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Relativistic Stellar Modeling with generalized Chapligyn Equation of State

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ABSTRACT

In this study, we obtained a new model for a charged anisotropic matter distribution by using the generalized Chaplygin equation of state. The Einstein-Maxwell field equations have been solved with a specific form of metric potential and electric field intensity. The graphical plots describe that physical features such as radial pressure, charge density, energy density, anisotropy, radial speed sound, and the mass are fully well explained and remain regular in the interior of the star. We have found models consistent with stellar objects.

Introduction

The study and understanding of static fluid spheres is an interesting field of research and of great relevance to astrophysics because of the formation of general theory of relativity [1,2]. The important issues in general relativity is to f ind the exact solutions to the Einstein's field equations to propose real physical models of compact stars as suggested by Delgaty and Lake [3] who created many analytic solutions that clearly describe static perfect fluid and meet all the important conditions to be physically acceptable [3]. These exact solutions have also provided the possible way to study cosmic censorship and examine the production of naked singularities [4]. In the creation of theoretical models of stellar objects, the research of Schwarzschild [5] found analytical solutions that allowed to describe the star with uniform density, Tolman made a method to find solutions for static fluid spheres, and Oppenheimer and Volkoff [7] used Tolman's [6] solutions to understand the gravitational balance of neutron stars. It is necessary to mention that Chandrasekhar's contributions [8] in the model construction of white dwarf and the presence of relativistic effects and the works of the Baade and Zwicky [9] fully propose the important physical concepts of neuron stars and also identify astronomic dense objects such as supernovas. The presence of the electric field can modify the values of physical conditions such as surface redshift, luminosity, density, and maximum mass for stars. Bekenstein [10] proposed that the gravitational attraction may be balanced by elec1trostatic repulsion due to electric charge and pressure gradient. Komathiraj and Maharaj [11] found new classes of exact solutions to the Einstein-Maxwell system of equations for a charged sphere with specific metric potentials. More recenly, Kasmaei and Malaver [12] used nonlinear equation of state and proposed a model for charged anisotropic matter. It is the fact that anisotropy plays a vital role in the studies of relativistic stellar objects [13–30]. The occurrence of a solid core, the presence of type 3A superfluid [26], a magnetic f ield, a pion condensation, a blend of two fluids, and an electric field [27] are the most necessary facts that describe the presence of anisotropy. Bowers and Liang [13] modified the equation of hydrostatic equilibrium for the case of local anisotropy. Many scholars have used different analytical methods to try to get exact solutions of the Einstein-Maxwell field equations for relativistic stars with anisotropic distribution of matter.It is necessary to mention the contributions of researchers such as Komathiraj and Maharaj [11], Thirukkanesh and Ragel [31,32], Feroze and Siddiqui [33,34], Sunzu et al [35]. and Malaver [37–40] need to be considered in this area of research study. Others authors suggest that the Einstein Maxwell field equations are very significant in the explanation of ultracompact objects [41-45]. The construction of theoretical models of stellar structures can consider many forms of equation of state [41]. Feroze and Siddiqui [33] assumed a quadratic equation of state for the matter distribution and modified particular forms for the gravitational potential and electric field density. Mafa Takisa and Maharaj [46] got new exact solutions to the EinsteinMaxwell system of equations wih a polytropic equation of state. Thirukkanesh and Ragel [47] have got specific models of anisotropic fluids with polytropic equation of state consistent with the reported experimental and observational evidences. Malaver [48] constructed new exact solutions to the Einstein-Maxwell system considering Van der Waals's modifield equation of state with polytropic exponent. Bhar and Murad [49] generated new relativistic stellar models with a specific type of metric function and a generalized Chaplygin equation of state. Recently Tello-Ortiz et al [50]. also discovered an isotropic fluid sphere solution of the Einstein-Maxwell field equations with a modified form of the Chaplygin equation. Recently there are efforts underway to understand the underlying quantum aspects with astrophysical-charged stellar models [51-53]. How the energy matter quantum wavefunction creates situations with the equation of state potential, expansions with quintessence field cosmologies with interior having dark energy matter generation compact stellar anisotropic gravitational potential and structure of man objects, especially strange quark stars as well have been key in Quantum Astrophysical projects ongoing [50-54]. There is also a study of the symmetry group theory with authors advancing that will help to classify general field-particle metrics linking towards Standard Model Particle Physics String Theories with Hubble and James Webb Telescope observations of the expanding universe models that are supposed to manifest from natural astrophysical Big Bang Theory [54-63]. It is necessary to mention the fact that general relativity not only studies the interior of stellar objects, it also helps the analysis of different cosmological scenarios through Einstein's gravity theory as the existence of dark energy, dark matter,Phantom and

Quintessence fields that were discovered to explan the accelerated expansion of the universe [50,64]. Chaplygin gas whose equation of state $P = -\frac{B}{\rho}$ where P is the pressure, ρ the energy densiy and B a positive constant, has been considered an alternative to the Phantom and Quintessence fields [49,52]. In order to adjust this equation of state to observational data has been rewritten as $P = -\frac{B}{\rho^{\omega}}$ with the parameter ω between 0 and 1 [65]. Furthermore, an extended version of the Chaplygin gas equation of state was given by Pourhassan [66] and its form is $P = A\rho - \frac{B}{\rho^{\omega}}$ where *A* a positive parameter constrained to $0 < A < 1/3$.

