

A NEW SPHERICALLY SYMMETRIC ANISOTROPIC NEUTRON STAR MODEL USING FIELD EQUATIONS

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Abstract

In this paper, we obtain a new static spherically symmetric anisotropic fluid model of a neutron star in curvature coordinates. We consider $e^v = B(1+x)^6$, where $x = Cr^2$, by taking the value of parameter $n = 6$ in Durgapal solutions (Durgapal, 1982). The energy density, radial pressure, tangential pressure, and redshift are positive finite, and decreasing with respect to the increasing radius in this model. The pressure and density also decrease from the inner core to the crust of the object. We obtain this model by the specific choice of the constants and the anisotropy factor $\Delta P = P_r - P_t$. The central value of the anisotropy factor is zero due to the perfect fluid nature at the center of the anisotropic model and it is increasing with the increasing radius. In our analysis we take $K > \frac{3}{2}$, $l = 0.1$, $a = 1.6$ and $C = 9.44 \times 10^{-5}$. The model well behaves for the anisotropic neutron stars, which is shown analytically and graphically. The solution is free from any central singularity. We take realistic objects such as EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1 to represent our solutions graphically and numerically. We obtain this solution for $n = 6$ for the first time. Therefore, the solution is quite new and derived for the first time.

Keywords: Anisotropic Spherical Symmetry; Einstein's field equations; exact solutions; neutron stars

Introduction

In theoretical physics, the general theory of relativity is studied using mathematical models. This concept is well understood after the relativistic theory devised by Einstein. According to Einstein the massive body in space noticeably curves the spacetime around it and hence causes the formation of a gravitational field around it. Therefore, to study the gravitational field produced by a body, the

curvature in spacetime is analyzed using the concepts of differential geometry. Neutron stars, white dwarf stars, quark stars, and strange stars are some massive stars in the universe having mass as a real number multiple of the mass of the Sun. In order to study such astrophysical objects the researchers try to find the exact solutions of Einstein field equations by considering the different

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conditions and parameters. Schwarzschild gave the first solution in 1916 (Schwarzschild, 1916) just after the field equations produced by Einstein (Einstein, 1915). The solution given by Schwarzschild was an initial attempt to find the exact solutions of the field equations and was appreciated by Einstein. But, the solution given by Schwarzschild was having limitations of singularity. Nevertheless, it was a fruitful attempt and acceptable for all at the time. Tolman (Tolman, 1939) took the solutions of field equations at a different level and proposed eight solutions of the field equations. All these eight solutions were not suitable for studying the internal structure of the super dense stellar objects. But, the fourth and the seventh solutions are well known for describing the internal structure and physical properties of massive dense stellar objects.

The compact strange stars are a popular and important subject of study for researchers in general relativity. In the recent past Li (Li *et al.*, 1999) checked if SAX J1808.4-3658 is a strange star, Thirukkanesh (Thirukkanesh and Ragel, 2013) derived a class of exact strange quark star model, Deb (Deb *et al.*, 2017) gave relativistic model for strange stars, Malaver (Malaver, 2014) created strange quark star model with quadratic equation of state, Islam (Islam *et al.*, 2019) developed analytical model of strange star in Durgapal spacetime, Szkudlarek (Szkudlarek *et al.*, 2019) derived the maximum mass of differentially rotating strange quark stars, Szkudlarek (Szkudlarek *et al.*, 2019) did fully relativistic numerical calculations of differentially rotating strange quark stars model, Goswami (Goswami *et al.*, 2020) devised a new class of relativistic anisotropic strange star in Vaidya-Tikekar model, Bordbar (Bordbar *et al.*, 2019) calculated the strange star structure, Tamta (Tamta and Fuloria, 2022) suggested physically realizable anisotropic strange star model, Hansraj (Hansraj *et al.*, 2022) tested strange stars in the framework of higher curvature gravity, Maurya (Maurya *et al.*, 2022) produced gravitationally decoupled strange star model, Molla (Molla *et al.*, 2022) proposed an analytical model to study strange stars.

