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A New model for charged anisotropic matter with modified Chaplygin equation of state

Manuel Malaver[1,2] and Hamed Daei Kasmaei[3]

[1]Bijective Physics Institute, Idrija, Slovenia

[2]Maritime University of the Caribbean, Department of Basic Sciences, Catia la Mar, Venezuela.
Email: mmf.umc@gmail.com

[3] Department of Applied Mathematics and Computer Science, Islamic Azad University, Central Tehran Branch, Tehran, Iran.
Email: hamedelectroj@gmail.com

Abstract: In this paper, we found a new model for compact star with charged anisotropic matter distribution considering an extended version of the Chaplygin equation of state. We specify a particular form of the metric potential *Z(x)* that allows us to solve the Einstein-Maxwell field equations. The obtained model satisfies all physical properties expected in a realistic star such that the expressions for the radial pressure, energy density, metric coefficients, measure of anisotropy and the mass are fully well defined and are regular in the interior of star. The solution obtained in this work can have multiple applications in astrophysics and cosmology.

Keywords: Einstein-Maxwell field equations, Chaplygin equation of state, Metric potential, Radial pressure, Measure of anisotropy.

1. Introduction

The study and description of static fluid spheres is an interesting area of research and one of great relevance in astrophysics due to formulation of the general theory of relativity [1, 2].One of the most important issues in general relativity is finding exact solutions to Einstein's field equations in order to propose physical models of compact stars as suggested by Delgaty and Lake [3] who constructed several analytic solutions that describe static perfect fluid and satisfy all the necessary conditions to be physically acceptable [3]. These exact solutions have also made it possible the way to study cosmic censorship and analyze the formation of naked singularities [4].

In the construction of theoretical models of stellar objects, the research of Schwarzschild [5], Tolman [6] and Oppenheimer and Volkoff [7] are very important to be considered. Schwarzschild [5] found analytical solutions that allowed describing a star with uniform density, Tolman [6] developed a method to find solutions of static spheres of fluid and Oppenheimer and Volkoff [7] used Tolman's solutions to study the gravitational balance of neutron stars. It is important to mention that Chandrasekhar's contributions [8] in the model production of white dwarfs and in presence of relativistic effects and the works of Baade and Zwicky [9] fully propose the main physical concepts of neutron stars and also identify astronomic dense objects known as supernovas.

The presence of the electric field can modify the values for surface redshift, luminosity, density and maximum mass for stars. Bekenstein [10] considered that the gravitational attraction may be balanced by electrostatic repulsion due to electric charge and pressure gradient. Komathiraj and Maharaj [11] obtained new classes of exact solutions to the Einstein-Maxwell system of equations for a charged sphere with a particular choice of one of the metric potentials. Ivanov [12] has studied and developed a wide variety of charged stellar models. More recently, Malaver and Kasmaei [13] proposed a model of charged anisotropic matter with nonlinear equation of state.

It is well known the fact that the anisotropy plays a significant role in the studies of relativistic stellar objects [14-26]. The existence of solid core, presence of type 3A superfluid [27], magnetic field, mixture of two fluids, a pion condensation and electric field [28] are most important reasonable facts that explain the presence of anisotropy. Bowers and Liang [14] generalized the equation of hydrostatic equilibrium for the case of local anisotropy. Bhar et al. [29] have studied the behavior of relativistic objects with anisotropic matter distribution considering the Tolman VII form for the gravitational potential.

Many researches have used a variety of analytical methods in order to try to obtain exact solutions of the Einstein-Maxwell field equations for anisotropic relativistic stars. It is very important to mention that the contributions of Komathiraj and Maharaj [11], Thirukkanesh and Maharaj [30], Maharaj et al.[31], Thirukkanesh and Ragel [32,33], Feroze and Siddiqui [34,35], Sunzu et al.[36], Pant et al. [37] and Malaver [38-41] needs to be considered in this field of research study. These studies suggest that the Einstein-Maxwell field equations are very important in the description of ultracompacts objects.

