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A new exact solution for anisotropic compact stellar objects of embedding class I space time

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ABSTRACT

In the present article we explore a new anisotropic solution for Einstein field equations for compact star models using embedding class-I space time. The solution is free from any singularities and satisfies all well behaved conditions, hence suitable for the modelling of super dense stars. Various features of present models are described analytically and with the help of graphical representation also. Present compact stellar models are quite compatible with the observational data of compact objects like PSRJ1903+327 and PSRJ 1614-2230.

Keywords Anisotropy, Compact stars, Embedding class I, Exact solution, General Relativity.

I. INTRODUCTION

Gravitational contraction is a collapse of a star under the influence of its own gravitational force. It is the basic mechanism which is responsible for the generation of compact stellar objects. When the cloud of interstellar matter suffers from continuous contraction a compact star is formed. During this contraction the temperature inside the star increases and thermonuclear fusion starts inside the star, it generates the thermal pressure which counterbalances the inward gravitational force. This condition is known as hydrostatic equilibrium condition. The thermal pressure inside the star arises due to both the gas and radiation present inside the stellar structure. In gravitational collapse half of the total energy produced increases the internal energy of the star and other half escapes from the star as radiation. When all of the energy sources exhausted the star again starts collapsing until the equilibrium condition is reached again. The stellar structure suffers various phases of contraction and expansion until the stability condition is reached .The stellar remnants obtained after this gravitational collapse are always a topic of immense interest. There is an equal probability of generation of neutron star and strange stars after such contraction process. The neutrons are responsible for the composition of neutron stars while the strange stars are structured by the u, d and s quarks .The structure of these strange stars can be figured in two ways first by the quark hadrons phase transition in the early universe and second at high densities some neutron stars converted into strange stars [1].

To study the nature and composition of such compact structures has become a field of immense interest in recent years. During the supernova explosion of massive star when the density becomes higher than the nuclear density there is a phase transition between hadronic and strange quark matter [2].Herrera and Santos [3] have shown the various effects of anisotropy on pressure in which the pressure inside the fluid sphere can be decomposed into two parts, the radial pressure p_r and transverse pressure p_t. Their difference measures the

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anisotropy and this anisotropy arises due to many reasons ,some of them are the existence of solid core, the presence of type P super fluid, phase transition, mixture of two fluid , existence of external field etc.[4][5]. Ruderman [6] also studied the various features of compact stellar models and concluded that anisotropy occurs when the density range is of the order of 10^{15} gm/cm^3.By considering the concept of anisotropy factor Newton Singh & Pant [7] have proposed a class of exact solutions for anisotropic stellar structures. Sharma and Maharaj [8] have given a new exact solution of Einstein's field equation by introducing anisotropy conditions. Bowers and Liang [9] also studied the spherically symmetric solutions of Einstein's field equation by considering the pressure anisotropy inside the fluid sphere. Li et. al [10] also studied the structure equations and stability conditions of compact stellar configurations structured from the Bose Einstein's condensation of dark matter. Bhar et.al [11] introduced a new model of compact star by considering Tolmann VII gravitational potential for g_{rr} metric. Eddingoton [12] predicted that the four dimensional space time can be embedded in higher dimensional flat space .Our new solution also satisfies the hydrostatic equilibrium, stability and energy conditions.

Motivated by the preceding work of Ksh Newton Singh et.al.[13] we have developed a new model of compact star by using the Karmarkar's condition[14]. The work is organized as follows: sect.2 contains Einstein's field equation for perfect fluid sphere. In sect.3 we have generated a new solution for anisotropic embedding class 1 relativistic stellar model. Sect.4 contains physical analysis of the new solution for relativistic stellar model. The exterior space time and matching conditions of exterior and interior space time are discussed in sect. 5.Results and conclusions are discussed in section 6.

II. EINSTEIN FIELD EQUATIONS FOR ANISOTROPIC FLUID SPHERE

The spherically symmetric interior space time for anisotropic fluid sphere is defined by the Schwarzschild canonical coordinate given as

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

Here v and λ are assumed to be the function of radial coordinate r.

