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A new class of anisotropic charged compact star

Abstract

A new model of charged compact star is reported by solving the Einstein-Maxwell field equations by choosing a suitable form of radial pressure. The model parameters $\rho, p_r, p_\perp$ and E^2 are in closed form and all are well behaved inside the stellar interior. A comparative study of charged and uncharged model is done with the help of graphical analysis.

Keywords: general relativity, exact solutions, anisotropy, relativistic compact stars, charged distribution

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Introduction

To find the exact solution of Einstein's field equations is difficult due to its non-linear nature. A large number of exact solutions of Einstein's field equations in literature but not all of them are physically relevant. A comprehensive collection of static, spherically symmetric solutions are found in.[1,2] A large collection of models of stellar objects incorporating charge can be found in literature.[3] Proposed that a fluid sphere of uniform density with a net surface charge is more stable than without charge. An interesting observation of[4] is that in the presence of charge, the gravitational collapse of a spherically symmetric distribution of matter to a point singularity may be avoided. Charged anisotropic matter with linear equation of state is discussed by.[5,6] Found that the solutions of Einstein-Maxwell system of equations are important to study the cosmic censorship hypothesis and the formation of naked singularities. The presence of charge affects the values for redshifts, luminosities, and maximum mass for stars. Charged perfect fluid sphere satisfying a linear equation of state was discussed by.[7] Regular models with quadratic equation of state were discussed by.[8] They obtained exact and physically reasonable solution of Einstein-Maxwell system of equations. Their model is well behaved and regular. In particular there is no singularity in the proper charge density.[9] Considered a self gravitating, charged and anisotropic fluid sphere. To solve Einstein-Maxwell field equation they have assumed both linear and nonlinear equation of state and discussed the result analytically.[10] Extend the work of[5] by considering quadratic equation of state for the matter distribution to study the general situation of a compact relativistic body in presence of electromagnetic field and anisotropy.

Ruderman R[11] investigated that for highly compact astrophysical objects like X-ray pulsar, Her-X-1, X-ray buster 4U 1820-30, millisecond pulsar SAX J 1804.4-3658, PSR J1614-2230, LMC X-4 etc. having core density beyond the nuclear density $(\sim 10^{15}\, gm/cm^3)$ there can be pressure anisotropy, i.e, the pressure inside these compact objects can be decomposed into two parts radial pressure $p_\perp$ and transverse pressure $p_\perp$ perpendicular direction to p_r. $\Delta = p_r - p_\perp$ is called the anisotropic factor which measures the anisotropy. The reason behind these anisotropic nature are the existence of solid core, in presence of type 3A super fluid,[12] phase transition,[13] pion condensation,[14] rotation, magnetic field, mixture of two fluid, existence of external field etc. Local anisotropy in self gravitating systems was studied by.[15,16] Demonstrated that pressure anisotropy affects the physical properties, stability and structure of stellar matter. Relativistic stellar model admitting a quadratic equation of state was proposed by[17] in finch-skea space-time.[18] Has generalized earlier work in modified Finch-Skea spacetime by incorporating a dimensionless parameter n. In a very recent work[19] obtained a new model of an anisotropic super dense star which admits conformal motions in the presence of a quintessence field which is characterized by a parameter ω_q with $-1 < \omega_q < -1/3$. The model has been developed by choosing *ansatz*.[20,21] Have studied the behavior of static spherically symmetric relativistic objects with locally anisotropic matter distribution considering the Tolman VII form for the gravitational potential g_{rr} in curvature coordinates together with the linear relation between the energy density and the radial pressure.

Charged anisotropic star on paraboloidal space-time was studied by.[22,23] Studied anisotropic star on pseudo-spheroidal space time. Charged anisotropic star on pseudo-spheroidal space time was studied by.[24] The study of compact stars having Matese and Whitman mass function was carried out by.[25] Motivated by these earlier works in the present paper we develop a model of compact star by incorporating charge. Our paper is organized as follows: In section 2, interior space time and the Einstein-Maxwell system is discussed. Section 3 deals with solution of field equations. Section 4 contains exterior space time and matching conditions. Physical analysis of the model is discussed in section 5. Section 6 contains conclusion.