The development of theoretical models of stellar structures can consider several forms of equations of state [42]. Komathiraj and Maharaj [43], Malaver [44], Bombaci [45], Thirukkanesh and Maharaj [30], Dey et al. [46] and Usov [28] assume linear equation of state for quark stars. Feroze and Siddiqui [34] 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 [47] obtained new exact solutions to the Einstein-Maxwell system of equations with a polytropic equation of state. Thirukkanesh and Ragel [48] have obtained particular models of anisotropic fluids with polytropic equation of state which are consistent with the reported experimental observations. Malaver [49] generated new exact solutions to the Einstein-Maxwell system considering Van der Waals modified equation of state with polytropic exponent. Bhar and Murad [50] obtained new relativistic stellar models with a particular type of metric function and a generalized Chaplygin equation of state. Recently Tello-Ortiz et al. [51] also found an anisotropic fluid

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sphere solution of the Einstein-Maxwell field equations with a modified version of the Chaplygin equation.

It is important to mention the fact that general relativity not only studies the interior of stellar objects, it also allows the analysis of different cosmological scenarios through the Einstein gravity theory as the existence of dark energy, dark matter, Phantom and Quintessence fields that were introduced to explain the accelerated expansion of the universe [51,52]. Chaplygin gas whose equation of state $P = -B/\rho^{\alpha}$ where p is the pressure, ρ the energy-density, B a positive constant and α a parameter has been considered an alternative to the Phantom and Quintessence fields [53].

In this paper, we generated a new model of charged anisotropic compact object with the modified Chaplygin equation of state proposed for Pourhassan [54] and studied by Bernardini and Bertolami [55].The modified Chaplygin equation of state is described by $P = A\rho - B/\rho^{\alpha}$ where A, B, α are constants and $0 \leq \alpha \leq 1$. Using a particular form of gravitational potential $Z(x)$ that is nonsingular, continuous and well behaved in the interior of the star, we can obtain a new class of static spherically symmetrical model for a charged anisotropic matter distribution. It is expected that the solution obtained in this work can be applied in the description and the study of internal structure of strange quark stars.

2. Einstein-Maxwell system of equations

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

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

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

The Einstein field equations for the charged anisotropic matter are given by [30]:

$$\frac{1}{r^2}\left(1-e^{-2\lambda}\right)+\frac{2\lambda'}{r}e^{-2\lambda} = \rho + \frac{1}{2}E^2 \tag{2}$$

$$-\frac{1}{r^2}\left(1-e^{-2\lambda}\right)+\frac{2\nu'}{r}e^{-2\lambda} = p_r - \frac{1}{2}E^2 \tag{3}$$

$$e^{-2\lambda}\left(\nu'' + \nu'^2 + \frac{\nu'}{r} - \nu'\lambda' - \frac{\lambda'}{r}\right) = p_t + \frac{1}{2}E^2 \tag{4}$$

$$\sigma = \frac{1}{r^2}e^{-\lambda}(r^2E)' \tag{5}$$

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where ρ is the energy density, p_r is the radial pressure, E is electric field intensity, p_t is the tangential pressure and primes denote differentiations with respect to r. 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 [56], the Einstein field equations can be written as:

$$\frac{1-Z}{x} - 2\dot{Z} = \frac{\rho}{c} + \frac{E^2}{2c} \tag{6}$$

$$4Z\frac{\dot{y}}{y} - \frac{1-Z}{x} = \frac{p_r}{c} - \frac{E^2}{2c} \tag{7}$$

$$4xZ\frac{\ddot{y}}{y} + (4Z + 2x\dot{Z})\frac{\dot{y}}{y} + \dot{Z} = \frac{p_t}{c} + \frac{E^2}{2c} \tag{8}$$

$$p_t = p_r + \Delta \tag{9}$$

$$\frac{\Delta}{c} = 4xZ\frac{\ddot{y}}{y} + \dot{Z}\left(1 + 2x\frac{\dot{y}}{y}\right) + \frac{1-Z}{x} - \frac{E^2}{c} \tag{10}$$

$$\sigma^2 = \frac{4cZ}{x}\left(x\dot{E} + E\right)^2 \tag{11}$$

σ is the charge density, $\Delta = p_t - p_r$ is the anisotropy factor and dots denote differentiations with respect to x. With the transformations of [56], the mass within a radius r of the sphere takes the form:

$$M(x) = \frac{1}{4c^{3/2}}\int_0^x \sqrt{x}\left(\rho^* + E^2\right)dx \tag{12}$$

Where

$$\rho^* = \left(\frac{1-Z}{x} - 2\dot{Z}\right)c$$

In this paper, we assume the following equation of state where the radial pressure and the density ρ are related to the following form:

$$p_r = A\rho - \frac{B}{\rho} \tag{13}$$

with A and B as constant parameters and $\alpha = 1$.

