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The $(2+1)$-dimensional charged gravastars

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ABSTRACT

This is a continuation and generalization of our earlier work on *gravastar* in $(2+1)$ anti-de Sitter space–time to $(2+1)$-dimensional solution of charged gravastar. Morphologically this gravastar contains three regions, namely: (i) charged interior, (ii) charged shell and (iii) electrovacuum exterior. We have studied different characteristics in terms of Length and Energy, Entropy, and Junction conditions of the spherical charged distribution. It is shown that the present model of charged gravastar is non-singular and represents itself an alternative of black hole.

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1. Introduction

Recently the study of *gravastars*, the gravitational vacuum star, has become a subject of considerable interest as it was proposed as an alternative to black holes. Mazur and Mottola [1,2] first proposed a new type of solution for the endpoint of a gravitational collapse in the form of cold, dark and compact objects. Therefore, physically this was an extension of the concept of Bose–Einstein condensate to gravitational systems. The Mazur–Mottola model [1,2] contains an isotropic de Sitter vacuum in the interior, while the exterior is defined by a Schwarzschild geometry, separated by a thin shell of stiff matter implying that the configuration of a gravastar has three different regions with different equations of state (EOS) [3–15], designated by: (I) Interior: $0 \leqslant r < r_1$, $p = -\rho$; (II) Shell: $r_1 < r < r_2$, $p = +\rho$; and (III) Exterior: $r_2 < r$, $p = \rho = 0$. It is argued that the presence of matter on the thin shell of thickness $r_2 - r_1 = \delta$ is essential to achieve the required stability of systems under expansion by exerting an inward force to balance the repulsion from within.

Usmani et al. [16] proposed a new model of a gravastar admitting conformal motion by assuming a charged interior. Their exterior was defined by a Reissner–Nordström line element instead of Schwarzschild's one. Later on Rahaman et al. [17] designed a neutral spherically symmetric model of gravastar in $(2+1)$ anti-de Sitter space–time contrary to the former work where, as usual, space–time was $(3+1)$-dimensional. The outer region of the Rahaman et al. [17] model of gravastar corresponds to the exterior $(2+1)$ anti-de Sitter space–time of BTZ-type black holes as presented by Bañados, Teitelboim and Zanelli [18]. Therefore, the above two works demand that one should investigate a $(2+1)$-dimensional solution for charged gravastar. This is the motivation of our present investigation.

In favour of inclusion of charge in stellar distribution it has been argued in the work of Usmani et al. [16] that compact stars tend to assemble a net charge on the surface [19–23]. This facilitates stability of a fluid sphere by avoiding gravitational collapse and hence singularity [19,20,24–26]. In this connection we would like to mention the interesting charged model of Horvat [13] which represents a gravastar where the analysis has carried out within Israel's thin shell formalism and the continuous profile approach.

In the present investigation we have followed the mechanism of Mazur and Mottola [1,2] in the framework of Einstein–Maxwell formalism. To solve the specified equations, related to the regions designated as Interior, Shell and Exterior, we have considered appropriate equations of state (EOS), viz. $\rho = -p$ (dark energy), $\rho = p$ (stiff fluid) and $\rho = p = 0$ (dust) respectively. Under this regional classification of the spherical configurations we have solved the Einstein–Maxwell field equations in the specific cases. Thereafter we have characterized the interfaces and shell in terms of Length, Energy and Entropy. The Junction conditions of the spherical charged distribution are imposed on the different regions by using Lanczos equations in $(2+1)$-dimensional space–time. The model thus obtained represents an alternative to black hole in the form of charged gravastar as it is free from any singularity.