It is not only a matter of interest as a whole of the object but also studied for the individual physical property. Harko (Harko and Cheng, 2002) calculated the maximum mass and radius of strange stars in the linear approximation of EOS. In this series of researchers, many others gave notable theoretical frameworks and models to study the massive compact bodies in space (Herrera *et al.*, 2009; Sana *et al.*, 2010; Borissova *et al.*, 2012; Maurya and Gupta, 2012; Tewari, 2013; Maurya and Gupta, 2014; Tewari and Charan, 2015a; 2015b; Tewari *et al.*, 2016; Messineo *et al.*, 2016).

The radial pressure of fluid distribution may be different from the tangential pressure which may lead to anisotropy in pressure (Fulara and Sah, 2018). This anisotropy is led by the various physical phenomena inside the body and the internal structure of the body. Most of the researchers considered the local anisotropy to find the solutions (Singh *et al.*, 2018; Bhar, 2019; Bhar *et al.*, 2021; Bhar and Rej, 2021; Das *et al.*, 2021; Deb *et al.*, 2021; Mustafa *et al.*, 2022). The anisotropy in fluid affects a number of physical properties including the mass and surface red-shift (Ali *et al.*, 2005; Karmakar *et al.*, 2007; Delliou *et al.*, 2020; Samuroff *et al.*, 2020). The non-singular and physically acceptable solutions are important in studying massive compact stellar objects. One non-singular physically acceptable solution was given by Sah (Sah and Chandra, 2016).

All the above work motivated us to take Durgapal metric to develop a neutron star model. In this paper, we took $n = 6$ in Durgapal model because the higher value of n produces more accurate physical characteristics of the neutron stars (Durgapal, 1982), we also considered the anisotropy factor of the compact stars. Kaur (Kaur and Shukla, 2022) took $n = 6$ to develop a new class of charged spherically symmetric and static superdense star configuration. The entire work of this paper is distributed into six sections. In the second section, we calculated the anisotropy factor. In the third section, we discussed the physical acceptability conditions. In the fourth section, we calculated the exact solutions of the field equations. In the fifth section we discussed the properties of new solutions and in the sixth section, we calculated the numerical values of different physical components.

Einstein Field Equations and Anisotropy Factor

The equations of gravity and geometry of spacetime are given by non-linear differential equations

$$R_{ij} - \frac{1}{2}Rg_{ij} = -\frac{8\pi G}{c^4}T_{ij}, \quad (1)$$

where R_{ij} is the Ricci tensor, R is the Ricci scalar, g_{ij} is the metric tensor and T_{ij} is the energy-momentum tensor. This tensor is defined as follows for an anisotropic fluid distribution

$$T_{ij} = (\rho + P_r)u_i u_j - P_r g_{ij} + (P_r - P_t)x_i x_j, \quad (2)$$

where ρ is energy density, P_r is radial pressure, P_t is tangential pressure for an anisotropic fluid

distribution and perpendicular to the four-velocity u_i , x_i is a unit vector along the radial vector, u_j , x_j are the four-velocity and unit vector in the tangential direction, and g_{ij} is metric tensor, satisfying the following condition

$$g_{ij}u^iu^j = 1. \quad (3)$$

The line element for spherically symmetric fluid distribution can be given as

$$ds^2 = g_{tt}dt^2 - g_{ij}dx^i dx^j, \quad (4)$$

where $(i; j) = r, \theta, \phi$ in the coordinate system (t, r, θ, ϕ) , and

$$\begin{aligned} g_{tt} &= e^\nu, & g_{rr} &= -e^{-\lambda}, & g_{\theta\theta} &= -r^2, \\ g_{\phi\phi} &= -r^2 \sin^2 \theta & g_{ij} &= 0, \text{ if } i \neq j, \end{aligned} \quad (5)$$

where ν and λ are the functions of r only.