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3. Charged Anisotropic Model

In this work, we take the form of the gravitational potential $Z(x)$ as $Z(x)=1-ax$ proposed for Malaver [38] and Thirukanesh and Ragel [48] where a is a real constant.This potential is regular at the origin and well behaved in the interior of the sphere. Following Ngubelanga et al. [57] for the electric field ,we make the particular choice:

$$\frac{E^2}{2c} = x(a+bx) \tag{14}$$

This electric field is finite at the center of the star and remains continuous in the interior. Using $Z(x)$ and eq.(14) in eq.(6), we obtain

$$\rho = c(3a - ax - bx^2) \tag{15}$$

Substituting eq. (15) in eq. (13), the radial pressure can be written in the form:

$$p_r = Ac(3a-ax-bx^2) - \frac{B}{c\left(3a-ax-bx^2\right)} \tag{16}$$

Using eq. (15) in eq. (12), the expression of the mass function is

$$M(x) = \frac{\left(35a - 7ax - 5bx^2\right)x^{3/2}}{70\sqrt{c}} \tag{17}$$

With eq. (14) and Z(x) in eq. (11), the charge density is

$$\sigma^2 = \frac{2c^2(1-ax)(3a+4bx)^2}{(a+bx)} \tag{18}$$

With equations (13), (14), (15) and $Z(x)$,eq.(7) becomes:

$$\frac{\dot{y}}{y} = \frac{A\left(3a-ax-bx^2\right)}{4(1-ax)} - \frac{B}{4c^2(1-ax)\left(3a-ax-bx^2\right)} - \frac{x(a+bx)}{4(1-ax)} + \frac{a}{4(1-ax)} \tag{19}$$

Integrating eq. (19) we obtain:

$$y(x) = c_1\left(bx^2+ax-3a\right)^{A*}(3ax-1)^D e^{Ex^2+Fx+2Ba^2\left(a^2+2b\right)\arctan\left(\frac{2bx+a}{\sqrt{a(a+12b)}}\right)} \tag{20}$$

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where for the convenience we have let

$$A^{*}=-\frac{aB}{8c^{2}\left(3a^{3}-a^{2}-b\right)} \tag{21}$$

$$D=-\frac{3(3A+1)a^{6}-2(3A+2)a^{5}+(A-B+1)a^{4}-2(3A+2)ba^{3}+(A+1)\left(2ba^{3}+b^{2}\right)}{4a^{3}\left(3a^{3}-a^{2}-b\right)} \tag{22}$$

$$E=\frac{(A+1)\left(3a^{2}b-ab-b^{2}/a\right)}{8\left(3a^{3}-a^{2}-b\right)} \tag{23}$$

$$F=\frac{2(A+1)\left(3a^{3}-a^{2}+3ab-2b-b^{2}/a^{2}\right)}{8\left(3a^{3}-a^{2}-b\right)} \tag{24}$$

and c_1 is the constant of integration.

The metric functions $e^{2\lambda}$ and $e^{2\nu}$ can be written as:

$$e^{2\lambda}=\frac{1}{1-ax} \tag{25}$$

$$e^{2\nu(r)}=c_1^{2}A_{*}^{2}\left(bx^{2}+ax-3a\right)^{A*}(ax-1)^{2D}e^{2\left[Ex^{2}+Fx+2Ba^{2}\left(a^{2}+2b\right)\arctan\left(\frac{2bx+a}{\sqrt{a(a+12b)}}\right)\right]} \tag{26}$$

and the anisotropy factor Δ is given by:

