533–544, 1993.

[53] C. C. Moustakidis, “The stability of relativistic stars and the role of the adiabatic index,” *General Relativity and Gravitation*, vol. 49, no. 5, p. 68, 2017.

[54] S. K. Maurya and R. Nag, “MGD solution under class I generator,” *The European Physical Journal Plus*, vol. 136, no. 6, p. 679, 2021.

[55] J. Upreti, S. Gedela, N. Pant, and R. P. Pant, “Relativistic parametric embedding class I solutions of cold stars in Karmarkar space-time continuum,” *New Astronomy*, vol. 80, article 101403, 2020.

[56] L. Herrera, “Cracking of self-gravitating compact objects,” *Physics Letters A*, vol. 165, no. 3, pp. 206–210, 1992.

[57] M. Visser, *Lorentzian Wormholes: From Einstein to Hawking*, AIP Press, Woodbury, NY, USA, 1995.

[58] M. Zubair, S. Waheed, and H. Javaid, “A generic embedding class-I model via Karmarkar condition in $f(\mathscr{R}, \mathbb{T})$ gravity,” *Advances in Astronomy*, vol. 2021, Article ID 6685578, 16 pages, 2021.

[59] B. P. Brassel, S. D. Maharaj, and R. Goswami, “Inhomogeneous and radiating composite fluids,” *Entropy*, vol. 23, no. 11, p. 1400, 2021.

[60] F. C. Ragel and S. Thirukkanesh, “General relativistic model for mixed fluid sphere with equation of state,” *European Physical Journal C: Particles and Fields*, vol. 79, no. 4, p. 306, 2019.

[61] S. Das, F. Rahaman, and L. Baskey, “A new class of compact stellar model compatible with observational data,” *European Physical Journal C: Particles and Fields*, vol. 79, no. 10, p. 853, 2019.

[62] S. Hansraj and L. Moodly, “Stellar modelling of isotropic Einstein–Maxwell perfect fluid spheres of embedding class one,” *European Physical Journal C: Particles and Fields*, vol. 80, no. 6, p. 496, 2020.

[63] Y. B. Zeldovich, “The equation of state at utrahigh densities and its relativistic limitations,” *Soviet Physics Journal of Experimental and Theoretical Physics*, vol. 14, 1962.

[64] S. Chandrasekhar, “Dynamical instability of gaseous masses approaching the Schwarzschild limit in general relativity,” *Physical Review Letters*, vol. 12, no. 4, pp. 114–116, 1964.

[65] P. Elebert, M. T. Reynolds, P. J. Callanan et al., “Optical spectroscopy and photometry of SAX J 1808.4 – 3658 in outburst,” *Monthly Notices of the Royal Astronomical Society*, vol. 395, no. 2, pp. 884–894, 2009.

[66] M. L. Rawls, J. A. Orosz, J. E. McClintock, M. A. P. Torres, C. D. Bailyn, and M. M. Buxton, “Refined neutron star mass determinations for six eclipsing X-ray pulsar binaries,” *The Astrophysical Journal*, vol. 730, no. 1, p. 25, 2011.

[67] M. K. Abubekerov, E. A. Antokhina, A. M. Cherepashchuk, and V. V. Shimanskii, “The mass of the compact object in the X-ray binary her X-1/HZ her,” *Astronomy Reports*, vol. 52, no. 5, pp. 379–389, 2008.