Taking Equations (2) and (3) to calculate the different components and putting in Equation (1), we obtain the following field equations

$$\frac{8\pi G}{c^4} \rho = e^{-\lambda} \left(\frac{\lambda'}{r} - \frac{1}{r^2} \right) + \frac{1}{r^2}, \quad (6)$$

$$\frac{8\pi G}{c^4} P_r = e^{-\lambda} \left(\frac{\nu'}{r} + \frac{1}{r^2} \right) - \frac{1}{r^2}, \quad (7)$$

$$\frac{8\pi G}{c^4} P_t = e^{-\lambda} \left(\frac{1}{2} \nu'' + \frac{1}{4} \nu'^2 - \frac{1}{4} \nu' \lambda' + \frac{\nu' - \lambda'}{2r} \right). \quad (8)$$

If we subtract Equation (8) from Equation (7) we get the following equation

$$\begin{aligned} \frac{8\pi G}{c^4} (P_r - P_t) &= e^{-\lambda} \left(\frac{\nu'}{r} + \frac{1}{r^2} - \frac{1}{2} \nu'' - \frac{1}{4} \nu'^2 + \right. \\ &\left. \frac{1}{4} \nu' \lambda' - \frac{\nu' - \lambda'}{2r} \right) - \frac{1}{r^2}. \end{aligned} \quad (9)$$

Considering $\Delta P = \frac{8\pi G}{c^4} (P_r - P_t)$, we may re-write Equation (9) as follows

$$\Delta P = e^{-\lambda} \lambda' \left(\frac{1}{4} \nu' + \frac{1}{2r} \right) - e^{-\lambda} \left(\frac{1}{2} \nu'' + \frac{1}{4} \nu'^2 - \frac{\nu'}{2r} - \frac{1}{r^2} \right) - \frac{1}{r^2}. \quad (10)$$

Now, considering $e^{-\lambda} = Z$ and $e^\nu = B(1 + x)^6$, where $B > 0$ is a constant, C is any constant, and $x = Cr^2$. Therefore, Equation (10) becomes

$$\frac{dZ}{dx} + \frac{23x^2 - 2x - 1}{x(1+x)(1+7x)} Z + \frac{1+x}{1+7x} \left(\frac{1}{x} - \frac{\Delta P}{C} \right) = 0. \quad (11)$$

This is the governing equation including the anisotropy factor.

The Physical Acceptability Conditions of the Solutions

The solution in the curvature coordinate can be considered well-behaved if the following conditions are satisfied by the solution:

The solution is free from all the singularities e.g., geometrical and physical singularities. It must be free from infinite and negative values of the physical components at the center that is pressure density and e^λ and e^ν .

The pressure and density obtained through the solution should be monotonically decreasing with respect to the radius of the object. The pressure-density ratio must be less than 1 in the weak energy condition and must be less than $\frac{1}{3}$ in the strong energy condition and must be equal to $\frac{1}{3}$ in the maximum energy condition (Bowers and Liang, 1974).

The red shift must be finite-positive and monotonically decreasing with respect to the radius of the object.

As the radial and tangential pressure is equal at the center of the object so the anisotropy factor must be zero at the center of the object and must be increasing as we move towards the crust of the object.

A New Class of Exact Solutions

The exact solution of equation (11) gives the expression for $e^{-\lambda}$. We assume to solve Equation (11) as follows

$$\frac{\Delta P}{C} = \frac{ax(1+7x)^{-l/7}}{(1+x)^5}, \quad (12)$$

where $a, l \geq 0$ are constants and are real numbers. We considered the anisotropy factor in such a way that it is always positive beyond the center and zero at the center, which is quite natural in the case of an anisotropic fluid. Moreover, Equation (11) is easily solvable with this assumption. In this way, the solutions which we obtain from Equation (12) are physically valid. To verify the validity of the solution we examine the value of anisotropy from the inner core of the sphere of fluid towards the crust. We observe that the anisotropy increases with the increasing radius. Now, putting the value of $\frac{\Delta P}{C}$

from Equation (12) into Equation (11) we obtain the following solution

$$e^{-\lambda} = \frac{1}{(1+x)^4} \left(-\frac{x^4+7x^3+24x^2+103x-23}{23} + \frac{ax(1+7x)^{-l/7}}{2-l} \right) + \frac{Ax}{(1+x)^4(1+7x)^{2/7}}, \quad (13)$$

where A is an integration constant.