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$$\Delta = 4xc(1-ax)\left[\begin{array}{l}\dfrac{(A^{*2}-A^{*})(2bx+a)^2}{(bx^2+ax-3a)^2}+\dfrac{2A^{*}b}{bx^2+ax-3a}+\dfrac{2A^{*}Da(2bx+a)}{(bx^2+ax-3a)(ax-1)}\\ +2A^{*}(2bx+a)\left(2Ex+F+\dfrac{4Ba^2(a^2+12b)b}{\sqrt{a^2+12ab}\left(1+\dfrac{(2bx+a)^2}{a^2+12ab}\right)}\right)\\ +\dfrac{(D^2-D)a^2}{(ax-1)^2}+\dfrac{2Da}{ax-1}\left(2Ex+F+\dfrac{4Ba^2(a^2+12b)b}{\sqrt{a^2+12ab}\left(1+\dfrac{(2bx+a)^2}{a^2+12ab}\right)}\right)\\ 2E-\dfrac{16Ba^2b^2(a^2+12b)(2bx+a)}{(a^2+12ab)^{3/2}\left(1+\dfrac{(2bx+a)^2}{a^2+12ab}\right)^2}\\ +\left(2Ex+F+\dfrac{4Ba^2b(a^2+12b)}{\sqrt{a^2+12ab}\left(1+\dfrac{(2bx+a)^2}{a^2+12ab}\right)}\right)^2\end{array}\right]$$
$$-2xca\left[\dfrac{A^{*}(2bx+a)}{bx^2+ax-3a}+\dfrac{aD}{ax-1}+\left(2Ex+F+\dfrac{4Ba^2b(a^2+12b)}{\sqrt{a^2+12ab}\left(1+\dfrac{(2bx+a)^2}{a^2+12ab}\right)}\right)\right]$$
$$-2xc(a+bx)$$

(27)

4. Physical Requirements for the New Developed Model

Following Delgaty and Lake [3], Thirukkanesh and Ragel [48] and Bibi et al. [58] for a model to be physically acceptable, it must satisfy the following conditions:

(i) Regularity of the metric potentials in the stellar interior and at the origin.
(ii) The radial pressure should be positive, decreasing with the radial coordinate and vanishing at the centre of the fluid sphere.
(iii) The energy density should be positive inside of the star and a decreasing function of the radial parameter.

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(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 causality condition requires that the radial speed of sound should be less than speed of light throughout the model, i.e. $0 \leq \frac{dp_r}{d\rho} \leq 1$.

(vi) The radial pressure and the anisotropy is equal to zero at the centre of the fluid sphere $\Delta(r=0)=0$.

(vii) The charged interior solution should be matched with the Schwarzschild exterior solution, for which the metric is given by:

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)dt^2 + \left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2 d\varphi^2\right) \tag{28}$$

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

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

5. Physical Analysis

We now present the analysis of the physical characteristics for the new model. The metric functions $e^{2\lambda}$ and $e^{2\nu}$ should remain positive throughout the stellar interior and in the origin $e^{2\lambda(0)} = 1$, $e^{2\nu(0)} = A_*^2 c_1^2 (-3a)^{A*} (-1)^{2D} e^{4Ba^2(a^2+2b)\arctan\left(\frac{a}{\sqrt{a(a+12b)}}\right)}$ .We note in $r=0$ that $\left(e^{2\lambda(r)}\right)'_{r=0} = \left(e^{2\nu(r)}\right)'_{r=0} = 0$ .This demonstrates that the gravitational potentials are regular at the centre $r=0$. The energy density and radial pressure are positive and well behaved inside the stellar interior. Also, we have the central density and pressure $\rho(0) = 3ac$ and $p_r(0) = 3acA - \frac{B}{3ac}$. According to the expression of radial pressure, $p_r(0)$ will be non-negative at the centre as it is satisfied by the condition $3acA > \frac{B}{3ac}$.

In the surface of the star $r=R$, we have $p_r(r=R)=0$ and

$$R = \frac{\sqrt{-2Ab\left(Aac - \sqrt{A^2a^2c^2 + 12A^2abc^2 - 4Abc\sqrt{AB}}\right)}}{2Abc}$$