The energy momentum tensor for anisotropic compact star can be considered as

$$T_{\mu\nu} = \rho v_\mu v_\nu + p_r \chi_\mu \chi_\nu + p_t(v_\mu v_\nu - \chi_\mu \chi_\nu - g_{\mu\nu}) \quad (2)$$

Where the symbols have their usual meaning .For the line element given by equation (1) and energy momentum tensor given by equation (2) Einstein's field equations can be written as-

$$8\pi\, p_r = \frac{v' e^{-\lambda}}{r} - \frac{(1-e^{-\lambda})}{r^2} \quad (3)$$

$$8\pi\, p_t = \frac{e^{-\lambda}}{4}\left(2v'' + v'^2 - v'\lambda' + \frac{2v'}{r} - \frac{2\lambda'}{r}\right) \quad (4)$$

$$8\pi\rho = \frac{1-e^{-\lambda}}{r^2} + \frac{\lambda' e^{-\lambda}}{r} \quad (5)$$

On subtracting equation (3) from (4) the anisotropic factor Δ is obtained as-

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$$8\pi(p_t - p_r) = \Delta = e^{-\lambda}\left(\frac{v''}{2} - \frac{\lambda' v'}{4} + \frac{v'^2}{4} - \frac{v' + \lambda'}{2r} + \frac{e^{\lambda} - 1}{r^2}\right) \tag{6}$$

2.1. The Karmarkar condition

If a symmetric tensor $b_{\mu\nu}$ satisfies the Gauss and Codazzi condition [15] any 4-dimensional Riemannian space can be embedded into a 5-dimensional Pseudo-Euclidean space expressed as

$$R_{\mu\nu\alpha\beta} = \in (b_{\mu\alpha} b_{\nu\beta} - b_{\mu\beta} b_{\nu\alpha}) \tag{7}$$

$$b_{\mu\nu;\alpha} - b_{\mu\alpha;\nu} = 0 \tag{8}$$

Here the value of Є=+1 when the normal to the manifold is space like and Є=-1 when the normal to the manifold is time like. The symbol (;) represent covariant derivatives. For the Schwarz child's line element given by equation (1) the components of Riemann curvature tensor are expressed as-

$$R_{1414} = -e^{\nu}\left(\frac{v''}{2} + \frac{v'^2}{4} - \frac{\lambda' v'}{4}\right) \tag{9}$$

$$R_{2323} = -e^{\lambda} r^2 \sin^2\theta (e^{\lambda} - 1) \tag{10}$$

$$R_{1334} = R_{1224} \sin^2\theta = 0 \tag{11}$$

$$R_{1212} = \frac{1}{2} r \lambda' \tag{12}$$

$$R_{3434} = -\frac{1}{2} r \sin^2\theta v' e^{\nu - \lambda} \tag{13}$$

On eliminating the components of $b_{\mu\nu}$ from equation (7) we obtain

$$R_{1414} R_{2323} = R_{1212} R_{3434} + R_{1224} R_{1334} \tag{14}$$

Here we use the line element satisfying the Karmarkar's condition as-

$$ds^2 = e^{\nu} dt^2 - dr^2 - r^2 (d\theta^2 + \sin^2\theta d\phi^2) \tag{15}$$

On substituting equations (9)-(13) in (14) we obtain a differential equation given as-

$$\frac{2v''}{v'} + v' = \frac{\lambda' e^{\lambda}}{e^{\lambda} - 1} \tag{16}$$

On integration we get a relationship between ν and λ as

$$e^{\nu} = \left(A + B\int \sqrt{e^{\lambda} - 1}\ dr\right)^2 \tag{17}$$

Here A and B are constants of integration. Using equation (17) equation (6) can be rewritten as

$$\Delta = \frac{v'}{4e^{\lambda}}\left[\frac{2}{r} - \frac{\lambda'}{e^{\lambda} - 1}\right]\left[\frac{v' e^{\nu}}{2rB^2} - 1\right] \tag{18}$$

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III. GENERATING A NEW SOLUTION FOR ANISOTROPIC EMBEDDING CLASS-I RELATIVISTIC STELLAR MODEL