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2. Einstein–Maxwell equations

We first consider the line element for the interior space–time of a static spherically symmetric charged distribution of matter in $(2+1)$ dimensions in the form [27,28]

$$ds^2 = -e^{\gamma(r)}\,dt^2 + e^{\lambda(r)}\,dr^2 + r^2\,d\theta^2. \tag{1}$$

The Hilbert action coupled to electromagnetism is given by

$$I = \int dx^3 \sqrt{-g}\left(\frac{R-2\Lambda}{16\pi} - \frac{1}{4}F_a^c F_{bc} + L_m\right), \tag{2}$$

where L_m is the Lagrangian for matter. The variation with respect to the metric gives the following self-consistent Einstein–Maxwell equations with cosmological constant Λ for a charged perfect fluid distribution

$$R_{ab} - \frac{1}{2}Rg_{ab} + \Lambda g_{ab} = -8\pi\left(T_{ab}^{PF} + T_{ab}^{EM}\right). \tag{3}$$

The explicit forms of the energy momentum tensor (EMT) components for the matter source (we assumed that the matter distribution at the interior of the star is perfect fluid type) and electromagnetic fields are given by

$$T_{ab}^{PF} = (\rho + p)u_i u_k + p g_{ik}, \tag{4}$$

$$T_{ab}^{EM} = -\frac{1}{4\pi}\left(F_a^c F_{bc} - \frac{1}{4}g_{ab}F_{cd}F^{cd}\right), \tag{5}$$

where ρ, p, u_i and F_{ab} are, respectively, matter-energy density, fluid pressure and velocity three vector of a fluid element and electromagnetic field. Here, the electromagnetic field is related to current three vector

$$J^c = \sigma(r)u^c, \tag{6}$$

as

$$F^{ab}_{;b} = -4\pi J^a, \tag{7}$$

where, $\sigma(r)$ is the proper charge density of the distribution. In our consideration, the three velocity is assumed as $u_a = \delta_a^t$ and consequently, the electromagnetic field tensor can be given as

$$F_{ab} = E(r)\left(\delta_a^t\delta_b^r - \delta_a^r\delta_b^t\right), \tag{8}$$

where $E(r)$ is the electric field.

The Einstein–Maxwell equations with a cosmological constant ($\Lambda < 0$), for the space–time described by the metric (1) together with the energy–momentum tensor given in Eqs. (4) and (5), yield (rendering $G = c = 1$)

$$\frac{\lambda' e^{-\lambda}}{2r} = 8\pi\rho + E^2 + \Lambda, \tag{9}$$

$$\frac{\gamma' e^{-\lambda}}{2r} = 8\pi p - E^2 - \Lambda, \tag{10}$$

$$\frac{e^{-\lambda}}{2}\left(\frac{1}{2}\gamma'^2 + \gamma'' - \frac{1}{2}\gamma'\lambda'\right) = 8\pi p + E^2 - \Lambda, \tag{11}$$

$$\sigma(r) = \frac{e^{-\frac{\lambda}{2}}}{4\pi r}(rE)', \tag{12}$$

where a '′' denotes differentiation with respect to the radial parameter r. Eq. (12) can equivalently be expressed in the form

$$E(r) = \frac{4\pi}{r}\int_0^r r\sigma(r)e^{\frac{\lambda(r)}{2}}\,dr = \frac{q(r)}{r}, \tag{13}$$

where $q(r)$ is total charge of the sphere under consideration. For a charged fluid distribution, the generalized Tolman–Oppenheimer–Volkov (TOV) equation may be written as

$$\frac{1}{2}(\rho + p)\gamma' + p' = \frac{1}{8\pi r^2}\left(r^2E^2\right)', \tag{14}$$

which is the conservation equation in $(2+1)$ dimensions.

We note that the term inside the integral sign in Eq. (13) is $\sigma(r)e^{\frac{\lambda(r)}{2}}$, which is equivalent to the volume charge density. We will consider the volume charge density in polynomial function of r. Hence we use the condition

$$\sigma(r)e^{\frac{\lambda(r)}{2}} = \sigma_0 r^n, \tag{15}$$

where n is arbitrary constant as polynomial index and the constant σ_0 is referred to the central charge density.