For a realistic star, it is expected that the gradient of energy density and radial pressure should be decreasing functions of the radial coordinate r. In this model, for all $0 < r < R$, we obtain respectively:

$$\frac{d\rho}{dr} = -2ac^2 r - 4bc^3 r^3 < 0 \tag{29}$$

$$\frac{dp_r}{dr} = -A\left(2ac^2 r + 4bc^3 r^3\right) - \frac{B\left(2a + 4bcr^3\right)}{3a - acr^2 - bc^2 r^4} < 0 \tag{30}$$

and according to the equations (29) and (30), the energy density and radial pressure decrease from the centre to the surface of the star.
From eq. (17), we have:

$$M(r) = \frac{\left(35a - 7acr^2 - 5bc^2 r^4\right)cr^3}{70} \tag{31}$$

and the total mass of the star is:

$$M(r=R) = \left[\frac{2aA^2bc^2 + \frac{aAc}{10}\left(Aac - \sqrt{A^2a^2c^2 + 12A^2abc^2 - 4Abc\sqrt{AB}}\right) - 40\left(Aac - \sqrt{A^2a^2c^2 + 12A^2abc^2 - 4Abc\sqrt{AB}}\right)^2}{32A^5b^4c^4}\right]$$
$$\left[-2Ab\left(Aac - \sqrt{A^2a^2c^2 + 12A^2abc^2 - 4Abc\sqrt{AB}}\right)\right]^{3/2} \tag{32}$$

The causality condition demands that the radial sound speed defined as $v_{sr}^2 = \frac{dp_r}{d\rho}$ should not exceed the speed of light and it must be within the limit $0 \le v_{sr}^2 \le 1$ in the interior of the star [3]. In this model, we have:

$$v_{sr}^2 = \frac{dp_r}{d\rho} = A + \frac{B}{c^2\left(3a - ax - bx^2\right)^2} \tag{33}$$

For the eq. (33) and with the transformations of Durgapal and Bannerji [56] we can impose the condition:

$$0 \le \frac{Ab^2c^6r^8 + 2Aabc^5r^6 + (a-6b)Aac^4r^4 - 6Aa^2c^3r^2 + 9Aa^2c^2 + B}{b^2c^6r^8 + 2abc^5r^6 + (a-6b)ac^4r^4 - 6a^2c^3r^2 + 9a^2c^2} \le 1 \tag{34}$$

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

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

and therefore, the continuity of e^{ν} and e^{λ} across the boundary $r=R$ is

$$e^{2\nu} = e^{-2\lambda} = 1 - \frac{2M}{R} + \frac{Q^2}{R^2} \tag{35}$$

Then for the matching conditions, we obtain:

$$\frac{2M}{R} = acR^2\left(1 + 2R^2 + \frac{2bc}{a}R^4\right) \tag{36}$$

The figures 1,2,3,4, 5, 6, 7 and 8 represent the graphs of p_r , ρ , $M(x)$, σ^2 , Δ , v^2_{sr} , $\frac{dp_r}{dr}$ and $\frac{d\rho}{dr}$ respectively with $a=0.09$, $b=0.015$, $A=0.066$, $B=0.0000054$, $c=1$ and stellar radius of $r=1.46\ km$.

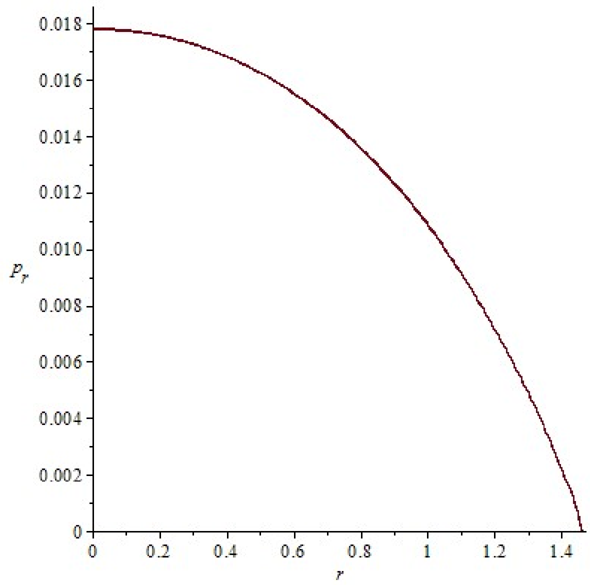

Figure 1. Variation of radial pressure with the radial coordinate.