To solve equation (17) a metric potential is assumed as

$$e^{\lambda} = 1 + ar^2\{\cos ec^2(br^2 + c) + 1\}^2 \tag{19}$$

Here a and b are constants, which have the dimensions of length^{-2} .Substituting the value of this metric potential in equation (17)

$$e^{\nu} = \left[A + \frac{B\sqrt{a}}{2b}\{br^2 - \cot(br^2 + c)\} \right]^2 \tag{20}$$

Using these values of metric potentials (19) and (20) $P_{r,}$ Δ, P_t and ρ can be expressed as-

$$8\pi p_r = \frac{\{(1 + \cos ec^2(br^2 + c))\}}{[1 + ar^2\{(\cos ec^2(br^2 + c) + 1)\}^2]} \left[\frac{2B\sqrt{a}}{\left[A + \frac{B\sqrt{a}}{2b}\{(br^2 - \cot(br^2 + c))\} \right]} - a\{\cos ec^2(br^2 + c) + 1\} \right] \tag{21}$$

$$\Delta = \{[a(1 + \cos ec^2(br^2 + c)U(r) - B\sqrt{a}]\} \left[\frac{ar^2\{\cos ec^2(br^2 + c) + 1\}^3 + 4br^2 \cos ec^2(br^2 + c)\cot(br^2 + c)}{U(r)V^2(r)} \right] \tag{22}$$

$$8\pi\, p_t = 8\pi\, p_r + \Delta \tag{23}$$

And

$$8\pi\rho = \left[\frac{a\{1 + \cos ec^2(br^2 + c)\}}{[1 + ar^2\{1 + \cos ec^2(br^2 + c)\}^2]} \right] \left[\frac{2\{(1 + \cos ec^2(br^2 + c) - 4br^2 \cos ec^2(br^2 + c)\cot(br^2 + c))\}}{1 + ar^2\{\cos ec^2(br^2 + c) + 1\}^2} + a\{1 + \cos ec^2(br^2 + c)\} \right] \tag{24}$$

Here

$$U(r) = A + \frac{B\sqrt{a}}{2b}\{br^2 - \cot(br^2 + c)\} \tag{25}$$

Now the pressure and density gradients can be expressed as-

$$V(r) = 1 + ar^2\{\cos ec^2(br^2 + c) + 1\}^2 \tag{26}$$

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$$8\pi\frac{d\rho}{dr}=\left(\frac{-4abrV(r)\cos ec^2(br^2+c)\cot(br^2+c)-aV'(r)\{1+\cos ec^2(br^2+c)\}}{V^2(r)}\right)$$
$$\left(\frac{2\{1+\cos ec^2(br^2+c)-4br^2\cos ec^2(br^2+c)\cot(br^2+c)}{V(r)}+\{1+\cos ec^2(br^2+c)\}\right)$$
$$+\left(\frac{\{1+\cos ec^2(br^2+c)\}}{V(r)}\right)$$
$$\left(\frac{\begin{array}{l}2V(r)\{-12br\cos ec^2(br^2+c)\cot(br^2+c)+16b^2r^3\cos ec^2(br^2+c)\cot^2(br^2+c)\\+8b^2r^3\cos ec^4(br+c)\}\\-2V'(r)\{1+\cos ec^2(br^2+c)-4br^2\cos ec^2(br^2+c)\cot(br^2+c)\}\end{array}}{V(r)}\right) \tag{27}$$

$$8\pi\frac{dp_r}{dr}=\left(\frac{2B\sqrt{a}}{U(r)}-a\{\cos ec^2(br^2+c)+1\}\right)$$
$$\left(\frac{-4brV(r)\cos ec^2(br^2+c)\cot(br^2+c)-\{1+\cos ec^2(br^2+c)\}^2V'(r)}{V^2(r)}\right)$$
$$+\left(\frac{1+\cos ec^2(br^2+c)}{V(r)}\right)\left(\frac{-2B\sqrt{a}\,U'(r)}{U^2(r)}+4abr\cos ec^2(br^2+c)\cot(br^2+c)\right) \tag{28}$$