Interior spacetime

We consider the static spherically symmetric spacetime metric as,

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

Where ν and λ are functions of the radial coordinate 'r' only.

Einstein-Maxwell Field Equations is given by

$$R_i^j - \frac{1}{2}R\delta_i^j = 8\pi\left(T_i^j + \pi_i^j + E_i^j\right), \quad (2)$$

Where,

$$T_i^j = (\rho + p) u_i u^j - p\delta_i^j, \qquad (3)$$

$$\pi_i^j = \sqrt{3}S\left[c_i c^j - \frac{1}{2}\left(u_i u^j - \delta_i^j\right)\right], \qquad (4)$$

And

$$E_i^j = \frac{1}{4\pi}\left(-F_{ik}F^{jk} + \frac{1}{4}F_{mn}F^{mn}\delta_i^j\right). \qquad (5)$$

Here ρ is proper density, p is fluid pressure, u_i is unit four velocities, S denotes magnitude of anisotropic tensor and C^i is radial vector given by $\left(0, -e^{-\lambda/2}, 0, 0\right)$. F_{ij} Denotes the anti-symmetric electromagnetic field strength tensor defined by

$$F_{ij} = \frac{\partial A_j}{\partial x_i} - \frac{\partial A_i}{\partial x_j}, \qquad (6)$$

That satisfies the Maxwell equations

$$F_{ij,k} + F_{jk,i} + F_{ki,j} = 0, \qquad (7)$$

And

$$\frac{\partial}{\partial x^k}\left(F^{ik}\sqrt{-g}\right) = 4\pi\sqrt{-g}J^i, \qquad (8)$$

Where g denotes the determinant of g_{ij}, $A_i = \left(\phi(r), 0, 0, 0\right)$ is four-potential and

$$J^i = \sigma u^i, \qquad (9)$$

Is the four-current vector where F_{ij} denotes the charge density.

The only non-vanishing components of F_{ij} is $F_{01} = -F_{10}$. Here

$$F_{01} = -\frac{e^{\frac{\nu+\lambda}{2}}}{r^2}\int_0^r 4\pi r^2 \sigma e^{\lambda/2} dr, \qquad (10)$$

And the total charge inside a radius r is given by

$$q(r) = 4\pi\int_0^r \sigma r^2 e^{\lambda/2} dr. \qquad (11)$$

The electric field intensity $E(r)$ can be obtained from $E^2 = -F_{01}F^{01}$, which subsequently reduces to

$$E = \frac{q(r)}{r^2}. \qquad (12)$$

The field equations given by (2) are now equivalent to the following set of the non-linear ODE's

$$\frac{1 - e^{-\lambda}}{r^2} + \frac{e^{-\lambda}\lambda'}{r} = 8\pi\rho + E^2, \qquad (13)$$

$$\frac{e^{-\lambda} - 1}{r^2} + \frac{e^{-\lambda}\nu'}{r} = 8\pi p_r - E^2, \qquad (14)$$

$$e^{-\lambda}\left(\frac{\nu''}{2} + \frac{\nu'^2}{4} - \frac{\nu'\lambda'}{4} + \frac{\nu' - \lambda'}{2r}\right) = 8\pi p_\perp + E^2, \qquad (15)$$

Where we have taken

$$p_r = p + \frac{2S}{\sqrt{3}}, \qquad (16)$$

$$p_\perp = p - \frac{S}{\sqrt{3}}. \qquad (17)$$

$$8\pi\sqrt{3}S = p_r - p_\perp. \qquad (18)$$

Solution of field equations

To solve the above set of equations (13)-(15) we take the mass function of the form

$$m(r) = \frac{br^3}{2(1 + ar^2)}, \qquad (19)$$

Where 'a' and 'b' are two positive constants. The mass function given in (19) is known as Matese & Whitman[26] mass function that gives a monotonic decreasing matter density which was used by[27] to model an anisotropic fluid star,[28] to develop a model of dark energy star,[29] to model a class of relativistic stars with a linear equation of state and[30] to model a charged anisotropic matter with linear equation of state.