In this paper, we constructed a new model of a charged anisotropic compact object with the modified Chaplygin equation of state given by Porurhassan [66] and studied and explained by Bernardini and Bertolami [67]. The modified Chaplygin equation of state is described by where A,B,α are constants and 0 < α < 1. If we take α = 1 then it gives generalized Chaplygin equation of state [49]. Using a specific form of gravitational potential Z(x) that is non-singular, 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 explanation and the study of the internal structure of strange quark stars. The article is organized as follows: In section 2 we present Einstein-Maxwell field equations. In section 3 we make a particular choice for gravitational potential Z(x) and the electric field intensity and generate new models for charged anisotropic matter. In Section 4, physical acceptability conditions are discussed. The physical properties and physical validity of these new solutions are analyzed in section 5. the conclusions of the results obtained are shown in section 6.

2. Maxwell-Einstein Field Equations

We consider a spherically symmetric, static and homogeneous and anisotropic spacetime in Schwarzschild coordinates given by

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

We denote the metric functions $\nu(r)$ and $\lambda(r)$ in the standard Schwarzschild-like form. Both functions are assumed to be smooth and regular at the center. We consider a charged anisotropic fluid coupled to the electromagnetic field through the Maxwell equations.

The Einstein field equations for the charged anisotropic matter are given by

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

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

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

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

where ρ is the energy density, p_r is the radial pressure, E is electric field intensity and p_t is the tangential pressure, respectively. Using the transformations, $x=cr^2$, $Z(x)=e^{-2\lambda(r)}$ and $A_*^2y^2(x)=e^{2\nu(r)}$ with arbitrary constants A_* and c>0, suggested by Durgapal and Bannerji [68], the metric (1) takes the form

$$ds^2=-A_*^2y^2(x)dt^2+\frac{dx^2}{4Z(x)Cx}+\frac{x}{C}(d\theta^2+\sin^2\theta d\varphi^2) \tag{6}$$

and the Einstein field equations can be written as

$$\frac{1-Z}{x}-2\dot{Z}=\frac{\rho}{c}+\frac{E^2}{2c} \tag{7}$$

$$4Z\frac{\dot{y}}{y} - \frac{1-Z}{x} = \frac{p_r}{c} - \frac{E^2}{2c} \tag{8}$$

$$4xZ\frac{\ddot{y}}{y} + (4Z + 2x\dot{Z})\frac{\dot{y}}{y} + \dot{Z} = \frac{p_t}{c} + \frac{E^2}{2c} \tag{9}$$

$$p_t = p_r + \Delta \tag{10}$$

$$\frac{\Delta}{c} = 4xZ\frac{\ddot{y}}{y} + \dot{Z}\left(1 + 2x\frac{\dot{y}}{y}\right) + \frac{1-Z}{x} - \frac{E^2}{c} \tag{11}$$

$$\sigma^2 = \frac{4cZ}{x}\left(x\dot{E} + E\right)^2 \tag{12}$$

Here σ is the charge density and dots denoting differentiation with respect to x. The Durgapal–Bannerji transformations are introduced to simplify the structure of the field equations by reducing nonlinear terms and allowing the metric potentials to appear in rational form. This method is widely used in constructing exact solutions for compact configurations. With this transformation, the mass within a radius r of the sphere takes the form

$$M(x) = \frac{1}{4c^{3/2}}\int_0^x \sqrt{x}\rho(x)dx \tag{13}$$

The interior metric (1) with the charged matter distribution should match the exterior spacetime described by the Reissner-Nordström metric:

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)dt^2 + \left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2) \tag{14}$$

where the total mass and the total charge of the star are denoted by M and q^2, respectively. The junction conditions at the stellar surface are obtained by matching the first and the second fundamental forms for the interior metric (1) and the exterior metric (14).

Regularity at the center together with the matching to the Reissner–Nordström metric at the surface fully determines the free constants in the solution.

In this paper, we assume the following equation of state

$$p_r = H\rho - \frac{K}{\rho} \tag{15}$$

where H and K are arbitrary constants .