We can obtain the expression for density and pressure with the solution given in Equation (13)

$$\frac{8\pi G}{c^4} P_r = -\frac{12Ax^4+84x^3+288x^2+1236x-276}{23(1+x)^5} - \frac{103+23A+24x+7x^2+x^3}{23(1+x)^4} + \frac{13a(1+7x)^{-l/7}}{(2-l)(1+x)^5} + \frac{(12Ax-1)(1+7x)^{-l/7}}{(1+x)^5}, \quad (14)$$

and

$$\frac{8\pi G}{c^4} P_t = \frac{8\pi G}{c^4} P_r + \frac{ax(1+7x)^{-l/7}}{(1+x)^6}, \quad (15)$$

$$\frac{8\pi G}{c^2} \rho = -\frac{12-46A+46Ax+358x+63x^2+20x^3+3x^4}{23(1+x)^5} + \frac{a(1+7x)^{-l/7}(lx^2+(l-2)x+2)}{(2-l)(1+x)^5}. \quad (16)$$

Equations (14), (15), and (16) are the non-singular equations of radial pressure, tangential pressure, and energy density, respectively. Figure 1 shows the variation of $e^{-\lambda}$, Figure 2 shows e^{ν} , Figure 3 shows radial pressure, Figure 4 shows the energy density and Figure 5 shows the change in anisotropy factor for the compact stars EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1.

The expression for the mass can be given as follows

$$M = \frac{c^2 r}{2G} [B(1+x)^6 - 1]. \quad (17)$$

Properties of the Solution

The pressure and the density at the center of the anisotropic fluid object can be given by

$$\frac{8\pi G}{c^4} P_r = \frac{8\pi G}{c^4} P_t = \frac{356}{23} + \frac{12a}{2-l} + A. \quad (18)$$

$$\frac{8\pi G}{c^2} \rho = \frac{12}{23} + \frac{2a}{2-l} - 2A. \quad (19)$$

From the pressure and density equations (17) and (18) at $r = 0$, it is clear that the pressure and density are finite at the center of the anisotropic fluid object; hence, our solution is free from the singularity at the center. Moreover, the pressure and the density decrease from the inner core to the crust of the object.

The expression for the gravitational redshift may be given as

$$z = \frac{1-e^{\nu/2}}{e^{\nu/2}} = \frac{1-\sqrt{B}(1+x)^3}{\sqrt{B}(1+x)^3}. \quad (20)$$

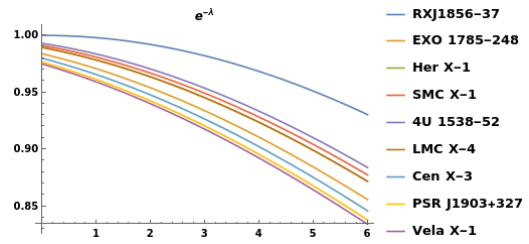


Figure 1. Plot of $e^{-\lambda}$ for EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1

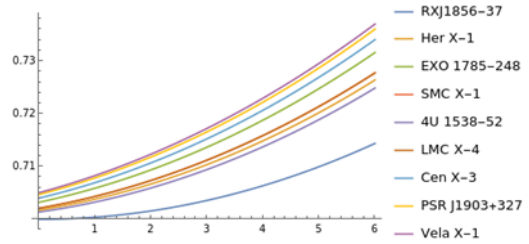


Figure 2. Plot of e^{ν} for EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1

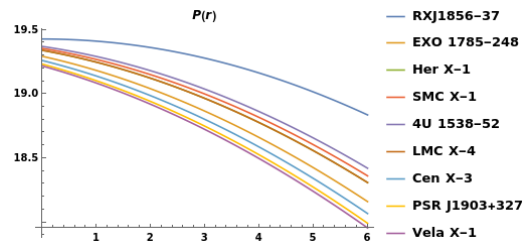


Figure 3. Plot of radial pressure for EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1