By using the latter result of Eq. (15), one obtains from Eq. (13) as

$$E(r) = \frac{4\pi\sigma_0}{n+2}r^{n+1}, \tag{16}$$

$$q(r) = \frac{4\pi\sigma_0}{n+2}r^{n+2}. \tag{17}$$

Now, we write some consequences of the filed equations and TOV equation. Eq. (9) implies

$$e^{-\lambda(r)} = M(r) - \Lambda r^2, \tag{18}$$

where

$$M(r) = C - 16\pi\int_0^r r\rho(r)\,dr - 2\int_0^r rE^2(r)\,dr \tag{19}$$

is the active gravitational mass of the spherical distribution. Since, $e^{\lambda(r)} > 0$ within the charged sphere of radius R as well as regular at the origin, we demand that $C > 0$. Using Eqs. (10), (13) and the above result (18), we finally obtain the TOV equation as

$$p' = -\frac{(p+\rho)(8\pi p - E^2 - \Lambda)r}{M(r) - \Lambda r^2} + \frac{1}{8\pi r^2}\left(q^2\right)'. \tag{20}$$

Following Mazur and Mottola [1,2] we consider a new $(2+1)$-dimensional charged perfect fluid configuration which has three different regions with different equations of state:

I Interior: $0 \leqslant r < R$, $\rho = -p$;
II Shell: $R \leqslant r < R + \epsilon$, $\rho = p$;
III Exterior: $r_2 < r$, $\rho = p = 0$.

Accordingly our configuration is supported by an interior region with equation of state $p = -\rho$. The shell of our configuration belongs to the interfaces, $r = R$ and $r = R + \epsilon$, where ϵ is the thickness of the shell. This thin shell, where the metric coefficients are continuous, contains ultra-relativistic fluid of soft quanta obeying equation of state $\rho = p$. The outer region of this gravastar corresponds to the electrovacuum exterior solution popularly known as the charged BTZ black hole space–time.

3. Interior region

Seeking interior solution which is free of any mass-singularity at the origin, we use the assumption $p = -\rho$ iteratively. We note that this type of equation of state is available in the literature and is known as a false vacuum, degenerate vacuum, or ρ-vacuum [29–32] and represents a repulsive pressure. Hence by using the result given in Eq. (16), we obtain the following interior solutions:

$$e^{\gamma}=e^{-\lambda}=C-8Ar^2R^{2n+2}+\frac{2B}{(n+2)(2n+2)}r^{2n+4}-\Lambda r^2, \quad (21)$$

$$\rho=-p=\frac{2\pi\sigma_0^2(2n+4)}{(2n+2)(n+2)^2}\left(R^{2n+2}-r^{2n+2}\right), \quad (22)$$

where $A=\frac{B(2n+4)}{8(2n+2)}$ and $B=\frac{16\pi^2\sigma_0^2}{(n+2)^2}$. Here C is an integration constant.

We assume the surface of the charged distribution, i.e. shell is located at $r=R$. Therefore, we have the boundary condition $p(R)=0$. Here, we find the active gravitational mass $M(r)$ in the following form

$$M(r)=\int_0^R 2\pi r\left(\rho+\frac{E^2}{8\pi}\right)dr$$
$$=\frac{4(2n^2+8n+6)\pi^2\sigma_0^2}{(n+2)^2(2n+2)(2n+4)}R^{2n+4}. \quad (23)$$

It can be noted from Eq. (21) that, C being a non-zero integration constant, the space–time metric thus obtained is free from any central singularity. It can also be observed via Eqs. (22) and (23) that the physical parameters, viz. density, pressure and mass, are dependent on the charge. Therefore the solutions provide *electromagnetic mass* model, such that for vanishing charge density σ all the physical parameters do not exist [33–44]. However, in this connection one interesting point we note that for the interior region the above mentioned physical parameters in no way are dependent on the cosmological constant Λ.

4. Exterior region of charged gravastar

The electrovacuum exterior ($p=\rho=0$) solution corresponds to a static, charged BTZ black hole is written in the following form as [27]

$$ds^2=-\left(-M_0-\Lambda r^2-Q^2\ln r\right)dt^2$$
$$+\left(-M_0-\Lambda r^2-Q^2\ln r\right)^{-1}dr^2+r^2d\theta^2. \quad (24)$$

The parameter M_0 is the conserved mass associated with asymptotic invariance under time displacements. This mass is given by a flux integral through a large circle at space-like infinity. The parameter Q is total charge of the gravastar.