Using the relationship $e^{-\lambda} = 1 - \frac{2m}{r}$ and equation (19) we get,

$$e^{\lambda} = \frac{1 + ar^2}{1 + (a - b)r^2}. \qquad (20)$$

From equation (13) and (20) we obtain

$$8\pi\rho = \frac{3b + abr^2}{(1 + ar^2)^2} - E^2. \qquad (21)$$

We choose E^2 of the form

$$E^2 = \frac{\alpha ar^2}{(1 + ar^2)^2}, \qquad (22)$$

Which is regular at the center of the star. Substituting the expression of E^2 into (21) we get,

$$8\pi\rho = \frac{3b + a(b - \alpha)r^2}{(1 + ar^2)^2}. \qquad (23)$$

To integrate the equation (14) we take radial pressure of the form,

$$8\pi p_r = \frac{bp_0(1 - ar^2)}{(1 + ar^2)^2}, \qquad (24)$$

Where p_0 is a positive constant, the choice of p_r is reasonable due to the fact that it is monotonic decreasing function of 'r' and the radial pressure vanishes at $r = \frac{1}{\sqrt{a}}$ which gives the radius of the star.

From (24) and (14) we get,

$$\nu' = \frac{(bp_0 + b)r - a(bp_0 + \alpha - b)r^3}{(1 + ar^2)\left[1 + (a - b)r^2\right]}. \qquad (25)$$

Integrating we get,

$$\nu = \log\left\{\frac{C\left(1 + ar^2\right)^{\left(\frac{2bp_0 + \alpha}{2b}\right)}}{\left[(b - a)r^2 - 1\right]\left[\frac{\left(b^2 - 2ab\right)p_0 + b^2 - \alpha a}{2b^2 - 2ab}\right]}\right\}, \qquad (26)$$

Where C is constant of integration, and the space time metric in the interior is given by

$$ds^2 = \left\{ \frac{C\left(1+ar^2\right)^{\left(\frac{2bp_0+\alpha}{2b}\right)}}{\left[(b-a)r^2-1\right]\left[\frac{\left(b^2-2ab\right)p_0+b^2-\alpha a}{2b^2-2ab}\right]} \right\} dt^2 - \left[\frac{1+ar^2}{1+(a-b)r^2}\right] dr^2 - r^2\left(d\theta^2+\sin^2\theta d\phi^2\right). \quad (27)$$

From (14), (15) and (18), we have

$$8\pi\sqrt{3}S = \frac{r^2\left[A_1+A_2r^2+A_3r^4\right]}{\left[-4+B_1r^2+B_2r^4+B_3r^6+B_4r^8\right]}, \quad (28)$$

Where, $A_1 = b^2p_0^2 + 14b^2p_0 - 12abp_0 + 3b^2 - 12\alpha a$,

$A_2 = -2ab^2p_0^2 + 8ab^2p_0 - 8a^2bp_0 - 2\alpha abp_0 + 2ab^2 + 8\alpha ab - 16\alpha a^2$

$A_3 = a^2b^2p_0^2 - 4a^2b^2p_0 + 4a^3bp_0 + 2\alpha a^2bp_0 - a^2b^2 + 4\alpha a^2b - 4\alpha a^3 + \alpha^2a^2$,

$B_2 = 12ab - 24a^2$, $B_2 = 12ab - 24a^2$, $B_3 = 12a^2b - 16a^3$ and $B_4 = 4a^3b - 4a^4$.

From (18) we obtain,

$$8\pi p_\perp = \frac{\left[4bp_0+C_1r^2+C_2r^4+C_3r^6\right]}{\left[4-B_1r^2-B_2r^4-B_3r^6-B_4r^8\right]}, \quad (29)$$

Where, $C_1 = b^2p_0^2 - 8abp_0 + 3b^2 - 12\alpha a$,

$C_2 = -2ab^2p_0^2 + 8ab^2p_0 - 12a^2bp_0 - 2\alpha abp_0 + 2ab^2 + 8\alpha ab - 16\alpha a^2$,

$C_3 = a^2b^2p_0^2 + 2\alpha a^2bp_0 - a^2b^2 + 4\alpha a^2b - 4\alpha a^3 + \alpha^2a^2$.

