Physics Letters B 767 (2017) 380–385

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Charged gravastars in higher dimensions

S. Ghosh [a], F. Rahaman [b], B.K. Guha [a], Saibal Ray [c,*]

[a] Department of Physics, Indian Institute of Engineering Science and Technology, B. Garden, Howrah 711103, West Bengal, India
[b] Department of Mathematics, Jadavpur University, Kolkata 700032, West Bengal, India
[c] Department of Physics, Government College of Engineering and Ceramic Technology, 73 A.C.B. Lane, Kolkata 700010, West Bengal, India

ARTICLE INFO

Article history:
Received 6 November 2016
Received in revised form 3 February 2017
Accepted 8 February 2017
Available online 14 February 2017
Editor: M. Cvetič

Keywords:
General relativity
Higher dimension
Charged gravastar

ABSTRACT

We explore possibility to find out a new model of gravastars in the extended *D*-dimensional Einstein–Maxwell space–time. The class of solutions as obtained by Mazur and Mottola of a neutral gravastar [1,2] have been observed as a competent alternative to *D*-dimensional versions of the Schwarzschild–Tangherlini black hole. The outer region of the charged gravastar model therefore corresponds to a higher dimensional Reissner–Nordström black hole. In connection to this junction conditions, therefore we have formulated mass and the related Equation of State of the gravastar. It has been shown that the model satisfies all the requirements of the physical features. However, overall observational survey of the results also provide probable indication of non-applicability of higher dimensional approach for construction of a gravastar with or without charge from an ordinary 4-dimensional seed as far as physical ground is concerned.

1. Introduction

A decade or more ago Mazur and Mottola [1,2] have proposed a new solution for the endpoint of a gravitationally collapsing neutral system. By extending the concept of Bose–Einstein condensation to gravitational systems they constructed a cold compact object which consists of an (i) interior de Sitter condensate phase, and (ii) exterior Schwarzschild geometry. These are separated by a phase boundary with a small but finite thickness $r_2 - r_1 = \delta$ of the thin shell, where r_1 and r_2 represent the interior and exterior radii of the gravastar. Therefore, the equation of state (EOS) under consideration are as follows:

I. Interior: $0 \leq r < r_1$, with EOS $p = -\rho$,
II. Shell: $r_1 < r < r_2$, with EOS $p = +\rho$,
III. Exterior: $r_2 < r$, with EOS $p = \rho = 0$.

Here the presence of matter on the shell is required to achieve the stability of the systems under expansion by exerting an inward force to balance the repulsion from within. These types of *grav*itationally *va*cuum *stars* were termed as *gravastars*. Thereafter several scientists have been studied these models under different viewpoints and have opened up a new field of research as an alternative to *Black Holes* [3–15].

Very recently, a charged $(3+1)$-dimensional gravastar admitting conformal motion has proposed by some of our collaborators [16] in the framework of Mazur and Mottola model [1,2]. In this work the authors provide an alternative to static black holes. However, energy density here is found to diverge in the interior region of the gravastar. This actually scales like an inverse second power of its radius and unfortunately makes the model singular at $r = 0$. However, interestingly in one of the solutions it is shown that the total gravitational mass vanishes for vanishing charge and turns the total gravitational mass into an electromagnetic mass under certain conditions. An extension on charged gravastar of Usmani et al. [16] can be found in the work of Bhar [17] admitting conformal motion with higher dimensional space–time.

In the present study we generalize the four-dimensional work on gravastar by Usmani et al. [16] to the higher dimensional space–time, however without admitting conformal motion. Our main motivation here is to construct gravastars in the Einstein–Maxwell geometry and see the higher dimensional effects, if any. Therefore this investigation is also extension of the work of Bhar [17] without admitting conformal motion and that of Rahaman et al. [18] with charge where originally higher dimensional gravastar has been studied. A detailed discussion on higher dimension and its applications in various fields of astrophysics as well as cosmology has been provided in Ref. [18].

* Corresponding author.
E-mail addresses: shnkghosh122@gmail.com (S. Ghosh), rahaman@associates.iucaa.in (F. Rahaman), bkguhaphys@gmail.com (B.K. Guha), saibal@associates.iucaa.in (S. Ray).

http://dx.doi.org/10.1016/j.physletb.2017.02.014

The plan of the present investigation is as follows: In Sec. 2 the Einstein–Maxwell space–time geometry has been provided as the background of the study whereas in Sec. 3 we discuss the Interior space–time, Exterior space–time and Thin shell cases of the gravastars with their respective solutions. The related junction conditions are provided in Sec. 4. We explore physical features of the models, viz. proper length, energy condition, entropy, mass and equation of state in Sec. 5. At the end in Sec. 6 we provide some critically discussed concluding remarks.

2. The Einstein–Maxwell space–time geometry

For higher dimensional gravastar, we assume a D-dimensional space–time with the typical mathematical structure $R^1XS^1XS^d$ ($d=D-2$), where S^1 is the range of the radial coordinate r and R^1 is the time axis. Let us therefore consider a static spherically symmetric metric in $D=d+2$ dimension as

$$ds^2=-e^{\nu}dt^2+e^{\lambda}dr^2+r^2d\Omega_d^2, \tag{1}$$

where $d\Omega_d^2$ is a linear element on a d-dimensional unit sphere, parametrized by the angles $\phi_1,\phi_2,...,\phi_d$, as follows: $d\Omega_d^2=d\phi_d^2+\sin_2\phi_d[d\phi_{d-1}^2+\sin_2\phi_{d-1}\{d\phi_{d-2}^2+...+\sin_2\phi_3(d\phi_2^2+\sin_2\phi_2 d\phi_1^2)...\}]$.