3. Charged Anisotropic Model

In this paper, we take the form of the gravitational potential *Z(x)* as $Z(x)= 1-ax$ proposed for [37] where a is the real constant. This potential is regularly applied at the origin and well behaved in the interior of the sphere. Following Liguda et al [69]. for the electric field, we make the specific choice

$$\frac{E^2}{2C} = Mx(1-ax) \tag{16}$$

where k > 0. The electric field is finite at the center of the star and stays continuous in the interior of the star.Using Z(x) and eq. (16) in eq. (7), we obtain

:

$$\rho = C[3a - Mx(1-ax)] \tag{17}$$

Through the substitution of (17) into (15), the radial pressure is obtained

$$p_r = HC[3a - Mx(1-ax)] - \frac{K}{C[3a - Mx(1-ax)]} \tag{18}$$

Using eq. (17) in eq. (13), the expression of the mass function is

$$M(x) = \frac{\left(5Max^2 - 7Mx + 35a\right)x^{3/2}}{70\sqrt{C}} \tag{19}$$

With equations (16) and *Z(x)* in eq. (12), the charge density is

$$\sigma^2 = 8MC^2\left(1 - 3ax\right)^2 \tag{20}$$

Equation (8) is changed by *Z(x)* , (15), and (16) as

$$\frac{y'}{y} = \frac{H\left[3a - Mx(1-ax)\right]}{4(1-ax)} - \frac{K}{4C^2(1-ax)\left[3a - Mx(1-ax)\right]} - \frac{Mx}{4} + \frac{3a}{4(1-ax)} \tag{21}$$

Integrating Eq.(21), we get the following

$$y(x) = C_1\left(Max^2 - Mx + 3a\right)^A\left(ax - 1\right)^B e^{-\frac{Dx^2 + 2K\arctan\left(\frac{2Max - M}{\sqrt{12Ma^2 - M^2}}\right)}{24C^2a^2\sqrt{12Ma^2 - M^2}}} \tag{22}$$

where for convenience

$$A = -\frac{K}{24C^2a^2} \tag{23}$$

$$B = -\frac{3}{4}\left(HC + 1\right) + \frac{K}{12C^2a^2} \tag{24}$$

$$D = 3MC^2 a^2 (HC+1)\sqrt{12Ma^2 - M^2} \tag{25}$$

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

$$e^{2\lambda(r)} = \frac{1}{1+ax} \tag{26}$$

$$e^{2\nu(r)} = A_*^2 C_1^2 \left(Max^2 - Mx + 3a\right)^{2A} (ax-1)^{2B} e^{-\frac{Dx^2 + 2K\arctan\left(\frac{2Max - M}{\sqrt{12Ma^2 - M^2}}\right)}{12C^2 a^2 \sqrt{12Ma^2 - M^2}}} \tag{27}$$

and the anisotropy Δ is given by

$$
\Delta = 4x(1-ax)\left[\begin{array}{l}
\frac{A^2(2Max-M)^2}{(Max^2-Mx+3a)^2}+\frac{2AMa}{Max^2-Mx+3a}-\frac{A(2Max-M)^2}{(Max^2-Mx+3a)^2} \\
+\frac{2AaB(2Max-M)}{(Max^2-Mx+3a)(ax-1)} \\
-\frac{A(2Max-M)\left(2Dx+\frac{4KMa}{\sqrt{12Ma^2-M^2}\left(1+\frac{(2Max-M)^2}{12Ma^2-M^2}\right)}\right)}{12(Max^2-Mx+3a)C^2a^2\sqrt{12Ma^2-M^2}} \\
+\frac{(B^2-B)a^2}{(ax-1)^2}-\frac{B\left(2Dx+\frac{4KMa}{\sqrt{12Ma^2-M^2}\left(1+\frac{(2Max-M)^2}{12Ma^2-M^2}\right)}\right)}{12aC^2(ax-1)\sqrt{12Ma^2-M^2}} \\
-\left(\frac{2D-\frac{16KM^2a^2(2Max-M)}{(12Ma^2-M^2)^{3/2}\left(1+\frac{(2Max-M)^2}{12Ma^2-M^2}\right)}}{24a^2C^2\sqrt{12Ma^2-M^2}}\right) \\
+\left(\frac{\left(2Dx+\frac{4KMa}{\sqrt{12Ma^2-M^2}\left(1+\frac{(2Max-M)^2}{12Ma^2-M^2}\right)}\right)^2}{576a^4C^4(12Ma^2-M^2)}\right)
\end{array}\right]
$$

$$
-a\left[1+2x\left(\frac{A(2Max-M)}{Max^2-Mx+3a}+\frac{aB}{ax-1}-\left(\frac{2Dx+\frac{4KMa}{\sqrt{12Ma^2-M^2}\left(1+\frac{(2Max-M)^2}{12Ma^2-M^2}\right)}}{24a^2C^2\sqrt{12Ma^2-M^2}}\right)\right)\right]
$$

$$
+a-2CMx(1-ax) \qquad (28)
$$

4. Physical Requirements for the new model

The solution for Einstein-Maxwell field equations is considered as a model for a compact object if it satisfies the physical conditions. The basic conditions for a physically valid solution are [47,70]:

I) The solution should be free from the singularities. This means that the metric coefficients $e^{2\lambda(r)}$ and $e^{2\nu(r)}$ should be well defined and finite.