Exterior space time and matching condition

We match our interior space time (27) to the exterior Reissner-Nordström space time at the boundary $r = r_b$ (where r_b is the radius of the star.). The exterior space time is given by the line element

$$ds^2 = \left(1-\frac{2M}{r}+\frac{q^2}{r^2}\right)dt^2 - \left(1-\frac{2M}{r}+\frac{q^2}{r^2}\right)^{-1} dr^2 - r^2\left(d\theta^2+\sin^2\theta d\phi^2\right). \quad (30)$$

By using the continuity of the metric potential g_{rr} and g_{tt} at the boundary $r = r_b$ we get,

$$e^{\nu(r_b)} = 1 - \frac{2M}{r_b} + \frac{q^2}{r^2}, \quad (31)$$

$$e^{\lambda(r_b)} = \left(1-\frac{2M}{r_b}+\frac{q^2}{r^2}\right)^{-1}. \quad (32)$$

The radial pressure should vanish at the boundary of the star, hence from equation (24) we obtain

$$a = \frac{1}{r_b^2}. \quad (33)$$

Using (33) & (19) we obtain

$$b = \frac{4m}{r_b^3}. \quad (34)$$

We compute the values of 'a' and 'b' for different compact stars which is given in Table 1.

Table 1 The values of 'a' and 'b' obtained from the equation (33) and (34)

Compact star	$M(M_\odot)$	Mass(km)	Radius(km)	a(km^{-2})	b(km^{-2})	u	z_s
U 1820-30	1.58	2.33050	9.1	0.012076	0.012370	0.256099	0.431786
PSR J1903+327	1.667	2.45882	9.438	0.011226	0.011699	0.260524	0.444954
U 1608-52	1.74	2.56650	9.31	0.011537	0.012722	0.275671	0.492941
Vela X-1	1.77	2.61075	9.56	0.010942	0.011952	0.273091	0.484428
PSR J1614-2230	1.97	2.90575	9.69	0.01065	0.012775	0.299871	0.580629
Cen X-3	1.49	2.19775	9.178	0.011871	0.011371	0.239458	0.385309

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Physical analysis

To be a physically acceptable model matter density (ρ), radial pressure (p_r), transverse pressure (p_r) all should be non-negative inside the stellar interior. It is clear from equations (22) and (24) it is clear that p_r is positive throughout the distribution. The profile of $p_\perp$ and $p_\perp$ are shown in Figures 1 & 2 respectively. From the figure it is clear that all are positive inside the stellar interior.

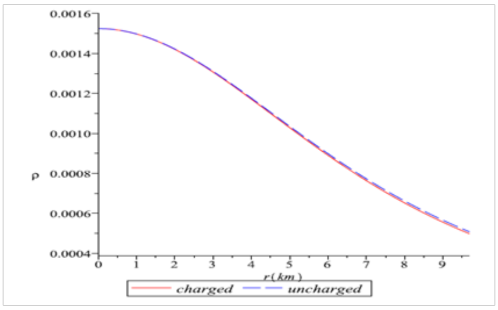


Figure 1 The matter density is plotted against r for the star PSR J1614-2230.

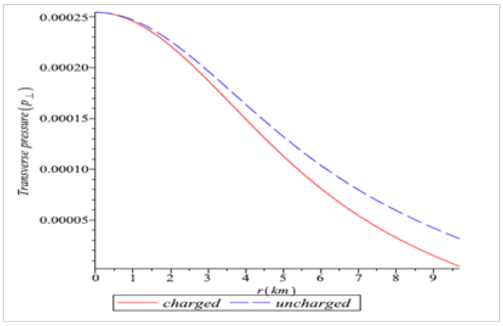


Figure 2 The transverse pressure p_t is plotted against r for the star PSR J1614-2230.