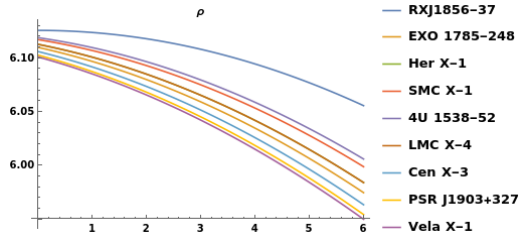


Figure 4. Plot of energy density for EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1

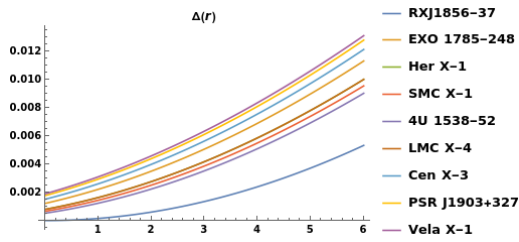


Figure 5. Plot of change in anisotropy factor for EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1

The value of the redshift must be greater than zero and finite at the center of the anisotropic fluid object. Therefore, the value of B must be less than 1 that is $B < 1$. The adiabatic index can be given by

$$\gamma = \left(\frac{P_r + \rho}{P_r} \right) \frac{dP_r}{d\rho}. \quad (21)$$

From Equation (21) we obtain

$$\gamma P_r = (P_r + \rho) \frac{dP_r}{d\rho} = K, \quad (22)$$

where K is called compression moduli, which can be used to determine the density of the object made up of the anisotropic fluid. The density should be maximum at the center and it must decrease when moving toward the surface of the object. Hence, the compression moduli should be maximum at the center and decreasing towards the surface.

The pressure and density are decreasing from the inner core of the neutron star to the crust that is

$$\left[\frac{8\pi G}{Cc^4} \frac{d^2 P_r}{dx^2} \right] < 0; \left[\frac{8\pi G}{Cc^4} \frac{d^2 P_t}{dx^2} \right] < 0; \left[\frac{8\pi G}{Cc^4} \frac{d^2 \rho}{dx^2} \right] < 0; \quad \text{at } r = 0.$$

The square of speed of sound is given by

$$v_r^2 = \frac{dP_r}{d\rho}; \quad v_t^2 = \frac{dP_t}{d\rho},$$

v_r^2 and v_t^2 must have the values less than that of square of the speed of light that is c^2 , to meet the causality condition and the stability factor must satisfy $0 < |v_t^2 - v_r^2| < 1$ (Andréasson, 2009).

Boundary Conditions

The interior solution obtained for the neutron stars should be matched with the Schwarzschild metric at the boundary. The Schwarzschild metric is given as follows

$$ds^2 = \left(1 - \frac{2GM}{c^2 r} \right) c^2 dt^2 - \left(1 - \frac{2GM}{c^2 r} \right)^{-1} dr^2 - r^2 d\theta^2 - r^2 \sin^2 \theta d\phi^2. \quad (23)$$

where M is the mass of neutron star.

If e^λ and e^ν are continuous at the boundary then these components at the boundary $r = r_b$ can be given as

$$e^{\nu_b} = \left(1 - \frac{2GM}{c^2 r_b} \right) c^2 = B(1 + x)^6. \quad (24)$$

$$e^{-\lambda_b} = \left(1 - \frac{2GM}{c^2 r_b} \right) = Y(x). \quad (25)$$

Where e^{ν_b} and $e^{-\lambda_b}$ represents the e^ν and $e^{-\lambda}$, respectively at the boundary, also $x = X = Cr_b^2$ at the boundary. As the pressure at the boundary is zero, so

$$P_r(r = r_b) = 0, \quad (26)$$

we can obtain the value of A using the condition of Equation (26) as follows

$$A = \frac{1}{12X^4 + 276X(1+7X)^{-1/7} + 23X + 23} \left(23(1+7X)^{-1/7} - (X^4 + 92X^3 + 319X^2 + 1390X - 173) - \frac{299a(1+7X)^{-1/7}}{2-l} \right). \quad (27)$$

$$B = \frac{1}{(1+X)^9} \left(\frac{X^4 + 7X^3 + 24X^2 + 103X - 23}{23} + \frac{aX(1+7X)^{-1/7}}{2-l} \right) + \frac{AX}{(1+X)^4}. \quad (28)$$