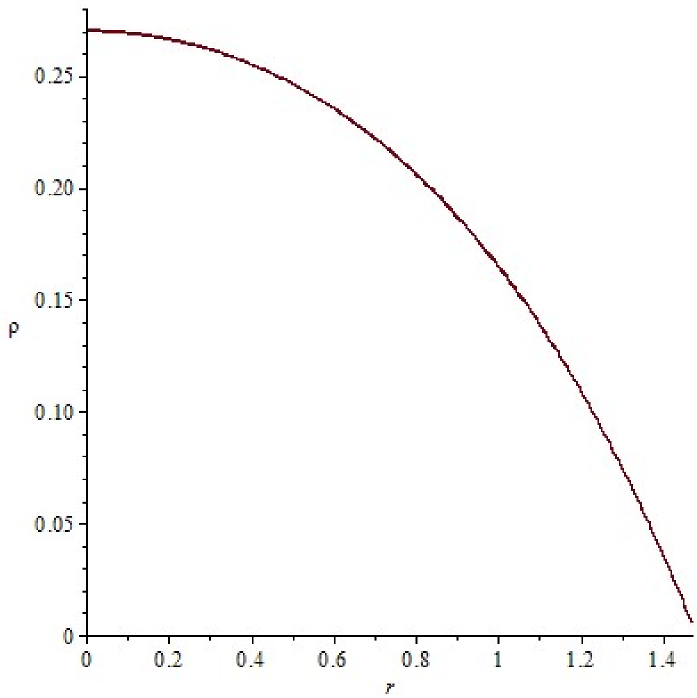

Figure 2. Variation of energy density with the radial coordinate.

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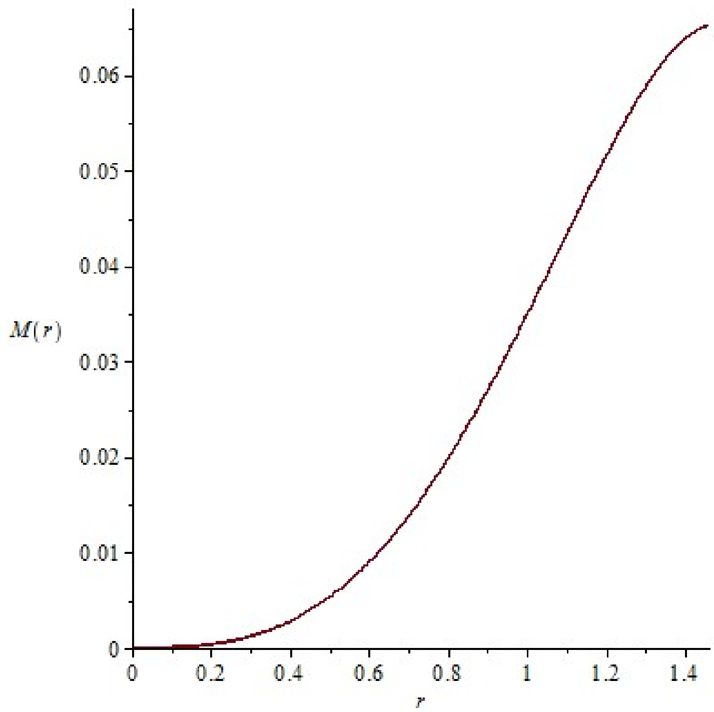

Figure 3. Variation of Mass function *M(r)* with the radial parameter.

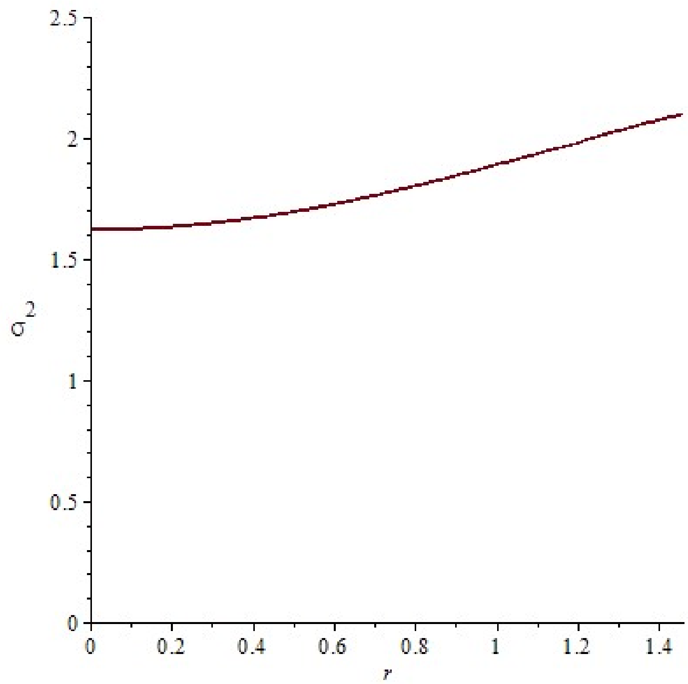

Figure 4. Variation of charge density σ^2 with the radial parameter.