and

$$8\pi\frac{dp_t}{dr}=8\pi\frac{dp_r}{dr}+\frac{d\Delta}{dr} \tag{29}$$

Here

$$\frac{d\Delta}{dr} = \left\{a(1+\cos ec^2(br^2+c))U(r) - B\sqrt{a}\right\}$$

$$\left[\frac{\begin{array}{l}2rU(r)V(r)[a\{\cos ec^2(br^2+c)+1\}^3 - 6abr^2\{\cos ec^2(br^2+c)+1\}^3 \\ \cos ec^2(br^2+c)\cot(br^2+c) + 4b\cos ec^2(br^2+c)\cot(br^2+c) \\ -8b^2r^2\cos ec^2(br^2+c)\cot^2(br^2+c) - 4b^2r^2\cos ec^4(br^2+c)] \\ -[ar^2\{\cos ec^2(br^2+c)\}^3 + 4br^2\cos ec^2(br^2+c)\cot(br+c)\}] \\ \qquad [U'(r)V(r) + 2U(r)V'(r)]\end{array}}{U^2(r)\ \ V^3(r)}\right]$$

$$+\left[\left\{\frac{ar^2\{\cos ec^2(br^2+c)+1\}^3 + 4br^2\cos ec^2(br^2+c)\cot(br^2+c)}{U(r)V^2(r)}\right\}\right]$$
$$\left[\left\{a\{1+\cos ec^2(br^2+c)\}U'(r) - 4abr\cos ec^2(br^2+c)\cot(br^2+c)U(r)\right\}\right] \tag{30}$$

IV. PHYSICAL PROPERTIES OF THE NEW SOLUTION FOR RELATIVISTIC STELLAR MODEL

Values of p_r , p_t and ρ at the centre are given as

$$8\pi\, p_{rc} = 8\pi\, p_{tc} = \frac{2B\sqrt{a}(1+\cos ec^2 c)}{A - \dfrac{B\sqrt{a}}{2b}\cot c} - a(1+\cos ec^2 c)^2 > 0 \tag{31}$$

$$8\pi\rho_c = 3a(1+\cos ec^2 c)^2 \quad > 0\,; \qquad \forall a > 0 \tag{32}$$

Zeldovich’s condition[16] at the interior of the star is satisfied if and only if p_r/ρ at the centre must be ≤1.Hence we have

$$\frac{B}{A} \le \frac{2\sqrt{a}b(1+\cos ec^2 c)}{b + a\cot c(1+\cos ec^2 c)} \tag{33}$$

Using equations (31) and (33) B/A can be limited as

$$\frac{2\sqrt{a}b(1+\cos ec^2 c)}{4b + a\cot c(1+\cos ec^2 c)} < \frac{B}{A} \le \frac{2\sqrt{a}b(1+\cos ec^2 c)}{b + a\cot c(1+\cos ec^2 c)} \tag{34}$$

The mass function m(r) can be obtained using the value of metric potential

$$e^{-\lambda} = 1 - \frac{2m}{r} \tag{35}$$

As

$$m(r) = \frac{ar^3\{\operatorname{cosec}^2(br^2+c)+1\}^2}{2[1+ar^2\{\operatorname{cosec}^2(br^2+c)+1\}^2]} \tag{36}$$

And the compactness factor for this stellar model is formulated with the help of equation (36) as

$$u(r) = \frac{2m(r)}{r} = \frac{ar^2\{\operatorname{cosec}^2(br^2+c)+1\}^2}{[1+ar^2\{\operatorname{cosec}^2(br^2+c)+1\}^2]} \tag{37}$$

And the gravitational red shift is related with the metric potential e^{ν} as

$$z(r) = e^{-\nu/2} - 1 = \left[A + \frac{B\sqrt{a}\{br^2 - \cot(br^2+c)\}}{2b} \right]^{-1} - 1 \tag{38}$$

