

Article

Charged Anisotropic Stellar Models with the MIT Bag Model Equation of State

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Abstract: In this paper we present a new classes of solutions for the Einstein-Maxwell system of field equations in a spherically symmetric spacetime under the influence of an electric field considering the MIT bag model equation of state with a particular form the metric potential that depends on an adjustable parameter. The obtained solutions can be written in terms of elementary functions, namely polynomials and algebraic functions. The obtained models satisfy all physical properties expected in a realistic star. The results of this research can be useful in the development and description of new models of compact structures.

Keywords: MIT bag model, Einstein-Maxwell system, Metric potential, Adjustable parameter, Compact structures

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1. Introduction

The search of new solutions for the Einstein-Maxwell field equations is an important area of research because it allows describe compact objects with strong gravitational fields as neutron stars, white dwarfs and quark stars [1,2]. Within this context it is appropriate to mention the findings of Delgaty and Lake [3] who constructed several analytic solutions that can describe realistic stellar configurations and satisfy all the necessary conditions to be physically acceptable. These exact solutions have also made it possible the way to study cosmic censorship and analyze the formation of naked singularities [4].

In the development of the first stellar models it is important to mention the pioneering research of Schwarzschild [5], Tolman [6], Oppenheimer and Volkoff [7] and Chandrasekhar [8]. Schwarzschild [5] obtained interior solutions that allows describing a star with uniform density, Tolman [6] generated new solutions for static spheres of fluid, Oppenheimer, and Volkoff [7] studied the gravitational equilibrium of neutron stars using Tolman's solutions and Chandrasekhar [8] produced new models of white dwarfs in presence of relativistic effects.

A great number of exact models from the Einstein-Maxwell field equations have been generated by Gupta and Maurya [9], Kiess [10], Mafa Takisa and Maharaj [11], Malaver and Kasmaei [12], Malaver [13,14], Ivanov [15] and Sunzu et al [16]. For the construction of these models, several forms of equations of state can be considered [17]. Komathiraj and Maharaj [18], Malaver [19], Bombaci [20], Thirukkanesh and Maharaj [21], Dey et al. [22] and Usov [23] assume linear equation of state for quark stars. Feroze and Siddiqui [24] considered a quadratic equation of state for the matter distribution and specified particular forms for the gravitational potential and electric field intensity. Mafa Takisa and Maharaj [11] obtained new exact solutions to the Einstein-Maxwell system of equations with a polytropic equation of state. Thirukkanesh and Ragel [25] have obtained particular models of anisotropic fluids with polytropic equation of state which are consistent with the reported experimental observations. Malaver [26] generated new exact solutions to the Einstein-Maxwell system considering Van der Waals modified equation

of state with polytropic exponent. Malaver and Kasmaei proposed a new model of compact star with charged anisotropic matter using a cosmological Chaplygin fluid [27]. Tello-Ortiz et al. [28] found an anisotropic fluid sphere solution of the Einstein-Maxwell field equations with a modified Chaplygin equation of state. More recently, Malaver *et al.* [29] obtained new solutions of Einstein's field equations in a Buchdahl spacetime considering a nonlinear electromagnetic field.

The analysis of compact objects with anisotropic matter distribution is very important, because that the anisotropy plays a significant role in the studies of relativistic spheres of fluid [30-42]. Anisotropy is defined as $\Delta = p_t - p_r$ where p_r is the radial pressure and p_t is the tangential pressure. The existence of solid core, presence of type 3A superfluid [43], magnetic field, phase transitions, a pion condensation and electric field [23] are most important reasonable facts that explain the presence of tangential pressures within a star. Many astrophysical objects as X-ray pulsar, Her X-1, 4U1820-30 and SAXJ1804.4-3658 have anisotropic pressures. Bowers and Liang [42] include in the equation of hydrostatic equilibrium the case of local anisotropy. Bhar et al. [44] have studied the behavior of relativistic objects with locally anisotropic matter distribution considering the Tolman VII form for the gravitational potential with a linear relation between the energy density and the radial pressure. Malaver [45-46], Feroze and Siddiqui [24,47] and Sunzu et al. [16] obtained solutions of the Einstein-Maxwell field equations for charged spherically symmetric spacetime by assuming anisotropic pressure.

