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Binding energy in self-gravitating charged plane symmetric systems

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ABSTRACT

This paper explores gravitational binding energy in static charged planar spacetime with perfect fluid configuration. We use Darmois formalism to explore the matching conditions of planar symmetry as an interior region and charged Vaidya as an exterior. The mass function is evaluated over the hypersurface to investigate the binding energy in the interior region. We conclude that gravitational field of the planar spacetime binds only the localized part while the non-localized part is due to the electric coupling.

1. Introduction

It is well-known that all forms of matter and energy act as a source of gravitational field. The energy required to disintegrate particles which are bounded by electromagnetic or nuclear forces into its constituent elements is known as binding energy. The connection between the mass function and dynamical structure of celestial bodies is an important and challenging problem in today's physics. Alécian and Morsink [1] discussed the idea of binding energy for relativistic model of compact star and reviewed the mass deficit in the scenario of gravitational radiation.

The exploration of binding energy and mass function for self-gravitating systems in the cosmos has always been an interesting issue in relativistic astrophysics. Wolf [2] calculated the binding energy for Schwarzschild sphere and demonstrated the stability of higher dimensional spheres under certain limits. Using the results of mass in spherical symmetry, Chatterjee and Bhui [3] concluded that pressure at boundary turns out to be zero in higher dimensions with perfect fluid while this is not true in the radiating case. He et al. [4] investigated gravitational binding energy of spherical matter distribution by evaluating Tolman–Oppenheimer–Volkoff equations with equation of state. Different authors [5,6] suggested that binding energy contribution to the total mass is significant up to 25% of its rest mass and its exact size depends on the equation of state.

Singh [7] obtained solutions of the Einstein–Maxwell field equations representing fields due to infinite charged planes. Tsagas [8] studied electromagnetic effects in general curved spacetimes using non-perturbative analysis. Sharif and Yousaf [9–20] explored the electromagnetic and matter variable effects for different collapsing stars under physical conditions. We have also examined the effects of different physical factors including charge on different collapsing models [21–30]. The compact stars like gravastars, neutron stars and quark stars etc can be modeled to describe charged gravitating matter in

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the study of relativistic astrophysics. In such situation, the static spacetime provides basis to investigate the structural properties of stellar systems which has attracted many researchers.

The best known example of static spacetime in general relativity is referred as Schwarzschild black hole. There exist different metrics related with many astrophysical scenarios particularly dealing with extra degrees of freedom in alternative theories of gravity. The Einstein static universe was converted into a class of physically viable fluid spheres under static configuration, whose physical quantities were also expressed explicitly [31,32]. Most of the study that includes electromagnetic effects is based on isotropic stars. Many stellar models that describe charged and uncharged stars with anisotropic and isotropic pressure in the interior are available in the literature [33–43]. Tiwari et al. [44] constructed the electromagnetic mass model and showed that pressure and mass-energy density of the matter profile has electromagnetic origin.

It is believed that only localized contributions are represented by the energy-momentum tensor and the gravitational forces are necessary for an object to be bounded. Corne et al. [45] found that gravitational mass encloses the non-localized contribution due to electromagnetic field and does not contribute toward gravitational binding for static spherical stars. Sharif and Bhatti [46] investigated the gravitational binding energy for cylindrical geometry with electromagnetic effects and discussed the localized and non-localized contributions in the mass function. In order to discuss the early universe, Saha and Shikin [47] argued that planar models are more suitable than spherical one.

The aim of this work is to examine the electromagnetic effects on the binding of self-gravitating planar spacetime with perfect fluid. The format of this paper is as follows. In the next section, we deal with plane symmetric spacetime with contribution of electromagnetic field. Section 3 investigates the matching conditions for interior and exterior spacetimes and explores the mass function which has both local and non-local parts. Finally, we summarize our discussion in the last section.

2. Plane symmetry and charge distribution

The static plane symmetric spacetime is given as follows

$$ds^2=-A^2dt^2+B^2\left(dx^2+dy^2\right)+C^2dz^2, \tag{1}$$

where A, B and C are dimensionless functions of z. We assume that this is filled with perfect fluid and electromagnetic field as

$$T_{\alpha\beta}=(P+\mu)V_\alpha V_\beta+Pg_{\alpha\beta}+\frac{1}{4\pi}\left(F^\gamma_\alpha F_{\beta\gamma}-\frac{1}{4}F_{\gamma\delta}F^{\gamma\delta}g_{\alpha\beta}\right), \tag{2}$$

where P, μ and V_α are the pressure, energy density and four-velocity of the fluid, respectively while $F_{\alpha\beta}$ is the strength field tensor. For comoving fluid, the four-velocity reads $V_\alpha=-A\delta^0_\alpha$ satisfying $V^\alpha V_\alpha=-1$. The independent components of the Einstein tensor for Eq. (1) are

$$\begin{aligned}
G_{00} &= -\left(\frac{A}{C}\right)^2\left[\frac{2B''}{B}-\left(\frac{2C'}{C}-\frac{B'}{B}\right)\frac{B'}{B}\right],\\
G_{11} &= \left(\frac{B}{C}\right)^2\left[\frac{A''}{A}+\frac{B''}{B}-\frac{A'}{A}\left(\frac{C'}{C}-\frac{B'}{B}\right)-\frac{B'C'}{BC}\right]=G_{22},\\
G_{33} &= \left(\frac{B'}{B}\right)^2+\frac{2A'B'}{AB},
\end{aligned} \tag{3}$$

here prime indicates derivatives with respect to z. The electric field $\mathbf{E}=E(z)\mathbf{e_z}$ is a physical field, where $\mathbf{e_z}$ is the normal vector in z-direction. The independent components of the matter energy tensor in electromagnetic field yields

$$\begin{aligned}
T_{00} &= \left(\mu+2\pi\mathbf{E}^2\right)A^2,\quad T_{11}=\left(p+2\pi\mathbf{E}^2\right)B^2=T_{22},\\
T_{33} &= \left(p-2\pi\mathbf{E}^2\right)C^2.
\end{aligned} \tag{4}$$

Using Eqs. (3) and (4), the 00-component of Einstein–Maxwell field equation, $G_{\alpha\beta}=8\pi T_{\alpha\beta}$, leads to

$$-\frac{d}{dz}\left(\frac{BB'^2}{C^2}\right)=8\pi B'B^2\left(\mu+2\pi E^2\right), \tag{5}$$

where $E=\frac{\mu_0 s}{4\pi B^2}$. The electric field of the charge distribution can be evaluated through Gauss law

$$\nabla\cdot\mathbf{E}=4\pi\xi, \tag{6}$$

where ξ is termed as charge density.