The physical properties of our relativistic model can be observed by analyzing the trend of metric potential, density, radial and transverse pressures, anisotropic factor, the mass function and compactness parameter with respect to radial coordinate. The metric potentials have non zero values and positive values at r = 0 and regular inside the boundary of stellar structure. Density and pressures are monotonically decreasing with radial function r, they decrease when we move towards surface from the centre. So newly obtained solution is well behaved and acceptable. The anisotropic factor is zero at the centre and $\Delta > 0$ everywhere inside the stellar structure. The mass function as observed from graphical representation (fig.6) is the monotonically increasing with radial function r. The radial and transverse velocity of sound inside the relativistic fluid sphere can be calculated as

$$v_r^2 = \frac{dp_r/dr}{d\rho/dr} \qquad ; v_\perp^2 = \frac{dp_\perp/dr}{d\rho/dr} \tag{39}$$

We observe that both v_r^2 and v_t^2 have values less than 1 and so both velocities satisfy the causality condition. The relativistic adiabatic index defining the stability of stellar structure is given as the ratio of two specific heats-

$$\Gamma = \frac{\rho + p_r}{p_r}\frac{dp_r}{d\rho} \tag{40}$$

For neutral equilibrium condition Γ is equal to 4/3 and it should be more than 4/3 for the stable structure of relativistic sphere.

V. MATCHING CONDITION OF INTERIOR AND EXTERIOR SPACE TIME

We can find the values of constants A and B of our relativistic model by smoothly joining the interior metric of anisotropic fluid distribution to the exterior Schwarzschild solution given by

$$ds^2 = \left(1-\frac{2M}{r}\right)dt^2 - r^2(d\theta^2 \sin^2\theta\, d\phi^2) - \left(1-\frac{2M}{r}\right)^{-1} dr^2 \tag{41}$$

The metric functions e^{ν} and e^{λ} are continuous at the boundary of compact star. The radial pressure $p_r = 0$ at the boundary (r = R). using these conditions we obtain

$$e^{\upsilon_b} = 1-\frac{2M}{r_b} = \left[A + \frac{B\sqrt{a}}{2b}\{br_b^{\ 2} - \cot(br_b^{\ 2}+c)\}\right]^2 \tag{42}$$

$$e^{-\lambda_b} = 1-\frac{2M}{r_b} = \left[1 + ar_b^{\ 2}\{\cos ec^2(br_b^{\ 2}+c)+1\}^2\right]^{-1} \tag{43}$$

Using condition $p_r(r_b) = 0$ and boundary condition from equation (21) we obtain

$$a = \left[\frac{1}{r_b^{\ 2}\{\cos ec^2(br_b^{\ 2}+c)+1\}^2}\right]\left[\frac{1}{\left(1-\frac{2M}{r_b}\right)} - 1\right] \tag{44}$$

$$B = \frac{2A\sqrt{a}\, b\{1+\cos ec^2(br_b^{\ 2}+c)\}}{\left[4b - a\{1+\cos ec^2(br_b^{\ 2}+c)\}\{br_b^{\ 2} - \cot(br_b^{\ 2}+c)\}\right]} \tag{45}$$

$$A = \frac{4b - a\{1+\cos ec^2(br_b^2+c)\}\{br_b^{\ 2} - \cot(br_b^2+c)\}}{4b[1+ar_b^2\{\cos ec^2(br_b^2+c)+1\}^2]^{1/2}} \tag{46}$$

Constant b and c are assumed as a free parameter for the stellar structure and others can be calculated by substituting this value of free parameter in the corresponding equations.

TABLE.1: The well behaved values of the parameters used for two compact stars.

Compact Objects	b (km^{-2})	C (km^2)	A	A	B	Computed R(km)	Computed M/M_Θ	Observed R(km)	Observed M/M_Θ
PSR J1903+327	.0025	1.6	0.001435	0.76287	0.034805	9.438	1.667	9.438 ±0.03	1.667±0.021
PSR J1614-2230	.0025	1.6	0.001701	0.712423	0.037052	9.69	1.97	9.69±0.2	1.97±0.04