5. Shell

We consider thin shell contains ultra-relativistic fluid of soft quanta obeying equation of state $p=\rho$. This assumption is not new rather known as a stiff fluid and this type of equation of state which refers to a Zel'dovich Universe have been used by various authors to study some cosmological [45–47] as well as astrophysical [48–50] phenomena.

It is very difficult to solve the field equations within the non-vacuum region II, i.e. within the shell. However, one can obtain analytic solution within the framework of thin shell limit, $0<e^{-\lambda}\equiv h\ll 1$. The advantage of using this thin shell limit is that in this limit we can set h to be zero to the leading order. Then the field equations (9)–(11), with $p=\rho$, may be recast in the forms

$$h'=-4r\left(\Lambda+E^2\right), \quad (25)$$

$$\frac{\gamma'}{4}h'=2E^2. \quad (26)$$

Integrate (25) immediately to yield

$$h=D-2\Lambda r^2-\left[\frac{2B}{n+2}\right]r^{2n+4}, \quad (27)$$

where D is an integration constant. Since, in the interior of the shell, h takes very very small values, one can assume $h\approx 0(\epsilon)$, where ϵ is the thickness of the shell. We further assume that thickness of the shell is very very small. This means ϵ is very very small, $0<\epsilon\ll 1$. As a result, we demand that D, Λ and B all should be $\ll 1$. In other words, we can take D, Λ and B are all of order of ϵ, i.e. $\approx 0(\epsilon)$.

Employing this value in Eq. (26), we obtain the other metric coefficient as

$$e^{\gamma}=\frac{1}{[\Lambda+Br^{2n+2}]^{\frac{1}{n+1}}}. \quad (28)$$

Also, using TOV equation (20), one can get

$$8\pi p=8\pi\rho=\left[\frac{n+2}{n}\right]\left[\Lambda+Br^{2n+2}\right]. \quad (29)$$

Unlike the interior region, we note that the cosmological constant Λ has a definite contribution to the pressure and density parameters of the shell in an additive manner.

6. Proper length and energy

We assume the interfaces at $r=R$ and $r=R+\epsilon$ describing the joining surface between two regions I and III. Recall the joining surface is very thin. Now, we calculate the proper thickness between two interfaces, i.e. of the shell as:

$$\ell=\int_R^{R+\epsilon}\sqrt{e^{\lambda}}\,dr=\int_R^{R+\epsilon}\frac{1}{\sqrt{h(r)}}\,dr. \quad (30)$$

Let F be the primitive of $\frac{1}{\sqrt{h(r)}}$. Then, $\frac{dF}{dr}=\frac{1}{\sqrt{h(r)}}$.

Hence, we get

$$\ell=[F]_R^{R+\epsilon}. \quad (31)$$

Using Taylor's theorem, one can expand $F(R+\epsilon)$ about R and retaining terms up to the first order of ϵ, then, $F(R+\epsilon)\simeq F(R)+\epsilon F'(R)$ and our ℓ would be $\ell\approx\epsilon\frac{dF}{dr}|_{r=R}$.

Therefore, the expression for ℓ can be written as

$$\ell\approx\frac{\epsilon}{\sqrt{D-2\Lambda R^2-[\frac{2B}{n+2}]R^{2n+4}}}. \quad (32)$$

The real and positive value of proper length implies $D>2\Lambda R^2+[\frac{2B}{n+2}]R^{2n+4}$. However, it can be noted that the thickness between two interfaces becomes infinitely large if D takes the value very close to $2\Lambda R^2+[\frac{2B}{n+2}]R^{2n+4}$. On the other hand the proper length ℓ will decrease in the absence of the cosmological constant Λ. Obviously, the estimated size ℓ, i.e. proper thickness and coordinate thickness of the shell are different. Actually, $\ell\approx o(\sqrt{\epsilon})$ as D, Λ and $B\approx o(\epsilon)$.