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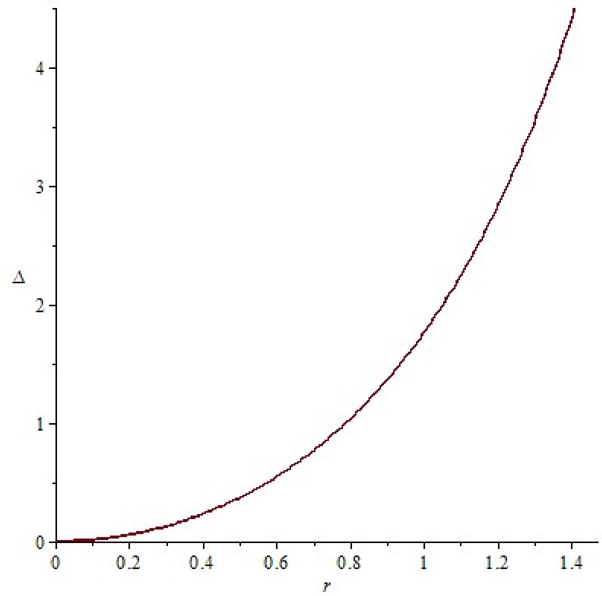

Figure 5. Variation of anisotropy Δ with the radial parameter.

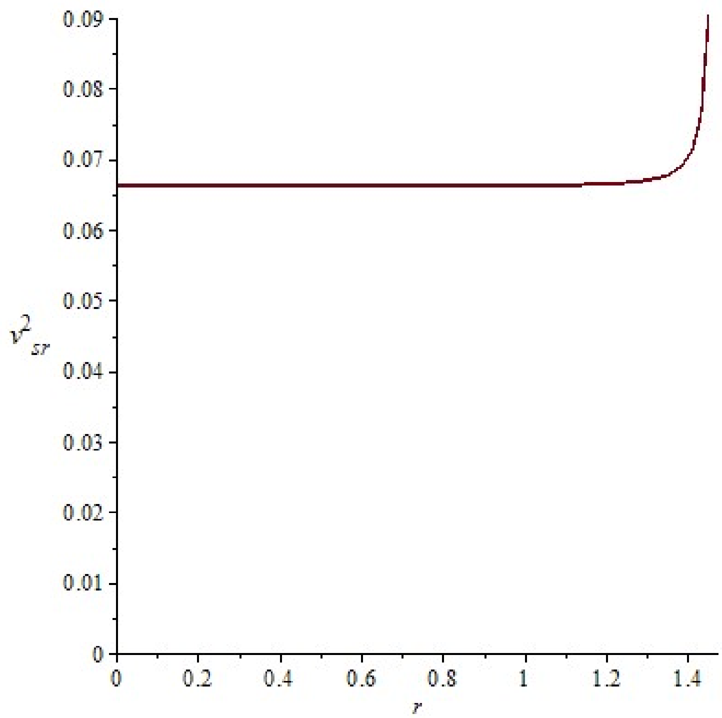

Figure 6. Variation of radial speed sound v_{sr}^2 with the radial parameter.

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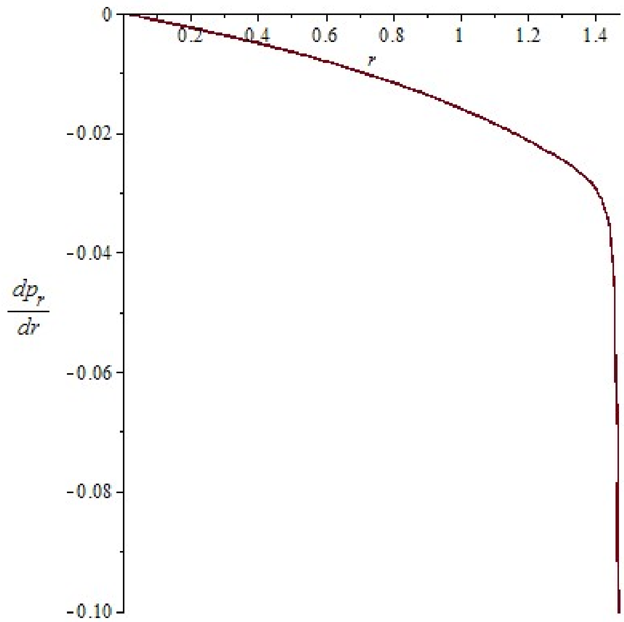