The mass of the neutron star can be given as

$$M = \frac{c^2 r_b}{2G} [B(1 + X)^6 - 1]. \quad (29)$$

Table 1. The various components of the compact stars such as x , $\frac{P_r}{\rho}$, mass, and radius

Compact Stars	Radius (Km)	Mass	Reference	$x = Cr^2$	$\left(\frac{P_r}{\rho}\right)_{=r}$
EXO 1785-248	8.849	1.3	Özel <i>et al.</i> (2009)	0.0073919	0.0074160
SMC X-1	8.301	1.04	Singh <i>et al.</i> (2016)	0.0065047	0.0084596
Her X-1	8.1	0.85	Singh <i>et al.</i> (2016)	0.0061935	0.0088979
4U 1538-52	7.866	0.87	Rawls <i>et al.</i> (2011)	0.0058430	0.0094548
LMC X-4	8.301	1.29	Rawls <i>et al.</i> (2011)	0.0065047	0.0084596
RX J1856-37	6.0	0.9663	Singh <i>et al.</i> (2016)	0.0033984	0.0166786
Cen X-3	9.178	1.49	Rawls <i>et al.</i> (2011)	0.0079510	0.0068806
PSR J1903+327	9.438	1.667	Maurya <i>et al.</i> (2015)	0.0084087	0.0064977
Vela X-1	9.56	1.77	Rawls <i>et al.</i> (2011)	0.0086275	0.0063288

The surface density of the neutron star can be expressed as

$$\frac{8\pi G}{Xc^2} \rho_b r_b^2 = \frac{1}{(1+X)^5} \left\{ \frac{3X^4 + 20X^3 + 63X^2 + 358X + 464X - 464 + 12}{23} + \frac{a(1+7X)^{-\frac{l}{7}}(lX^2 + (l-2)X + 2)}{l-2} \right\}. \quad (30)$$

The Numerical Approximation

We calculated the various components of EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1 by taking our solution for these anisotropic stars model. We took $C = 9.44 \times 10^{-5}$, $\alpha = 1.6$, $A = -1.96$ and $l = 0.1$. The values of the components are listed in Table 1.

The value of the ratio of the radial pressure and energy density is decreasing for the stars having a larger radius. The value of x is also decreasing when we take the compact stars from the smaller radius to the larger radius. Therefore, these components are having maximum values for the compact stars which are having a smallest radius.

Conclusions

In this paper, we have obtained a new exact solution for an anisotropic compact star model which satisfies the physical conditions and produces results similar to the results obtained practically. Our solution does not have central singularity with the exterior spacetime in the well-known Schwarzschild metric. We followed the assumption $e^\nu = B(1+x)^n$ given by Durgapal (Durgapal, 1982) beyond his 5th model and we took $e^\nu = B(1+x)^6$.

The physical property and the stability of the model given by us can be observed in Figure 1, Figure 2, Figure 3, Figure 4, and Figure 5. From all

these figures it is manifestly clear that the metric components are free from geometrical and physical singularities. Moreover, we calculated the value of $\frac{P_r}{\rho}$ on the surface of the compact stars EXO 1785-248, SMC X-1, Her X-1, 4U 1538-52, LMC X-4, RX J1856-37, Cen X-3, PSR J1903-327, and Vela X-1. We found that the ratio is decreasing as the radius increases. Therefore, the ratio is largest for the compact stars having the smallest radius. Similarly, the value of x is also decreasing for increasing radius. We also determined the redshift for our solution. The mass and the redshift for our model is $M = \frac{c^2 r_b}{2G} [B(1+X)^6 - 1]$ and $\frac{1 - \sqrt{B(1+x)^3}}{\sqrt{B(1+x)^3}}$, respectively. We also calculated the adiabatic index as $\gamma = \left(\frac{P_r + \rho}{P_r}\right) \frac{dP_r}{d\rho}$. The radial pressure, tangential pressure, and density are the functions of r and monotonically decreasing having positive finite values. The anisotropy factor vanishes at the center of a compact star which is a realistic property of an anisotropic star.

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