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VI. RESULTS AND CONCLUSION

It has been concluded from the present work that the physical parameters ($e^{-\lambda}$, ρ , p_r , p_t , p_r / ρ ,z) have positive values at the center obeying the limit of the realistic equation of state and these parameters are decreasing monotonically outwards shown in fig.(1,2,3,4,8).Metric potential e^{ν}, anisotropy factor Δ, p_t/ρ and adiabatic index Γ are increasing when we move outwards which is necessary condition for physically viable configuration fig.(1,4,5,12).Furthermore our new model satisfies all energy conditions which are required for physically possible configuration .The null energy condition (NEC), the weak energy condition (WEC) and strong energy condition (SEC) are shown in fig.(9).The stability factor $v_t^2 - v_r^2$ must have values between -1 and 0 ($-1 \leq v_t^2 - v_r^2 \leq 0$) for a stable configuration fig.(13). Therefore our solution satisfies the condition for stable stellar configuration .Variation of mass and compactness parameter with radial coordinate is shown in fig.(6,7). The decreasing nature of pressure and density gradients are shown in fig.(10). The hydrostatic equilibrium condition representing the counterbalancing of the different forces acting on the fluid sphere is shown in fig.(11).The value of adiabatic index is greater than 4/3 throughout the stellar structure which confirms the stability of our newly obtained configuration fig.(12). It has been also observed that anisotropy factor $\Delta > 0$ and increases when we move from centre towards boundary fig. (5). From the above analysis it is obvious that our proposed model satisfies all physical requirements as far as the compact star candidates PSRJ1903+327 and PSRJ1614-2230 are concerned.

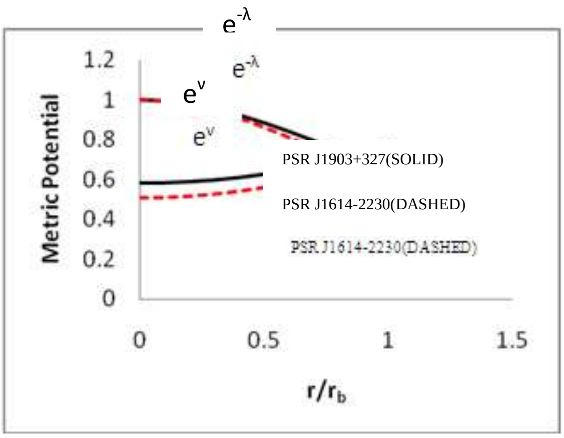

Fig:1 Variation of metric potentials with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

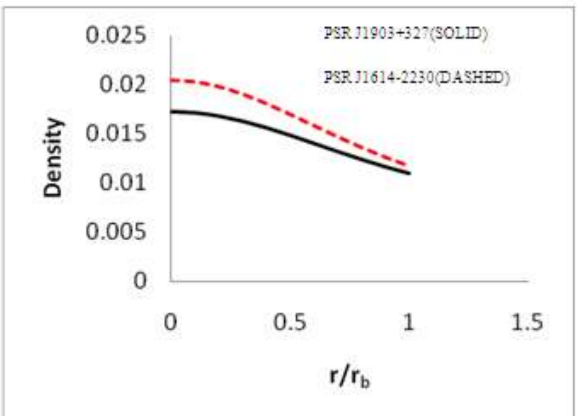

Fig:2 Variation of matter densities with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

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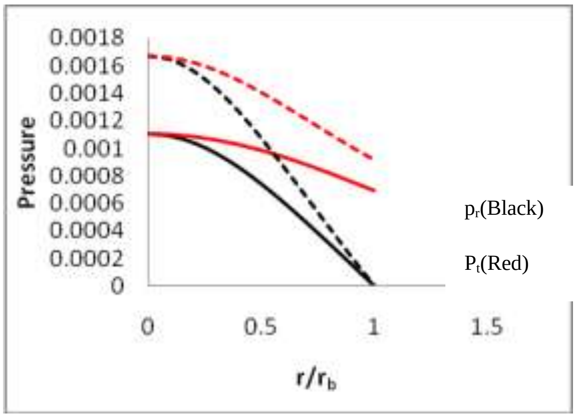

Fig:3 Variation of pressures with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