In this paper we generated new classes of exact solutions for anisotropic charged distribution with a consistent with quark matter. New models have been obtained by specifying a particular form for one of the metric potentials and for the electric field intensity. The paper has been organized as follows: In section 2, we present the Einstein-Maxwell field equations. In section 3, we have chosen a particular form for the metric potential and for the electric field intensity. In Section.4, physical requirements for the new models are described. In section 5 we present the physical analysis of the new models. In section 6, we conclude.

2. Field Equations

We consider a spherically symmetric, static and homogeneous spacetime. In Schwarzschild coordinates the metric is given by:

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

where $\nu(r)$ and $\lambda(r)$ are two arbitrary functions.

Using the transformations, $x = Cr^2$, $Z(x) = e^{-2\lambda(r)}$ and $A^2 y^2(x) = e^{2\nu(r)}$ with arbitrary constants A and $c > 0$, suggested by Durgapal and Bannerji [48], the Einstein-Maxwell field equations shown in [21] can be written as:

$$\frac{1-Z}{x} - 2\dot{Z} = \frac{\rho}{C} + \frac{E^2}{2C} \quad (2)$$

$$4Z \frac{\dot{y}}{y} - \frac{1-Z}{x} = \frac{p_r}{C} - \frac{E^2}{2C} \quad (3)$$

$$p_t = p_r + \Delta \quad (4)$$

$$\frac{\Delta}{C} = 4xZ \frac{\ddot{y}}{y} + \dot{Z} \left(1 + 2x \frac{\dot{y}}{y} \right) + \frac{1-Z}{x} - \frac{E^2}{C} \quad (5)$$

$$\sigma^2 = \frac{4CZ}{x} (x\dot{E} + E)^2 \quad (6)$$

ρ is the energy density, p_r is the radial pressure, E is electric field intensity, p_t is the tangential pressure, σ is the charge density, $\Delta = p_t - p_r$ is the measure of anisotropy and dots denote differentiations with respect to x .

With the transformations of [48], the mass within a radius r of the sphere take the form

$$M(x) = \frac{1}{4C^{3/2}} \int_0^x \sqrt{x} \rho(x) dx \quad (7)$$

In this paper, we assume the following linear equation of state in the bag model

$$p_r = \frac{1}{3}(\rho - 4B) \quad (8)$$

where B is the bag constant. We can write the Einstein-Maxwell field equations with the eq. (8) in the following form

$$\rho = 3p_r + 4B \quad (9)$$

$$\frac{p_r}{C} = Z \frac{\dot{y}}{y} - \frac{1}{2} \dot{Z} - \frac{B}{C} \quad (10)$$

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

$$\frac{E^2}{2C} = \frac{1-Z}{x} - 3Z \frac{\dot{y}}{y} - \frac{1}{2} \dot{Z} - \frac{B}{C} \quad (12)$$

$$\sigma = 2\sqrt{\frac{CZ}{x}} (x\dot{E} + E) \quad (13)$$

The equations (9), (10), (11), (12), (13) governs the gravitational behavior of an anisotropic charged quark star.

3. The New Models

In this research, we have chosen the Thirukanesh-Ragel-Malaver ansatz [25,37,49] as metric potential which has the form $Z(x) = (1 - ax)^n$, where a is a real constant and n is an adjustable parameter. This potential is regular at the stellar center and well behaved in the interior of the sphere. We have considered the particular cases $n=1, 2$. For the electric field intensity we make the choice

$$\frac{E^2}{2C} = \frac{ax}{(1+ax)} \quad (14)$$

This electric field is finite at the centre of the star and remains continuous in the interior. For the case $n=1$, substituting $Z(x)$ and eq. (14) in eq. (2) we obtain

$$\rho = C \left(\frac{3a(1+ax) - ax}{1+ax} \right) \quad (15)$$

Using eq. (15) in eq. (8), the radial pressure can be written in the form

$$p_r = \frac{1}{3} \left[\frac{C(3a(1+ax) - ax) - 4B(1+ax)}{1+ax} \right] \quad (16)$$

and for the mass function we obtain

$$M(x) = \frac{1}{6a\sqrt{aC}} \left[(3a^2x - ax + 3)\sqrt{ax} - 3\arctan(\sqrt{ax}) \right] \quad (17)$$

Substituting (14) and $Z(x)$ in eq. (12) we have

$$\frac{\dot{y}}{y} = \frac{1}{3(1-ax)} \left(\frac{3}{2}a - \frac{B}{C} \right) - \frac{ax}{3(1-a^2x^2)} \quad (18)$$

Integrating eq. (18)

$$y(x) = c_1 (1+ax)^{\frac{1}{6a}} (ax-1)^D \quad (19)$$

where c_1 is the constant within integration procedures.