Figure 7. Variation of **g**radient of radial pressure with radial coordinate.

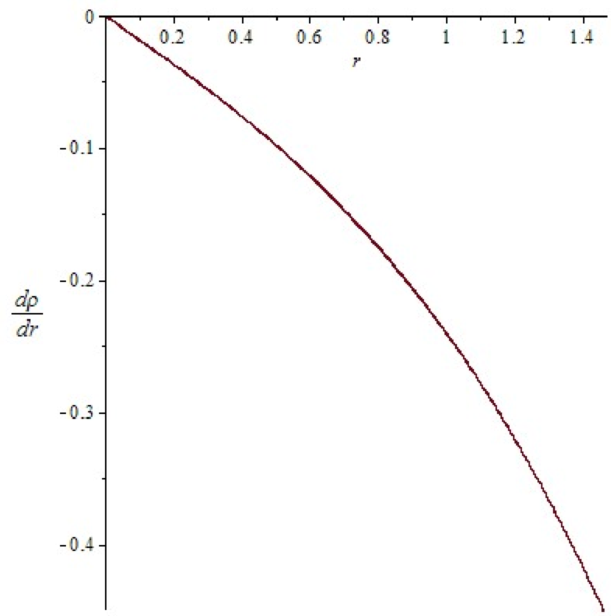

Figure 8. Variation of gradient of density with radial coordinate.

The Fig. 1 shows that the radial pressure is continuous, finite, decreases radially outward and vanishes at the boundary. In Fig. 2, we note that the energy density ρ also is finite, continuous and monotonically decreasing function. In Fig. 3, it is observed that the mass function is regular, strictly increasing and well behaved. Fig. 4 shows that the charge density is regular at the centre, non-negative and grows with the radial parameter. In Fig. 5, the anisotropy factor Δ vanishes at *r=0*, it monotonically increases and is continuous in the stellar interior reaching a maximum on the surface of the star. In Fig. 6, we note that the $v_{sr}^2 = \frac{dp_r}{d\rho}$ is within the desired range $0 \leq v_{sr}^2 \leq 1$, which is a physical requirement for the construction of a realistic star [3]. The Figures 7 and 8 respectively show that the gradients of radial pressure $\frac{dp_r}{dr}$ and energy density $\frac{d\rho}{dr}$ are decreasing throughout the star.

6. Conclusion

In this paper, we have solved Einstein-Maxwell field equations with a particular form of gravitational potential and a modified Chaplygin equation of state and presented a new class of solution that satisfies the physical requirements of a anisotropic charged stellar model. The radial pressure, energy density, anisotropy, mass function, charge density and all the metric coefficients behave well inside the stellar interior and are free of singularities.

The new obtained solution is expressed in terms of elementary functions which can be useful in the description of compact strange star candidates and the physical study of some kinds of white dwarfs with masses $\sim 0.06 M_{sol}$ and *r=1.5 Km* .

The values of parameters *A* and *B* have been chosen in order to maintain the causality condition and the regularity of metric potentials inside the radius of the star. With $E^2 = B = 0$, the model of Lobo for dark energy stars [59] can be recovered as a particular case of this work and choosing $E^2 \neq 0$, $B = 0$, we can obtain new models with linear equation of state within the framework of MIT-Bag model and generate families of exact solutions for the Einstein-Maxwell field equations for relativistic compact objects and configurations with anisotropic matter distribution. It is to be expected that the stellar models obtained in this research can be used in the description of the internal structure of strange quark stars. The arbitrary constants A, A* B, C, D, E must be well defined in order to reproduce numerical data consistent with super-dense star models like neutron star and pulsars.

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