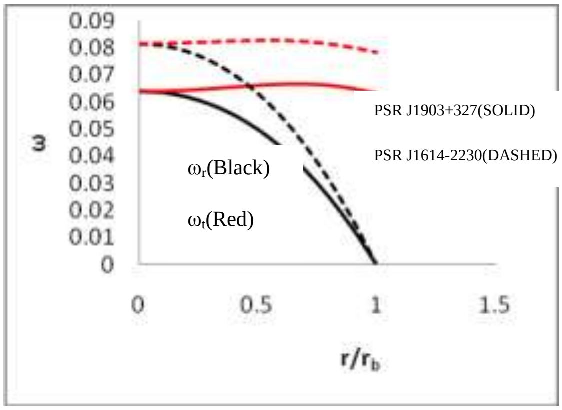

Fig:4 Variation of pressure to density ratios ($\omega_r=p_r/\rho,\omega_t=p_t/\rho$) with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

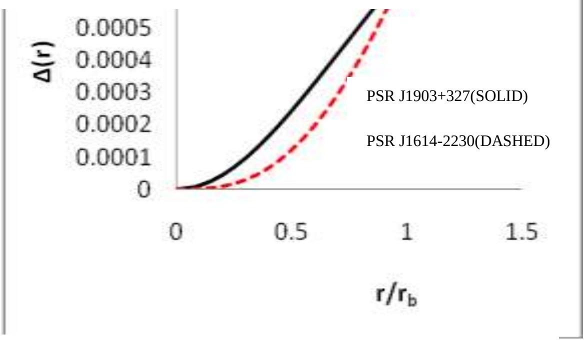

Fig:5 Variation of anisotropy with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

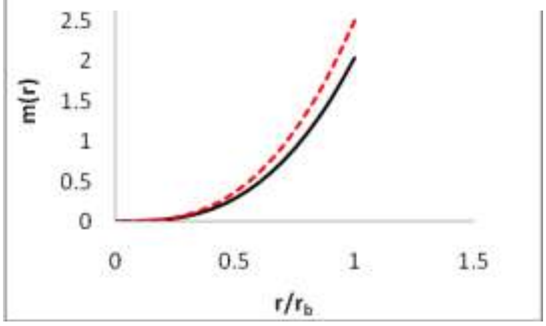

Fig:6 Variation of mass with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

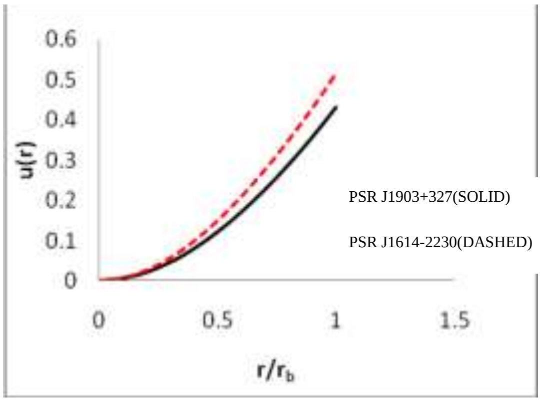

Fig:7 Variation of compactness parameter with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

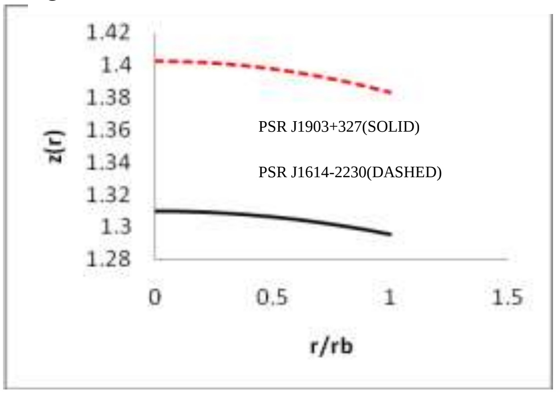

Fig:8 Variation of red shift with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