For convenience we have let

$$D = -\frac{1}{2} + \frac{B}{3aC} + \frac{1}{6a} \quad (20)$$

For the metric functions $e^{2\lambda}$, $e^{2\nu}$

$$e^{2\lambda} = \frac{1}{1-ax} \quad (21)$$

$$e^{2\nu} = A^2 c_1^2 (1+ax)^{1/3a} (ax-1)^{2D} \quad (22)$$

With eq. (14) and $Z(x)$ in eq. (13), the charge density is

$$\sigma^2 = \frac{2aC^2(1-ax)(2ax+3)^2}{(1+ax)^3} \quad (23)$$

and the anisotropy Δ can be written as

$$\Delta = 4xC(1-ax) \left[\frac{(D^2 - D)a^2}{(ax-1)^2} + \frac{Da}{3(a^2x^2-1)} + \frac{1-6a}{36(ax+1)^2} \right] - \frac{2xDa^2}{1-ax} - \frac{7ax}{1+ax} \quad (24)$$

With $n=2$, the expression for the energy density is

$$\rho = C \left(\frac{6a + a^2x - 5a^3x^2}{1+ax} \right) \quad (25)$$

replacing eq. (25) in eq. (8), we have for the radial pressure

$$p_r = \left(\frac{6aC - 4B + (a^2C - 4aB)x - 5a^3Cx^2}{3(1+ax)} \right) \quad (26)$$

and the mass function is

$$M(x) = \frac{1}{6a\sqrt{ac}} \left[(-3a^3x^2 + 6a^2x - ax + 3)\sqrt{ax} - 6\arctan(\sqrt{ax}) \right] \quad (27)$$

Substituting eq. (14) and $Z(x)$ in eq. (12) we obtain

$$\frac{\dot{y}}{y} = \frac{1}{3(1-ax)^2} \left(3a - 2a^2x - \frac{B}{C} \right) - \frac{ax}{3(1-a^2x^2)(1+ax)} \quad (28)$$

Integrating eq. (28)

$$y(x) = c_2 (1+ax)^{1/12a} (ax-1)^E e^{\frac{F}{ax-1}} \quad (29)$$

where c_2 is the constant of integration

Again for convenience

$$E = -\frac{2}{3} - \frac{1}{12a} \quad (30)$$

$$F = -\frac{1}{3} + \frac{B}{3aC} + \frac{1}{6a} \quad (31)$$

The charge density can be written as

$$\sigma^2 = \frac{2aC^2(1-ax)^2(2ax+3)^2}{(1+ax)^3} \quad (32)$$

and for the metric functions $e^{2\lambda}$, $e^{2\nu}$ and anisotropy Δ we have

$$e^{2\lambda} = \frac{1}{(1-ax)^2} \quad (33)$$

$$e^{2\nu} = A^2 c_2^2 (1+ax)^{1/6a} (ax-1)^{2E} e^{\frac{2F}{ax-1}} \quad (34)$$

$$\Delta = 4xC(1-ax)^2 \left[\frac{(E^2 - E)a^2}{(ax-1)^2} + \frac{Ea}{6(a^2x^2 - 1)} + \frac{2(F - E)a^2}{(ax+1)^3} + \frac{1-12a}{144(ax+1)^2} \right] \\ - \frac{Fa}{6(ax+1)(ax-1)^2} + \frac{F^2a^2}{(ax-1)^4} \\ + (1+4E)a^2x + \frac{ax(ax-1)}{3(ax+1)} - \frac{4Fa^2x}{(ax-1)^2} \quad (35)$$

4. Requirements of Physical Acceptability

For a model to be physically acceptable, the following conditions should be satisfied [3,4,25]:

- (i.) The metric potentials $e^{2\lambda}$ and $e^{2\nu}$ assume finite values throughout the stellar interior and are singularity-free at the center $r=0$.
- (ii.) The energy density ρ should be positive and a decreasing function inside the star.
- (iii.) The radial pressure also should be positive and a decreasing function of radial parameter.
- (iv.) The radial pressure and density gradients $dp_r/dr \leq 0$ and $d\rho/dr \leq 0$ for $0 \leq r \leq R$.
- (v.) The anisotropy is zero at the center $r=0$, i.e. $\Delta(r=0) = 0$.
- (vi.) The interior solution should match with the exterior of the Reissner-Nordstrom spacetime, for which the metric is given by

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right) dt^2 + \left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)^{-1} dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\varphi^2 \quad (36)$$

through the boundary $r=R$ where M and Q are the total mass and the total charge of the star, respectively.