The profile of c and $\frac{dp_\perp}{dr}$ are shown in Figure 3, it is clearly indicates that p_r, p_r and $p_\perp$ are decreasing in radially outward direction. According to[31] for an anisotropic fluid spheres the trace of the energy tensor should be positive. To check this condition for our model we plot $\rho - p_r - 2p_\perp$ against r in Figure 4. From the figure it is clear that our proposed model of compact star satisfies Bondi's conditions.

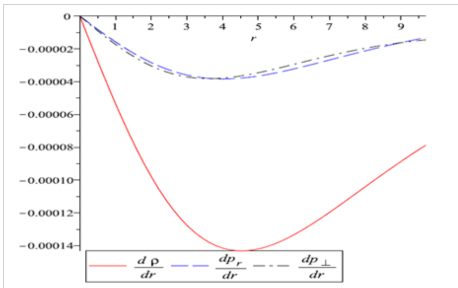


Figure 3 $\frac{d\rho}{dr}$, $\frac{dp_\perp}{dr}$ and $\frac{dp_\perp}{dr}$ are plotted against r for the star PSR J1614-2230.

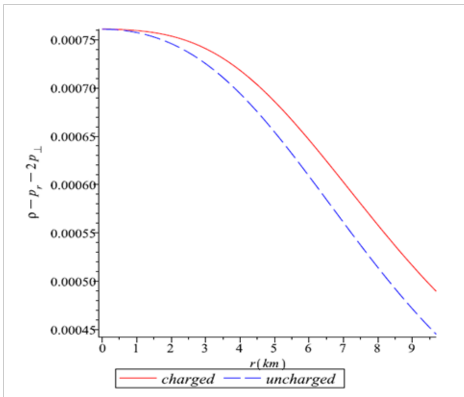


Figure 4 $\rho - p_r - 2p_t$ is plotted against r for the star PSR J1614-2230.

For a physically acceptable model of anisotropic fluid sphere the radial and transverse velocity of sound should be less than 1 which is known as causality conditions.

Where the radial velocity (v_{st}^2) and transverse velocity (v_{st}^2) of sound can be obtained as

$$\frac{dp_r}{d\rho} = \frac{bp_0(3-ar^2)}{5b+\alpha+a(b-\alpha)r^2}. \qquad (35)$$

$$\frac{dp_\perp}{d\rho} = \frac{(1+ar^2)^3\left[D_1+D_2r^2+D_3r^4+D_4r^6+D_5r^8\right]}{\left[-10ab-2a\alpha-2a^2(b-\alpha)r^2\right]\left[2+E_1r^2+E_2r^4+E_3r^6+E_4r^8+E_5r^{10}+E_6r^{12}\right]}. \qquad (36)$$

Where,

$D_2 = -6ab^2p_0^2 + 32ab^2p_0 - 24a^2bp_0 - 4\alpha abp_0 - 2ab^2 + 16\alpha ab - 8\alpha a^2,$

$D_2 = -6ab^2p_0^2 + 32ab^2p_0 - 24a^2bp_0 - 4\alpha abp_0 - 2ab^2 + 16\alpha ab - 8\alpha a^2,$

$D_3 = 5ab^3p_0^2 - 8ab^3p_0 + 2\alpha ab^2p_0 - 12a^2b^2p_0 + 24a^3bp_0 + 6\alpha a^2bp_0 + 7ab^3 - 12a^2b^2 - 8\alpha ab^2 - 8\alpha a^2b + 24\alpha a^3 + 3\alpha^2a^2,$

$D_4 = 6a^3b^bp_0^2 - 6a^2b^3p_0^2 + 16a^2b^3p_0 - 40a^3b^2p_0 - 8\alpha a^2b^2p_0 + 24a^4bp_0 + 8\alpha a^3bp_0 + 6a^2b^3 + 8\alpha a^2b^2 - 6a^3b^2 - 32\alpha a^3b - 2\alpha^2a^2b + 24\alpha a^4 + 2\alpha^2a^3,$

$D_5 = a^3b^3p_0^2 - a^4b^2p_0^2 + 2\alpha a^3b^2p_0 - 2\alpha a^4bp_0 - a^3b^3 + a^4b^2 + 4\alpha a^3b^2 + \alpha^2a^3b - 8\alpha a^4b + 4\alpha a^5 - \alpha^2a^4,$

$E_1 = 12a - 4b$, $E_2 = 2b^2 - 20ab + 30a^2$, $E_4 = 12a^2b^2 - 40a^3b + 30a^4$, $E_4 = 12a^2b^2 - 40a^3b + 30a^4$,

$E_5 = 8a^3b^2 - 20a^4b + 12a^5$ and $E_6 = 2a^4b^2 - 4a^5b + 2a^6$.