II) The energy density, ρ, must be positive and monotonically decreasing function of the radius r. Mathematically, we have ρ(r) ≥ 0.

III) The radial pressure p_r should be positive and monotonically decreasing function of the radius r. Mathematically $p_r \geq 0$.

IV) The density and radial pressure gradients should be $dp_r/dr \leq 0$ and $d\rho/dr \leq 0$ for $0 \leq r \leq R$.

V) At the center, the anisotropy is zero r=0, i.e. Δ(r=0) =0.

VI) Both radial pressure and transverse pressure must be equal at r=0. Mathematically, we have

$$p_r(r=0) = p_t(r=0). \tag{29}$$

VII) The solution should must satisfy the casuality condition that speed of sound must be less than, c, the speed of light, we may write it as

$$0 \leq v_{sr}^2 = \frac{dp_r}{d\rho} \leq 1. \tag{30}$$

VIII) For the charged case the solution at the boundary, r = R , must match with the Reissner-Nordstrom exterior solution, i.e

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

where M is the mass and Q is the charge of the compact object at the boundary. In case of an uncharged compact object, the solution must match the exterior Schwarzschild solution

5. Physical Analysis

In this section we will discuss the physical conditions of the obtained solution

1. The metric potentials at the center, r = 0 are

$$e^{2\lambda(0)} = 1$$

(31)

$$e^{2\nu(0)} = A_*^2 C_1^2 (3a)^{2A} (-1)^{2B} e^{-\frac{K \arctan\left(\frac{-M}{\sqrt{12Ma^2 - M^2}}\right)}{6C^2 a^2 \sqrt{12Ma^2 - M^2}}}$$

(32)

where A is an arbitrary constant and A > 0. As the metric potentials are finite so there is no singularity in the solution.

2. The energy density ρ at the center r = 0, is expressed as

$$\rho(0) = 3aC$$

(33)

as a > 0 so ρ(0) > 0, i.e. the density at the center is finite.

3. The radial pressure at center $r = 0$, is given a

$$P_r(0) = 3HaC - \frac{K}{3aC}$$

(34)

4. Here the derivative of the energy density ρ is expressed a

$$\frac{d\rho}{dr} = C\left[-2MCr\left(1-aCr^2\right)+2aMC^2r^3\right]$$

(35)

5. The derivative of radial pressure, p_r, is given as

$$\frac{dp_r}{dr} = HC\left[-2MCr\left(1-aCr^2\right)+2aMC^2r^3\right]+\frac{K\left[-2MCr\left(1-aCr^2\right)+2aMC^2r^3\right]}{C\left[3a-MCr^2\left(1-aCr^2\right)\right]^2}$$

(36)

6. The radial sound speed is given as

$$0 \le \frac{dp_r}{d\rho} = H + \frac{K}{C^2\left[3a-MCr^2\left(1-aCr^2\right)\right]} \le 1.$$

(37)

7. At the outer boundary, the interior solution must smoothly join with the Reissner–Nordström exterior space–time as

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

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

$$e^{2\nu(r)} = 1-\frac{2M}{R}+\frac{Q^2}{R^2} \qquad (38)$$

$$e^{2\lambda(r)} = \left(1-\frac{2M}{R}+\frac{Q^2}{R^2}\right)^{-1} \qquad (39)$$

Then for the matching conditions at $r = R$, we obtain

$$\frac{2M}{R} = aCR^2 + 2C^2KR^4 - 2aKC^3R^6 \tag{40}$$

The figures 1,2,3,4,5,6,7,8, 9 and 10 represent the plots of $\frac{E^2}{2C}$, σ^2, ρ, P_r, $\frac{d\rho}{dr}$, $\frac{dP_r}{dr}$, v_{sr}^2, Δ, M and Z_s with the radial coordinate. In every graph we looked at C=1.