We now calculate the energy $\tilde{E}$ within the shell only and we get

$$\tilde{E}=2\pi\int_R^{R+\epsilon}\left[\rho+\frac{E^2}{8\pi}\right]r\,dr$$
$$=\frac{1}{4}\left[\frac{(2n+4)\Lambda}{4n}\left[(R+\epsilon)^2-R^2\right]+\frac{(4n+4)B}{2n(2n+4)}\left[(R+\epsilon)^{2n+4}-R^{2n+4}\right]\right].$$

Since the thickness ϵ of the shell is very small, i.e. $\epsilon \ll 1$, we expand it binomially about R and taking first order of ϵ, we get

$$\tilde{E} \approx \frac{\epsilon}{4}\left[\frac{(2n+4)\Lambda R}{2n} + \frac{(4n+4)B}{2n}R^{2n+3}\right]. \tag{33}$$

Obviously here $n \neq 0$. As before, we also notice that the energy $\tilde{E}$ is of the order of ϵ^2, i.e. $\tilde{E} \approx o(\epsilon^2)$.

7. Entropy

Adopting concept of Mazur and Mottola [1,2], we try to calculate the entropy of the fluid within the shell

$$S = 2\pi \int_R^{R+\epsilon} s(r) r \sqrt{e^{\lambda}}\, dr. \tag{34}$$

Here $s(r)$, the entropy density for the local temperature $T(r)$, is given by

$$s(r) = \frac{\alpha^2 k_B^2 T(r)}{4\pi \hbar^2} = \alpha\left(\frac{k_B}{\hbar}\right)\sqrt{\frac{p}{2\pi}}, \tag{35}$$

where α^2 is a dimensionless constant.

Thus the entropy of the fluid within the shell, via Eq. (29), becomes

$$S = 2\pi \int_R^{R+\epsilon} \alpha\left(\frac{k_B}{\hbar}\right)\frac{1}{4\pi}\frac{\sqrt{\left[\frac{2n+4}{2n}\right]}\sqrt{\left[\Lambda r^2 + Br^{2n+4}\right]}\, dr}{\sqrt{D - 2\Lambda r^2 - \left[\frac{2B}{n+2}\right]r^{2n+4}}}. \tag{36}$$

Since, thickness of the shell is negligibly small compared to its position R from the centre of the gravastar (i.e. $\epsilon \ll R$), in the similar way, as we have done above, by expanding the primitive of the above integrand about R and retaining terms up to the first order of ϵ, we have the entropy as

$$S \approx \alpha\left(\frac{k_B}{\hbar}\right)\frac{\epsilon}{2}\frac{\sqrt{\left[\frac{2n+4}{2n}\right]}\sqrt{\left[\Lambda R^2 + BR^{2n+4}\right]}}{\sqrt{D - 2\Lambda R^2 - \left[\frac{2B}{n+2}\right]R^{2n+4}}}. \tag{37}$$

The expression for the entropy shows that the cosmological constant Λ contributes to it a constant part. The entropy of the shell is of the order of ϵ, i.e. $S \approx 0(\epsilon)$.

8. Junction condition

To match the interior region to the exterior electrovacuum solution at a junction interface S, situated at $r = R$, one needs to use extrinsic curvature of S. The surface stress energy and surface tension of the junction surface S could be determined from the discontinuity of the extrinsic curvature of S at $r = R$. Here the junction surface is a one-dimensional ring of matter. Let η denote the Riemann normal coordinate at the junction. We assume η be positive in the manifold in region III described by exterior electrovacuum BTZ space–time and η be negative in the manifold in region I described by our interior space–time. In terms of mathematical notations, we have $x^{\mu} = (\tau, \phi, \eta)$ and the normal vector components $\xi^{\mu} = (0, 0, 1)$ with the metric $g_{\eta\eta} = 1$, $g_{\eta i} = 0$ and $g_{ij} = \mathrm{diag}(-1, r^2)$. The second fundamental forms associated with the two sides of the shell [51–56] are given by

$$K_j^{i\pm} = \frac{1}{2} g^{ik}\frac{\partial g_{kj}}{\partial \eta}\bigg|_{\eta=\pm 0} = \frac{1}{2}\frac{\partial r}{\partial \eta}\bigg|_{r=R} g^{ik}\frac{\partial g_{kj}}{\partial r}\bigg|_{r=R}. \tag{38}$$