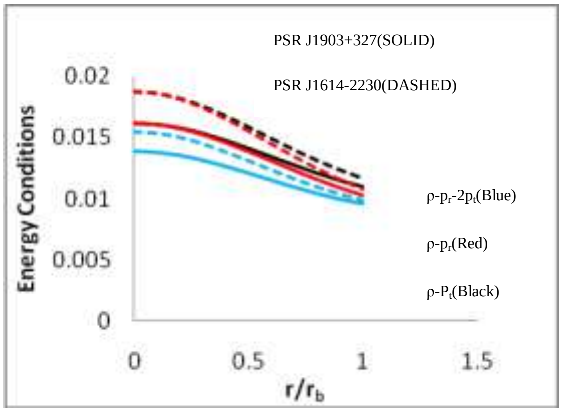

Fig:9 Variation of energy conditions with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

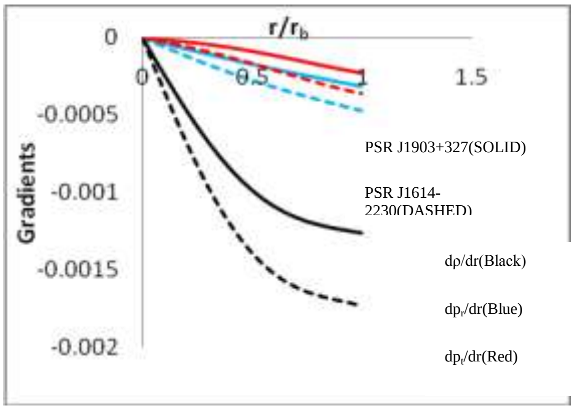

Fig:10 Variation of pressure and density gradients with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

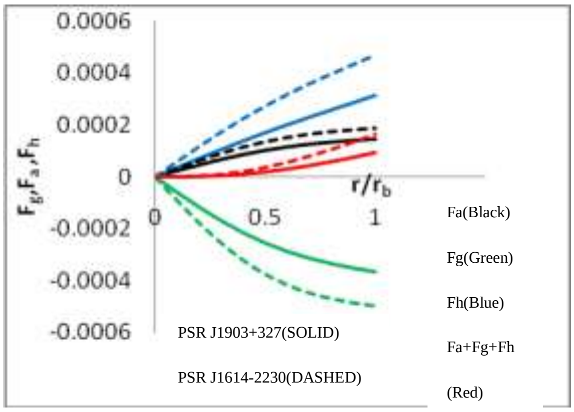

Fig:11 Variation of different forces with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

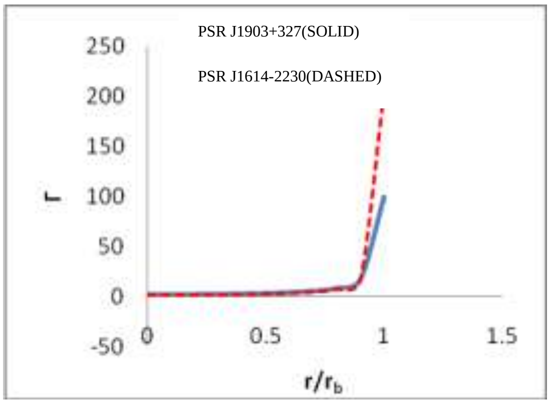

Fig:12 Variation of relativistic adiabatic index with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

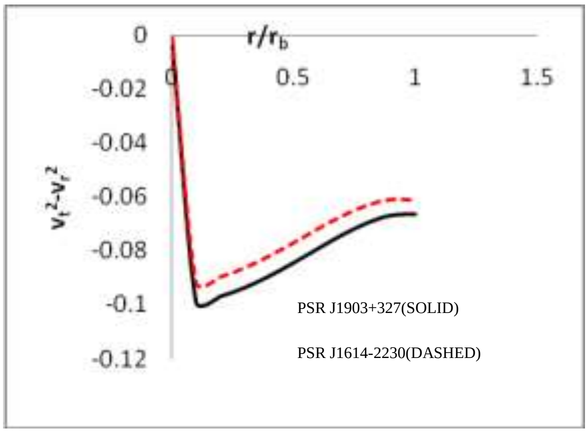

Fig:13 Variation of stability factor with radial coordinate for PSRJ1903+327 and PSRJ1614-2230 for the parameters given in Table 1

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