The conditions (ii) and (iv) imply that the energy density must reach a maximum at the centre and decreasing towards the surface of the sphere.

5. Physical Analysis

With $n=1$, the metric potentials $e^{2\lambda}$ and $e^{2\nu}$ have finite values and remain positive throughout the stellar interior. At the center $e^{2\lambda(0)} = 1$ and $e^{2\nu(0)} = A^2 C_1^2 (-1)^{2D}$. We show that in $r=0$ $(e^{2\lambda(r)})'_{r=0} = (e^{2\nu(r)})'_{r=0} = 0$ and this makes is possible to verify that the gravitational potentials are regular at the center. The energy density and radial pressure are positive and well behaved between the center and the surface of the star. In the center $\rho(r=0) = 6aC$ and $p_r(r=0) = aC - \frac{4B}{3}$, therefore the energy density will be non-negative in $r=0$ and $p_r(r=0) > 0$. In the surface of the star $r = R$ and we have $p_r(r=R)=0$ and $R = \sqrt{\frac{4B - 3aC}{(3a^2 - a)C - 4Ba}C}$. For the radial pressure of density gradients we obtain

$$\frac{d\rho}{dr} = \frac{C^2(6a^2r - 2ar)}{1 + aCr^2} - \frac{2arC^2[3a(1 + aCr^2) - aCr^2]}{(1 + aCr^2)^2} \quad (37)$$

$$\frac{dp_r}{dr} = \frac{2aCr(3aC - 4B) - 2aC^2r}{3 + 3aCr^2} - \frac{6aCr[(1 + aCr^2)(3aC - 4B) - aC^2r^2]}{(3 + 3aCr^2)^2} \quad (38)$$

The energy density and radial pressure decrease from the centre to the surface of the star. From eq.(17), the mass function can be written as

$$M(r) = \frac{1}{6a\sqrt{aC}} \left[((3a^2 - a)Cr^2 + 3)\sqrt{aCr} - 3\arctan(\sqrt{aCr}) \right] \quad (39)$$

and the total mass of the star is

$$M(r=R) = \frac{1}{6a\sqrt{aC}} \left[\left((3a^2 - a) \left(\frac{4aB - 3a^2C}{(3a^2 - a)C - 4aB} \right) + 3 \right) \sqrt{\frac{4aB - 3a^2C}{(3a^2 - a)C - 4aB}} - 3\arctan \left(\sqrt{\frac{4aB - 3a^2C}{(3a^2 - a)C - 4aB}} \right) \right] \quad (40)$$

On the boundary $r=R$, the solution must match the Reissner–Nordström exterior space–time as

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right) dt^2 + \left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2)$$

and therefore, the continuity of $e^{2\lambda}$ and $e^{2\nu}$ across the boundary $r=R$ is

$$e^{2\nu} = e^{-2\lambda} = 1 - \frac{2M}{R} + \frac{Q^2}{R^2} \quad (41)$$

Then for the matching conditions, we obtain:

$$\frac{2M}{R} = \frac{(a^2 + 2a)C^2R^4 + aCR^2}{1 + aCR^2} \quad (42)$$

For the case $n=2$, we have for the metric potentials $e^{2\lambda(0)} = 1$, $e^{2\nu(0)} = A^2 c_1^2 (-1)^{2E} e^{-2F}$ and $(e^{2\lambda(r)})'_{r=0} = (e^{2\nu(r)})'_{r=0} = 0$ at the centre $r=0$. Again the gravitational potentials are regular in the origin. The energy density and radial pressure also are positive and well behaved in the stellar interior. In the center $\rho(r=0) = 2aC$ and $p_r(r=0) = 2aC - \frac{4B}{3}$, therefore the energy density will be non-negative in $r=0$ and $p_r(r=0) > 0$. In the surface of the star $r=R$ and we have $p_r(r=R)=0$ and $R = \frac{\sqrt{30aC - 20B}}{5aC}$. For the radial pressure of density gradients we obtain

$$\frac{d\rho}{dr} = -10a^2C^2r - \frac{2aCr}{1 + aCr^2} + \frac{2a^2C^2r^3}{(1 + aCr^2)^2} \quad (43)$$

$$\frac{dp_r}{dr} = \frac{1}{3} \left[-10a^2Cr - \frac{8aBCr + 2aCr}{1 + aCr^2} + \frac{2aCr(aCr^2 + 4B(1 + aCr^2))}{(1 + aCr^2)^2} \right] \quad (44)$$