So, the discontinuity in the second fundamental forms is given as

$$\kappa_{ij} = K_{ij}^{+} - K_{ij}^{-}. \tag{39}$$

Now, from Lanczos equation in $(2+1)$-dimensional space–time, the field equations are derived [52]:

$$\sigma = -\frac{1}{8\pi}\kappa_{\phi}^{\phi}, \tag{40}$$

$$v = -\frac{1}{8\pi}\kappa_{\tau}^{\tau}, \tag{41}$$

where σ and v are line energy density and line tension. Employing relevant information into Eqs. (40) and (41), and also by setting $r = R$, we obtain

$$\sigma = -\frac{1}{8\pi R}\left[\sqrt{-\Lambda R^2 - M_0 - Q^2 \ln R} + \sqrt{C - 8\Lambda R^{2n+4} - \frac{2B(2n+3)}{(2n+4)(2n+2)}R^{2n+4}}\right], \tag{42}$$

$$v = -\frac{1}{8\pi}\left[\frac{-\Lambda R - \frac{Q^2}{2R}}{\sqrt{-\Lambda R^2 - M_0 - Q^2 \ln R}} + \frac{(-8\Lambda R^{2n+3} - \frac{B(2n+3)}{(2n+2)}R^{2n+3})}{\sqrt{C - 8\Lambda R^{2n+4} - \frac{2B(2n+3)}{(2n+4)(2n+2)}R^{2n+4}}}\right]. \tag{43}$$

Similar to the $(3+1)$-dimensional case the energy density is negative in the junction shell. It is also noted that the line tension is negative which implies that there is a line pressure as opposed to a line tension. The thin shell, i.e. region II of our configuration contains two types of fluid namely, the ultra-relativistic fluid obeying $p = \rho$ and matter component with above stress tensor components (42) and (43) that are arisen due to the discontinuity of second fundamental form of the junction interface.

These two non-interacting components of the stress energy tensors are characterizing features of our non-vacuum region II.

9. Concluding remarks

In this Letter, we have presented a new model of charged gravastar in connection to the electrovacuum exterior $(2+1)$ anti-de Sitter space–time. One of the most interesting features of this model is that it is free from any singularity and hence represents a competent candidate in the class of gravastar as an alternative to black holes [1,2].

The solutions obtained here represent *electromagnetic mass* model [35]. Historically, Lorentz [33] proposed his model for extended electron and conjectured that "there is no other, no 'true' or 'material' mass", and thus provides only 'electromagnetic masses of the electron' whereas Wheeler [57] and Wilczek [58] pointed out that electron has a "mass without mass". Later on several works have been carried out by different investigators [34,36–44] under the framework of general relativity.

The cosmological constant Λ as proposed by Einstein [59] for stability of his cosmological model has been adopted here as a purely scalar quantity which has a definite contribution to the physical parameters with a constant additive manner. However, due to accelerating phase of the present Universe [60,61], this erstwhile Λ is now-a-days considered as a dynamical parameter varying with time in general. It is therefore a matter of curious issue whether varying Λ has any contribution in formation of the gravastars. It is to be noted that one should consider $\Lambda < 0$ as Cataldo and Cruz [27] obtained charged black hole solution with $\Lambda < 0$ that has a horizon. However, for $\Lambda > 0$ a cosmological type horizon exists with a naked singularity. Since the concept of gravastar is to search configuration which is alternative to black hole, therefore, $\Lambda < 0$ is the only possible choice for the gravastar configuration in three-dimensional space–time.

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