Due to the complexity of the expression of $\frac{1}{3} < p_0 < 0.3944$ we prove the causality conditions with the help of graphical representation. The graphs of (v_{sr}^2) and (v_{st}^2) have been plotted in Figures 5 & 6 respectively. From the figure it is clear that $0 < v_{st}^2 \leq 1$ and $0 < v_{st}^2 \leq 1$ everywhere within the stellar configuration. Moreover $\frac{dp_t}{d\rho}$ and $\frac{dp_r}{d\rho}$ are monotonic decreasing function of radius 'r' for $0 \leq r \leq r_b$ which implies that the velocity of sound is increasing with the increase of density.

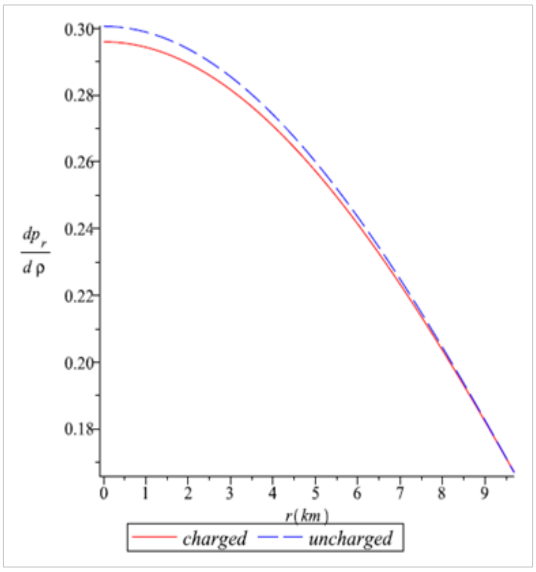


Figure 5 $v_{sr}^2 = \frac{dp_r}{d\rho}$ is plotted against r for the star PSR J1614-2230.

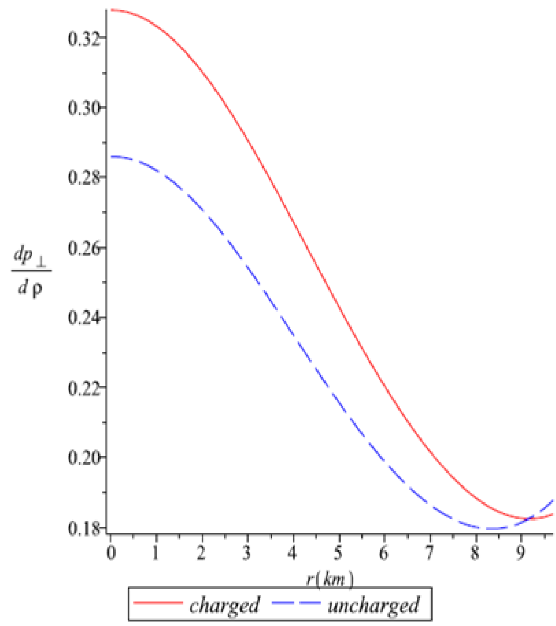


Figure 6 $v_{st}^2 = \frac{dp_\perp}{d\rho}$ is plotted against r for the star PSR J1614-2230.

A relativistic star will be stable if the relativistic adiabatic index $\Gamma > \frac{4}{3}$. Where Γ is given by

$$\Gamma = \frac{\rho + p_r}{p_r}\frac{dp_r}{d\rho} \qquad (37)$$

To see the variation of the relativistic index we plot Γ for our present of compact star which is plotted in Figure 7. The figure ensures that our model is stable.