The energy density and radial pressure decrease from the centre to the surface of the star. For the mass function we have

$$M(r) = \frac{1}{6a\sqrt{ac}} \left[(-3a^3C^2r^4 + 6a^2Cr^2 - aCr^2 + 3)\sqrt{aCr} - 6\arctan(\sqrt{aCr}) \right] \quad (45)$$

The total mass of the star is

$$M(r=R) = \frac{1}{6a\sqrt{ac}} \left[\left(-3 \frac{(30aC - 20B)^2}{625aC^2} + \frac{(6a^2 - a)(30aC - 20B)}{25a^2C} + 3 \right) \frac{\sqrt{30a^2C^2 - 20aBC}}{5aC} - 6 \arctan \left(\frac{\sqrt{30a^2C^2 - 20aBC}}{5aC} \right) \right] \quad (46)$$

On the boundary $r=R$, the solution must match the Reissner–Nordström exterior space–time and therefore for the matching conditions, we obtain:

$$\frac{2M}{R} = \frac{aCR^2 + (a^2 + 2a)C^2R^4 - a^3C^3R^6}{1 + aCR^2} \quad (47)$$

The figures 1, 2, 3, 4, 5, 6 and 7 present the dependence of ρ , $\frac{d\rho}{dr}$, p_r , $\frac{dp_r}{dr}$, M , Δ and σ^2 with the radial coordinate respectively with $a=0.2$, $B=0.05$, $C=1$ for $n=1$ and $n=2$. We considered $r=1.8 \text{ Km}$.

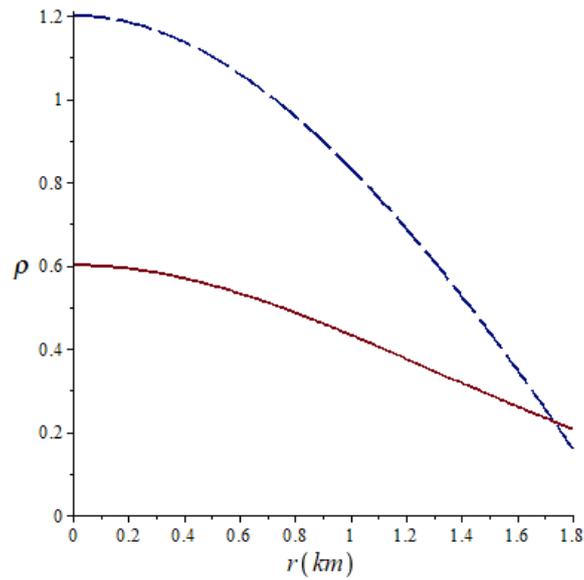


Figure 1. Energy density against radial coordinate. It has been considered that $n=1$ (solid line); $n=2$ (long-dash line).

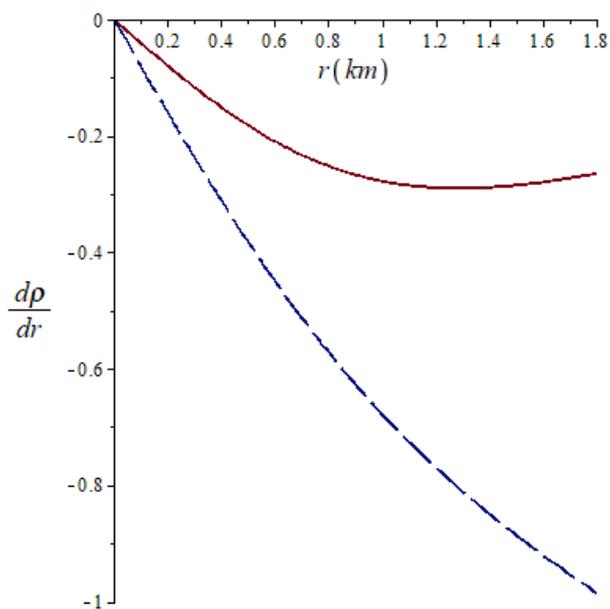


Figure 2. Density gradient against radial coordinate. It has been considered that $n=1$ (solid line) ; $n=2$ (long-dash line).