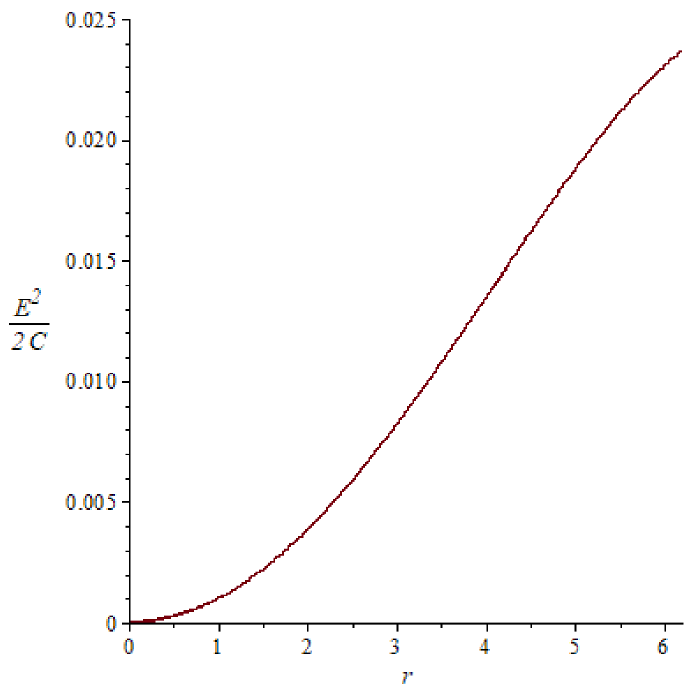

Figure 1. Electric field intensity $\frac{E^2}{2C}$ in opposition to the radial coordinate for a=0.01 and M=0.001

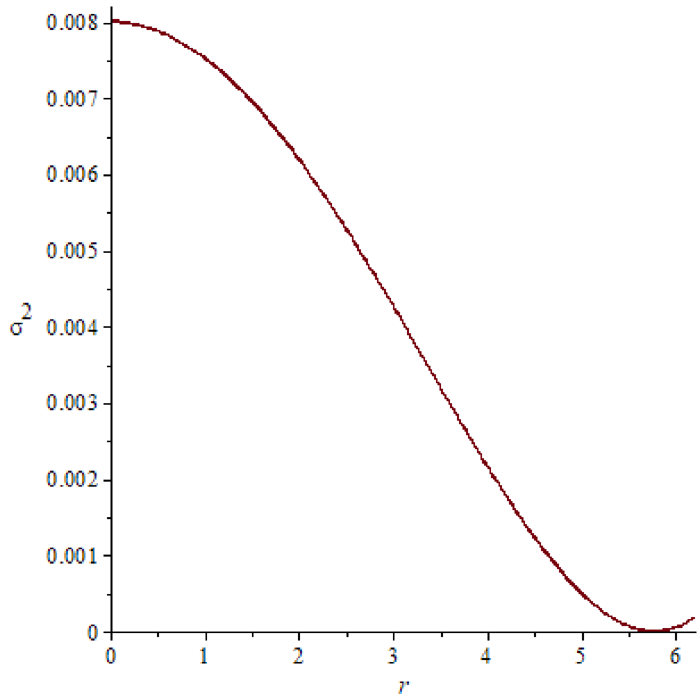

Figure 2. Charge density σ^2 in opposition to the radial parameter with a=0.01 and M=0.001

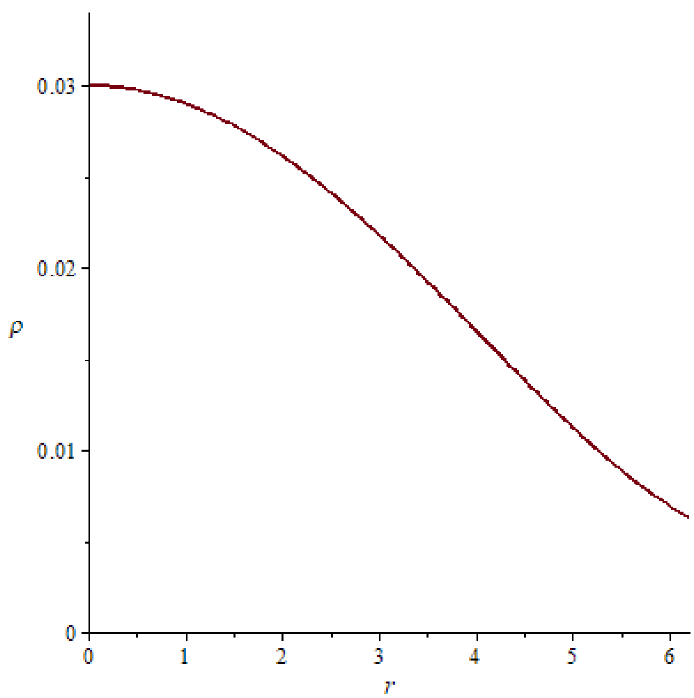

Figure 3. Energy density ρ in opposition to the radial parameter with a=0.01 and M=0.001