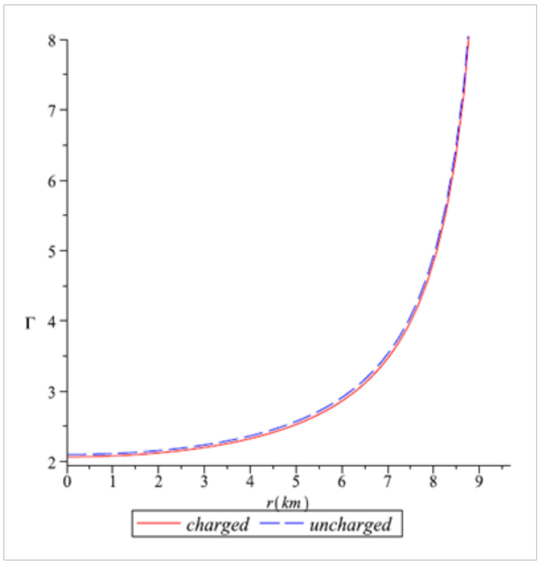


Figure 7 The adiabatic index is plotted against r for the star PSR J1614-2230.

For an anisotropic fluid sphere all the energy conditions namely Weak Energy Condition (WEC), Null Energy Condition (NEC), Strong Energy Condition (SEC) and Dominant Energy Condition (DEC) are satisfied if and only if the following inequalities hold simultaneously in every point inside the fluid sphere.

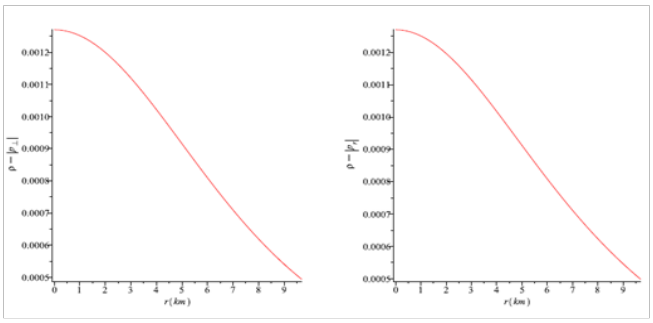
$$(i) NEC: \rho + p_r \geq 0 \qquad (38)$$

$$(ii) WEC: p_r + \rho \geq 0, \quad \rho > 0 \qquad (39)$$

$$(iv) DEC: \rho > |p_r| \quad , \rho > |p_\perp| \qquad (41)$$

$$(iv) DEC: \rho > |p_r| \quad , \rho > |p_\perp| \qquad (41)$$

Due to the complexity of the expression of $p_\perp$ we will prove the inequality (38)-(41) with the help of graphical representation. The profiles of the L.H.S of the above inequalities are depicted in Figure 8 for the compact star PSR J1614-2230. The figure shows that all the energy conditions are satisfied by our model of compact star (Figures 9 & 10).



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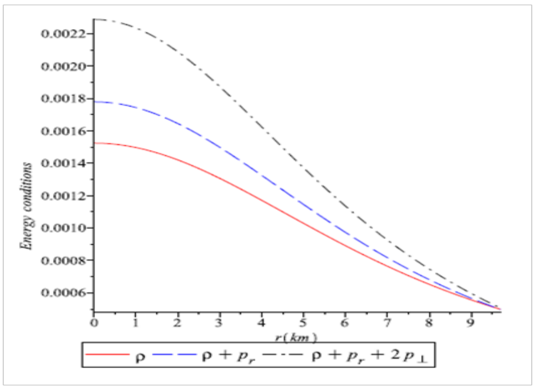

Figure 8 The left and middle figures show the dominant energy conditions where as the right figure shows the weak null and strong energy conditions are satisfied by our model for the star PSR J1614-2230.

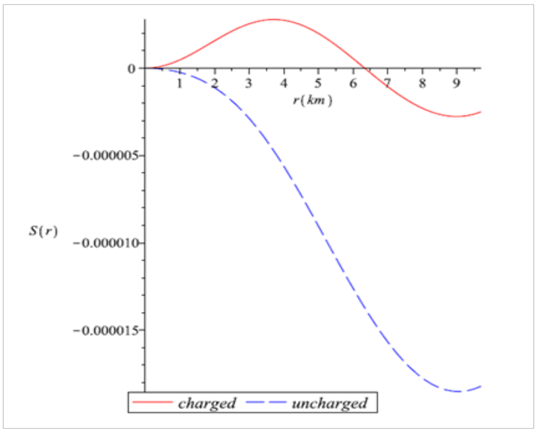

Figure 9 Variation of anisotropy is shown against r for the star PSR J1614-2230.