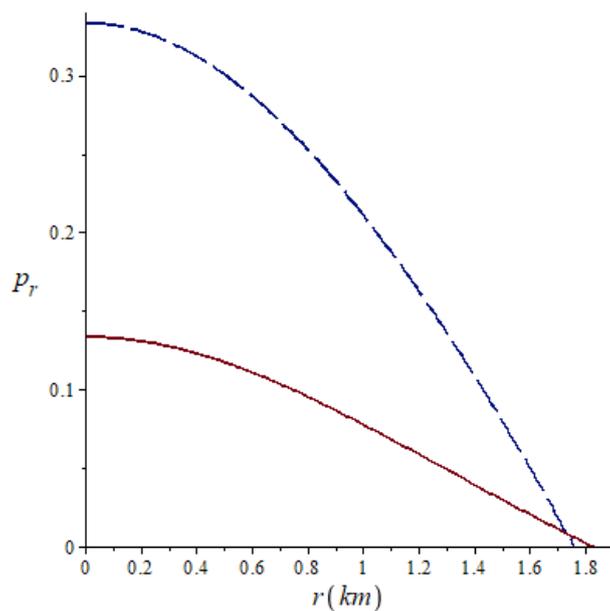


Figure 3. Radial pressure against radial coordinate. It has been considered that $n=1$ (solid line) ; $n=2$ (long-dash line).

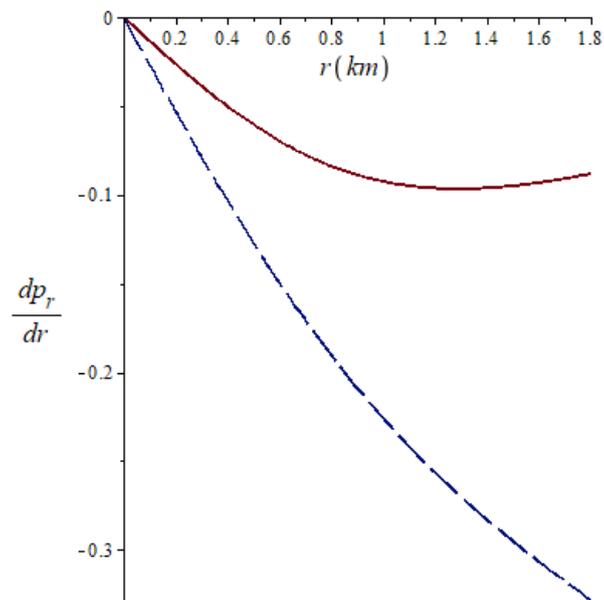


Figure 4. Radial pressure against radial coordinate. It has been considered that $n=1$ (solid line) ; $n=2$ (long-dash line).

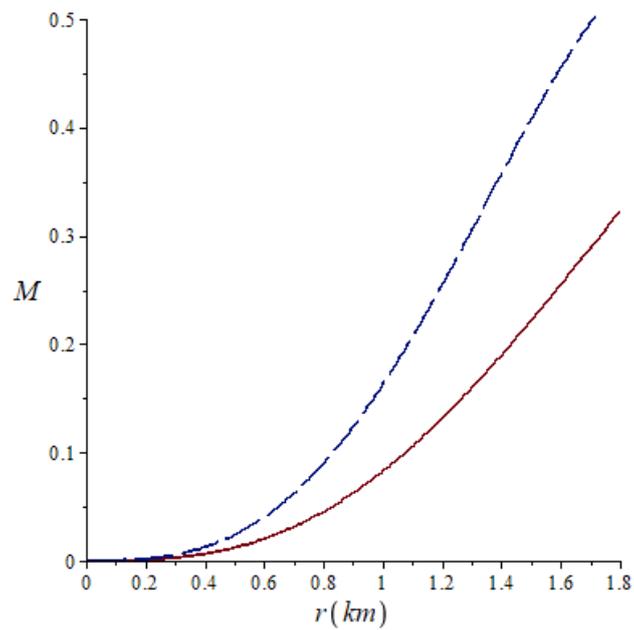


Figure 5. Mass function against radial coordinate. It has been considered that $n=1$ (solid line) ; $n=2$ (long-dash line).