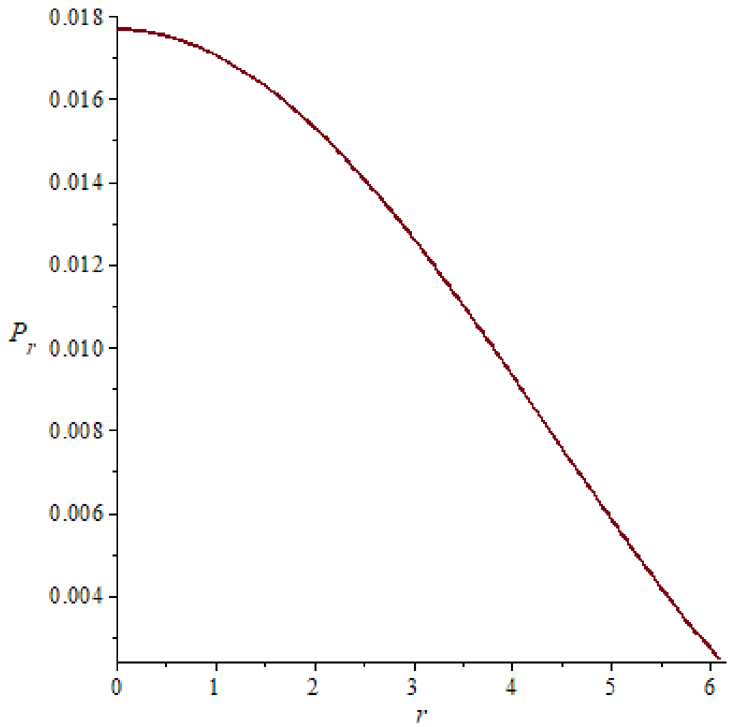

Figure 4. Radial pressure in opposition to the radial parameter with *a*= 0.01, *M*=0.0001, *H* = 0.6 and *K*=0.00001

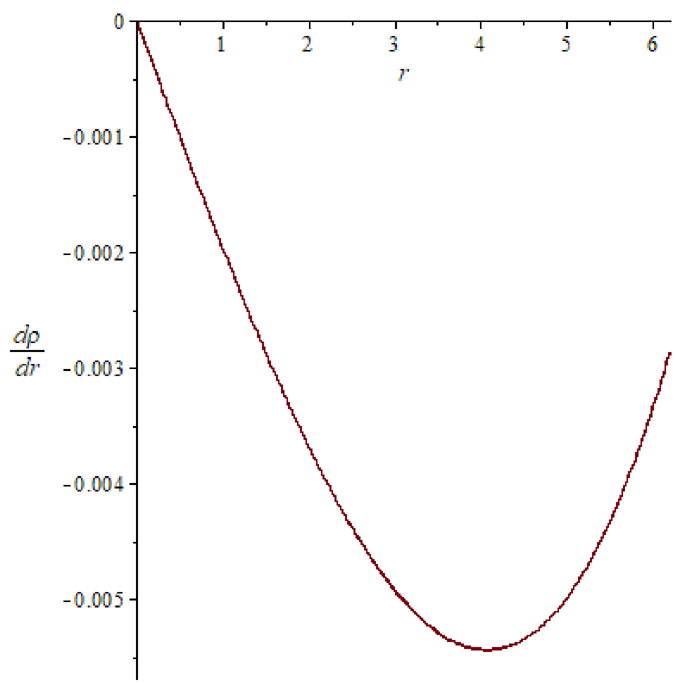

Figure 5. Gradient of energy density versus the radial coordinate with a= 0.01, M=0.001.

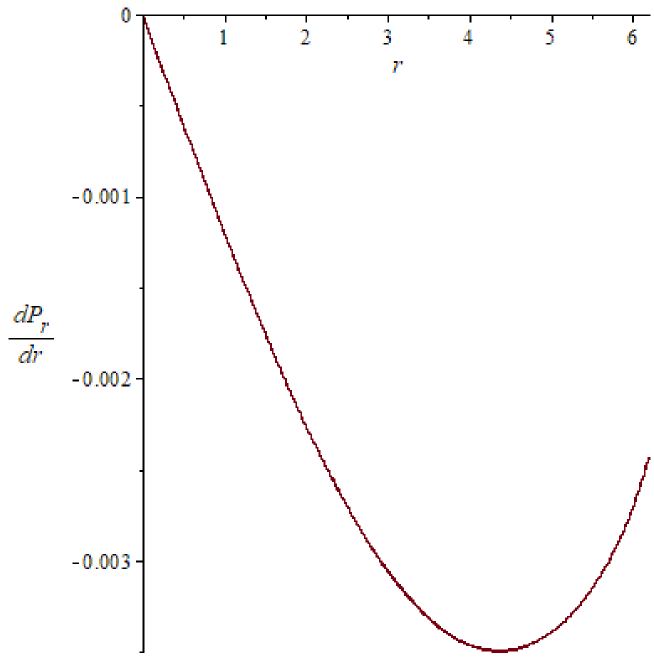

Figure 6. Gradient of radial pressure versus the radial coordinate with *a*= 0.01, *M*=0.001,