Now, the Hilbert action coupled to matter and electromagnetic field can be provided as

$$I=\int d^Dx\sqrt{-g}\left[\frac{R_D}{16\pi G_D}+(L_m+F_{ik}F^{ik})\right], \tag{2}$$

where L_m is the matter part of the Lagrangian and F_{ij} is the electromagnetic field tensor which is related to the electromagnetic potentials through the relation $F_{ij}=A_{i,j}-A_{j,i}$.

In the above Eq. (2) the term R_D is the curvature scalar in D-dimensional space–time whereas G_D is the D-dimensional Newtonian constant and L_m is the Lagrangian for matter–energy distribution.

The Einstein–Maxwell field equations now can be written as

$$G_{ij}^D=-8\pi G_D[T_{ij}^m+T_{ij}^{em}], \tag{3}$$

where G_{ij}^D is the Einstein tensor in D-dimensional space–time, T_{ij}^m and T_{ij}^{em} are the matter–energy and electromagnetic tensors respectively.

We assume that the interior of the star is filled up with perfect fluid and therefore the matter–energy tensors can be considered in the following form

$$T_{ij}^m=(\rho+p)u_iu_j+pg_{ij}, \tag{4}$$

where ρ is the energy density, p is the isotropic pressure and u^i (with $u_iu^i=1$) is the D-velocity of the fluid under consideration.

On the other hand, the electromagnetic tensors can be provided as

$$T_{ij}^{em}=-\frac{1}{4\pi G_D}\left[F_{jk}F_i^k-\frac{1}{4}g_{ij}F_{kl}F^{kl}\right]. \tag{5}$$

The corresponding Maxwell electromagnetic field equations are

$$[(-g)^{1/2}F^{ij}]_{,j}=4\pi J^i(-g)^{1/2}, \tag{6}$$

$$F_{[ij,k]}=0, \tag{7}$$

where J^i is the current four-vector satisfying $J^i=\sigma u^i$, the parameter σ being the charge density.

Hence the Einstein–Maxwell field equation (3), for the metric (1) along with the energy–momentum tensors, Eqs. (4)–(7), can be provided in the following explicit forms

$$-e^{-\lambda}\left[\frac{d(d-1)}{2r^2}-\frac{d\lambda'}{2r}\right]+\frac{d(d-1)}{2r^2}=8\pi G_D\,\rho+E^2, \tag{8}$$

$$e^{-\lambda}\left[\frac{d(d-1)}{2r^2}+\frac{d\nu'}{2r}\right]-\frac{d(d-1)}{2r^2}=8\pi G_D\,p-E^2, \tag{9}$$

$$\frac{e^{-\lambda}}{2}\left[\nu''-\frac{\lambda'\nu'}{2}+\frac{\nu'^2}{2}-\frac{(d-1)(\lambda'-\nu')}{r}+\frac{(d-1)(d-2)}{r^2}\right]-\frac{(d-1)(d-2)}{2r^2}=8\pi G_D\,p+E^2, \tag{10}$$

where E is the electric field. Here the symbol '$\prime$' denotes differentiation with respect to the radial parameter r and $c=1$ (in geometrical unit).

Therefore, the energy conservation equation in the D-dimensions is given by

$$\frac{1}{2}(\rho+p)\,\nu'+p'=\frac{1}{4\pi G_D r^d}(r^dE^2)', \tag{11}$$

with the electric field E as follows

$$(r^dE)'=\frac{2\pi^{\frac{d+1}{2}}}{\Gamma(\frac{d+1}{2})}r^d\sigma(r)e^{\lambda/2}. \tag{12}$$

In traditional sense, the term $\sigma e^{\lambda/2}$ appearing in the right hand side of Eq. (12), is known as the volume charge density. The assumption $\sigma e^{\lambda/2}=\sigma_0 r^m$, can consistently be understood as the higher dimensional volume charge density being polynomial function of r where the constant σ_0 is the central charge density.

Now from the above Eq. (12) by assuming $\sigma e^{\lambda/2}=\sigma_0 r^m$, we obtain the explicit form of the electric field as given by

$$E=\frac{q}{r^d}=\frac{2\pi^{\frac{d+1}{2}}\sigma_0}{\Gamma(\frac{d+1}{2})}\frac{r^{m+1}}{(d+m+1)}=Ar^{m+1}, \tag{13}$$

where $A=\frac{2\pi^{\frac{d+1}{2}}\sigma_0}{\Gamma(\frac{d+1}{2})(d+m+1)}$.

3. The gravastar models

3.1. Interior space–time

Following [1] we assume that the EOS for the interior region has the form

$$p=-\rho. \tag{14}$$

The above EOS is known in the literature as a 'false vacuum', 'degenerate vacuum', or 'ρ-vacuum' [19–22] which represents a repulsive pressure, an agent responsible for the accelerating phase of the Universe, and is termed as the Λ-dark energy [23–27]. It is argued by [16] that a charged gravastar seems to be connected to the dark star [28–30].

The above EOS along with Eq. (11) readily provides

$$p=-\rho=k_1r^{2(m+1)}+k_2. \tag{15}$$

where $k_1=\frac{A^2(2m+d+2)}{4\pi G_D(2m+2)}$ and k_2 is an integration constant. However, if we put $r=0$ in Eq. (15), then it easily assigns the value of the integration constant $k_2=p_c=-\rho_c$. In general there is no sufficient argument to take pressure and density to be zero at the junction surface. Actually, in the thin shell limit the pressure and density are step functions at the junction surface [31]. However, for the sake of brevity and convenience, if one considers boundary condition on the spherical surface that at $r=R$ the pressure and density in Eq. (15) vanish, then it yields $k_2=-k_1R^{2(m+1)}=-\rho_c$,