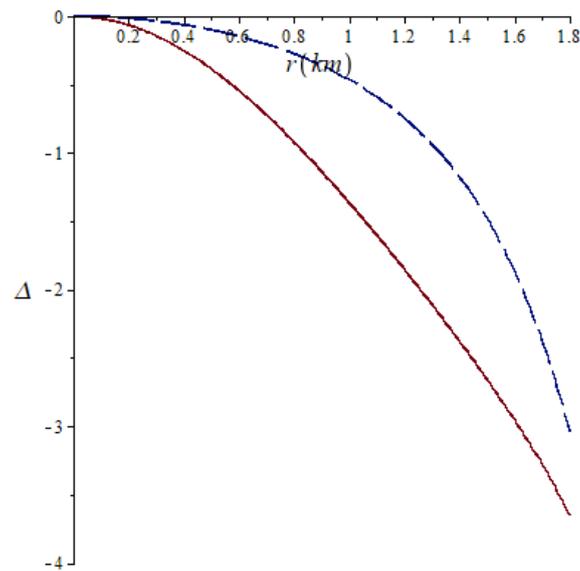


Figure 6. Anisotropy against radial coordinate. It has been considered that $n=1$ (solid line) ; $n=2$ (long-dash line).

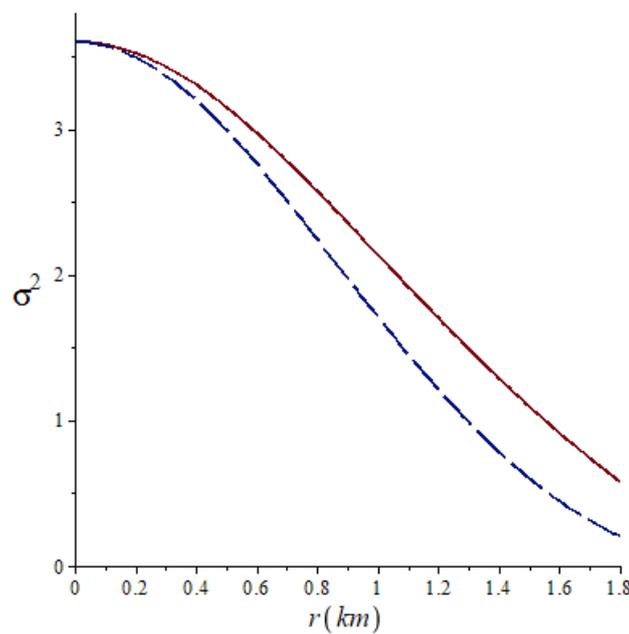


Figure 7. Charge density against radial coordinate. It has been considered that $n=1$ (solid line) ; $n=2$ (long-dash line).

In the [Figure 1](#) is shown that the energy density remains positive, continuous and is monotonically decreasing function throughout the stellar interior for all values of a . In the [Figure 2](#) it is noted that for the radial variation of energy density gradient $\frac{d\rho}{dr} < 0$ in the two cases studied. The radial pressure showed the same behavior by the energy density, that is, it is growing within the star and vanishes at a greater radial distance and its results are shown in [Figure 3](#). Again, according to [Figure 4](#), the profile of $\frac{dp_r}{dr}$ shows that radial pressure gradient is negative inside the star for $n=1$ and $n=2$. In [Figure 5](#), the mass function

is continuous, strictly increasing and well behaved for all the cases. The anisotropic factor is plotted in Figure 6 and it shows that vanishes at the centre of the star, i.e. $\Delta(r=0) = 0$ [30,37]. Figure 7 shows that the charge density is regular at the centre, non-negative and grows with the radial parameter.

6. Conclusions

In this paper we have generated new models of anisotropic stars considering the Thirukkanesh-Ragel-Malaver ansatz for the gravitational potential and the MIT bag model equation of state. These models may be used in the description of compact objects in absence of charge and in the study of internal structure of strange quark stars. We show that the developed configuration obeys the physical conditions required for the physical viability of the stellar model. A graphical analysis shows that the radial pressure, energy density, mass function and anisotropy are regular at the origin and well behaved in the interior. The new solutions match smoothly with the Reissner–Nordström exterior metric at the boundary $r=R$ because matter variables and the gravitational potentials of this work are consistent with the physical analysis of these stars. It is expected that the results of this research can contribute to modeling of relativistic compact objects and configurations with anisotropic matter distribution.

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