H = 0.6 , *K*=0.00001

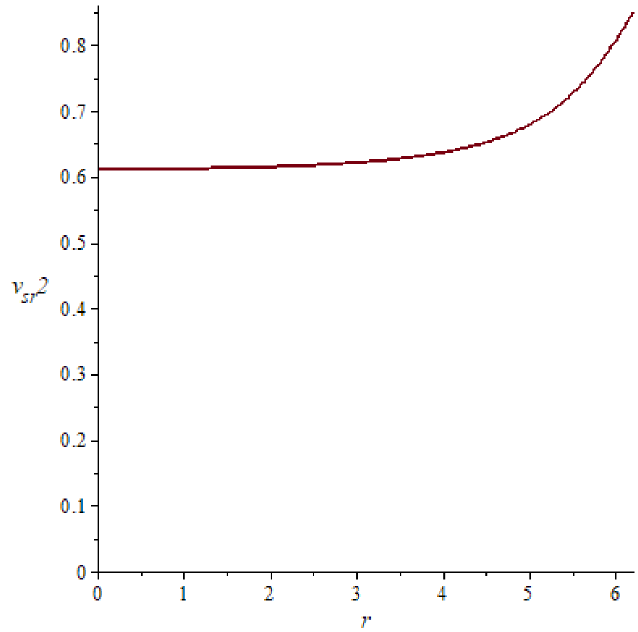

Figure 7. Radial speed sound v_{sr}^2 against the radial coordinate with *a*= 0.01, *M*=0.001, *H*= 0.6 , *K*=0.00001

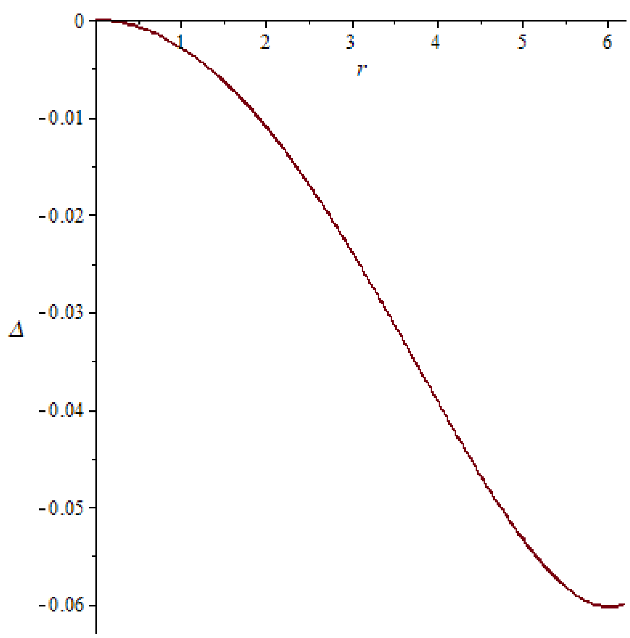

Figure 8. Anisotropy Δ against the radial coordinate with *a*= 0.01, *M*=0.001, H = 0.6 , K=0.00001