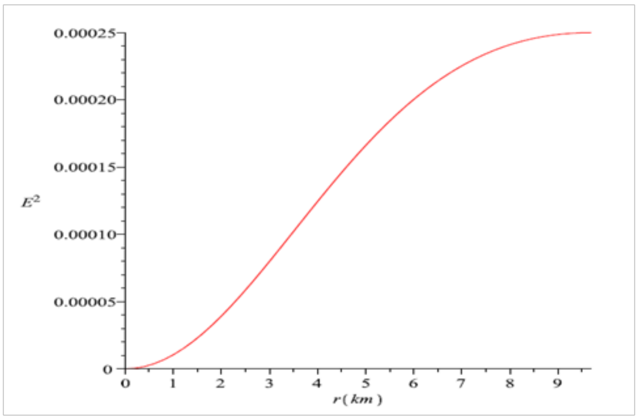

Figure 10 The variation of electric field is shown against r for the star PSR J1614-2230.

The ratio of mass to the radius of a compact star cannot be arbitrarily large.[32] showed that for a (3+1)-dimensional fluid sphere $\frac{2M}{r_b} < \frac{8}{9}$. To see the maximum ratio of mass to the radius for our model we calculate the compactness of the star given by

$$u(r) = \frac{m(r)}{r} = \frac{br^2}{2(1+ar^2)}, \qquad (42)$$

and the corresponding surface redshift z_s is obtained by,

$$1 + z_s(r_b) = \left[1 - 2u(r_b)\right]^{-1/2}$$

Therefore z_s can be obtained as,

$$z_s(r_b) = \left[\frac{1+(a-b)r_b^2}{1+ar_b^2}\right]^{-\frac{1}{2}} - 1. \qquad (43)$$

The surface redshift of different compact stars is given in Table 2.

Table 2 The values of central density, surface density, central pressure and radial velocity of the sound at the origin for different compact stars are obtained

Compact star	**Central Density** (ρ_0)	**Surface Density**	**Surface density**	**Central Pressure** (p_0)	$\frac{dp_r}{d\rho}\big\rvert_{r=0}$
	$gm.cm^{-3}$	(uncharged)	(charged)	$dyne.cm^{-2}$	(charged)
U 1820-30	1.994×10^{15}	6.648×10^{14}	6.514×10^{14}	2.989×10^{35}	0.295227
PSR J1903+327	1.886×10^{15}	6.287×10^{14}	2.827×10^{35}	2.827×10^{35}	0.294958
U 1608-52	2.051×10^{15}	3.074×10^{35}	3.074×10^{35}	3.074×10^{35}	0.295357
Vela X-1	1.927×10^{15}	6.423×10^{14}	2.888×10^{35}	2.888×10^{35}	0.295063
PSR J1614-2230	2.059×10^{15}	6.865×10^{14}	3.087×10^{35}	3.087×10^{35}	0.295376
Cen X-3	1.833×10^{15}	6.111×10^{14}	2.748×10^{35}	2.748×10^{35}	0.294815

Conclusion

We have obtained a new class of solution for charged compact stars having[26] mass function. The electric field intensity is increasing in radially outward direction and the adiabatic index $\Gamma > \frac{4}{3}$. The physical requirements are checked for the star PSR J1614-2230 and model satisfies all the physical conditions. Some salient features of the model are

In present model if $\alpha = 0$, the model corresponds to[23] model.

In present model if $\alpha = 0$, $a = b = \frac{1}{R^2}$, where R is geometric parameter then the model corresponds to[17] model, which is stable for $\frac{1}{3} < p_0 < 0.3944$.

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Conflicts of interest

Authors declare there is no conflict of interest.

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