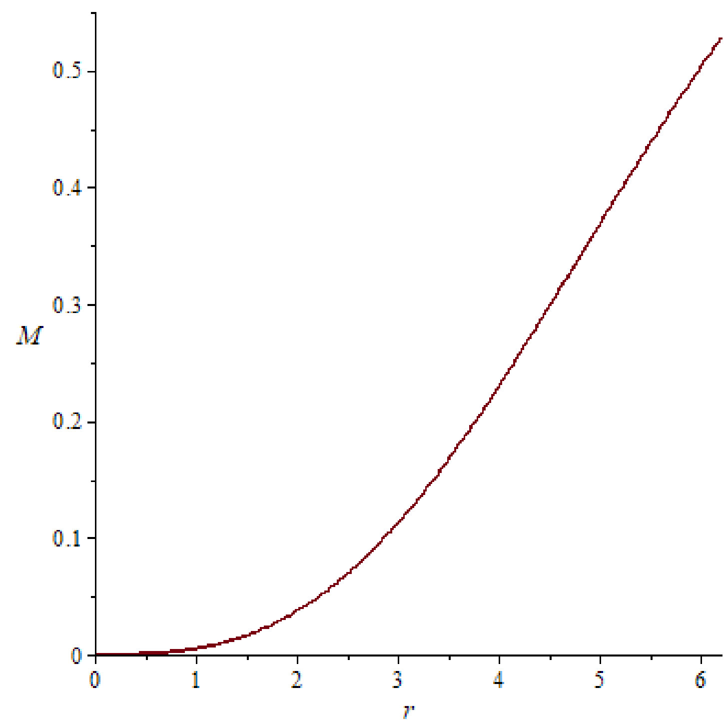

Figure 9. Mass function against the radial coordinate with *a*= 0.01, *M*=0.001

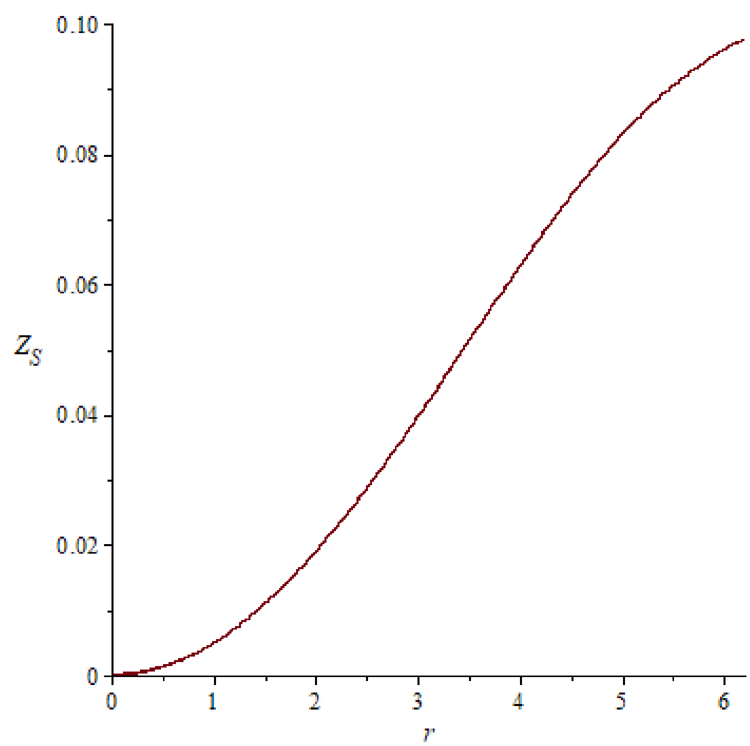

Figure 10. Surface redshift Z_S against the radial coordinate with *a*= 0.01, *M*=0.001

In Figure 1 the electric field intensity is a continuously growing function inside the star. In Figure 2 the charge density is a continuously decreasing function within the stellar interior. The energy density remains positive, continuous and is monotonically decreasingfunction in the interior of the sphere as noted in Figure 3 and the Figure 4 shows that the radial pressure is non-negative and decreases with the radial parameter. The radial variation of energy density gradient has been shown in Figure 5, in which it is observed that $\frac{d\rho}{dr} < 0$ in all the cases studied. In Figure 6 it is also shown that the profile of $\frac{dP_r}{dr}$ indicates the radial pressure gradient is negative inside the star. In Figure 7 the profile of radial speed sound is plotted with radial parameter and is noted that v_{sr}^2 as demonstrated by Delgaty and Lake, is always less than the unity and causality condition, which is a crucial physical need [70]. Plotting the anisotropic component Δ in Figure 8 reveals that it disappears at the star's center, or $\Delta(r=0)=0$. The mass function in Figure 9 is continuous, rising, takes finite values, and behaves nicely in the star interior. Figure 10 shows that the maximum value for the red-shift is $Z_S = 0.097653493$. This value is acceptable for realistic compact objects because the values for Z_S must not exceed 5.211 [71-72].

The new solution obtained can be related to particular astronomical object Lacaille 9352 which is a red dwarf. We can compare the estimated value for the mass with observational data of astrophysical object shown in Table I [73-75].

Table I. Observed and calculated values of stellar masses and surface redshift for a = 0.01 and M=0.001 .

Stellar Object	Observed mass $M(M_\Theta)$	Calculated mass $M(M_\Theta)$	Surface redshift Z_S
Lacaille 9352	0.4950	0.5270510686	0.097653493

The values found in this study using the Chaplygin equation of state for the mass, electric field and surface redshift for r system corresponding to Lacaille 9352 are regular and behave well in the stellar interior.

6. Conclusion

In this research paper, we have constructed some simple relativistic charged stellar models obtained by solving Einstein-Maxwell field equations for a static spherically symmetric locally anisotropic fluid distribution. By selecting the metric potential and electrical charge distribution, together with the Chaplygin equation of state the behavior of fluid distribution has been studied and described. These models may be used to describe compact objects and to investigate the internal structure of strange quark stars. We show that the developed confiuration meets the physical requirements for the stellar model to be effective. The graphical analysis indicates that radial pressure, energy density, mass function, and anisotropy are consistent at the origin and behave well in thge interior. The new solutions correspond with the Schwarzschild exterior metric at the boundary $r = R$, as the matter variables and gravitational potentials align with the physical analysis of the stars. This research aims to model relativistic compact objects and configurations with anisotropic matter distribution.

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