acta phys. slov. 42 (1992), No. 5, 257–266

COMPACT GENERAL RELATIVISTIC CONFIGURATION OF CHARGED MATTER AND SCALAR FIELD IN D SPACE TIME DIMENSIONS

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The general relativistic problem of charged matter coupled to a symmetry breaking scalar field is studied in D space time dimensions. The interior and exterior metric are found using a certain approximation and the condition that the normal pressure vanishes within the charge configuration. The matching of the exterior and interior solution leads to expressions for the mass and charge of the configuration.

I. INTRODUCTION

The problem of spherically symmetric solutions to the Einstein equations coupled to matter has certainly been a well worked field of research. The historic interior Schwarzschild solution [1], charged fluid spheres [2, 3] and solutions involving a scalar field coupled to matter [4] represent a class of problems that have been thoroughly studied in the past. The problem of compact configurations of fermionic matter received attention because of the possibility that it might represent a neutron star. In fact, limits on the maximum mass of a neutron star have been established to within an order of magnitude of a stellar mass [5]. The motivation for work on the stability of gas spheres arose from the discovery of quasars which were conjectured to be of galatic size and became unstable through gravitational instability. Both Chandrasekhar [6] and Wright [7] did much of the original work on quasar stability. In a modern context the existence of super gravity theory has suggested the presence of scalar such as the dilaton and the graviscalar, which in principle couple to gravitation to form compact bound configurations [8, 9]. Questions of just how scalars couple to gravitation remain for the most part unanswered and at present models arise primarily from arguments involving symmetry. Since the superstring always leaves a scalar at low energy it would be of interest to find out just what type of configuration arises when such a scalar couples to gravity in D space time dimensions. In this paper we study a simple model of gravitation coupled to electromagnetism, a scalar field and matter with given equation of state that may simulate conditions near the pre-G.U.T. era. Quite long ago Florides [10] studied a spherical configuration of matter in GR with vanishing normal pressure and recently Krori et. al [11] studied the same problem in D space time dimensions with the cosmological constant present. In

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our analysis we study a configuration of gravitation coupled to electromagnetism and symmetry breaking the neutral scalar field along with matter of the prescribed equation of state. By solving the scalar equation approximately we find expressions for the mass and charge along with expressions for the interior and exterior metric in D space time dimensions. One of the interesting by-products of our analysis is that within the configuration we study, the scalar field at the center cannot be either in the false vacuum or true vacuum to have a spatial variation over the dimensions of the object we study. This fact may have significance in higher dimensional inflationary cosmology wherein the scalar field is assumed homogeneous prior to the development of perturbations. The possibility that such higher dimensional configurations may arise in the cosmos has been discussed by Sakharov, wherein he has suggested the presence of domains of higher dimensionality, non-trivial topology and varying signature which may communicate with the usual world of 4 space time dimensions through electromagnetic effects [12]. It is in this spirit that the following investigation be taken, both as a solution to a problem in higher dimensional gravitation as well as a probe to higher dimensions.

II. COMPACT CONFIGURATION OF ELECTROMAGNETISM AND MATTER COUPLED TO A SCALAR FIELD IN D SPACE TIME DIMENSIONS.

We begin our analysis by writing for the spherically symmetric metric in D space time dimensions

$$(ds)^2 = e^{\nu}(dx^0)^2 - e^{\lambda}(dr)^2 - r^2(d\Theta_1)^2 - r^2\sin^2\Theta_1(d\Theta_2)^2 - r^2\sin^2\Theta_1\sin^2\Theta_2(d\Theta_3)^2 - r^2\sin^2\Theta_1\sin^2\Theta_2\cdots\sin^2\Theta_{D-3}(d\Phi)^2 \quad (1)$$

with

$$0 \le r < \infty, \qquad 0 \le \Theta_i \le \pi, \qquad 0 \le \Phi \le 2\pi.$$

For the Ricci component we have

$$\begin{aligned} R_{00} &= -\frac{1}{4}(v')^2 e^{(\nu-\lambda)} - \frac{1}{2}v'' e^{(\nu-\lambda)} + \frac{1}{4}v'\lambda' e^{(\nu-\lambda)} - \frac{(D-2)}{2r}v' e^{(\nu-\lambda)}, \\ R_{11} &= \frac{v''}{2} + \frac{1}{4}(v')^2 - \frac{1}{4}v'\lambda' - \frac{(D-2)}{2r}\lambda', \\ R_{22} &= (D-3)(e^{-\lambda} - 1) - \frac{re^{-\lambda}}{2}(\lambda' - v'), \\ R_{33} &= R_{22}\sin^2\Theta_1 \\ &\vdots \\ R_{D-1,D-1} &= R_{22}\sin^2\Theta_1 - \sin^2\Theta_{D-3}(d\Phi)^2. \end{aligned} \quad (2)$$

For the lagrangian of the electromagnetic field plus scalar field we have

$$L = -\frac{1}{K}F_{\mu\nu}F^{\mu\nu}\sqrt{-g} - J^{\mu}A_{\mu}\sqrt{-g} + \left[\frac{\partial^{\mu}\Phi\partial_{\mu}\Phi}{2} - \frac{A_2}{4}\left(\Phi^2 - \frac{A_1}{A_2}\right)^2\right]\sqrt{-g}, \quad (3)$$

where we have included the symmetry breaking scalar field specified by the potential

$$\frac{A_2}{4}\left(\Phi^2 - \frac{A_1}{A_2}\right)^2.$$

For the matter with given pressure and energy density we have for $r \le R$

$$\begin{aligned} T_0^0 &= \varepsilon, \\ T_1^1 &= 0, \\ T_2^2 &= -P, \\ T_3^3 &= -P, \\ &\vdots \\ T_{D-1}^{D-1} &= -P \end{aligned} \quad (4)$$

(ε_0 = constant energy density). Here we have vanishing normal pressure tor the matter specified by $T_1^1 = 0$ for $r \le R$. For the field equations for the electromagnetic field we have

$$\frac{\partial}{\partial x^{\nu}}\left(\frac{4}{K}F^{\mu\nu}\sqrt{-g}\right) = \sqrt{-g}J^{\mu}, \quad (5)$$

where $F_{10} = E(r)$, $J^0 = \rho_0\frac{dx^0}{dS} = \rho_0 e^{-\nu/2}$; (6)

here ρ_0 = constant proper charge density for $r \le R$. Eq. (5) gives for $r \le R$

$$\frac{\partial}{\partial r}\left(\frac{4}{K}r^{(D-2)}E(r)e^{-(\nu+\lambda)/2}\right) = \rho_0 r^{(D-2)}e^{-\nu/2}e^{(\nu+\lambda)/2}$$

or

$$E(r) = \frac{Ke^{(\nu+\lambda)/2}}{4r^{(D-2)}}\int^r \rho_0 r^{(D-2)}e^{\lambda/2}dr \quad (7)$$

for $r \le R$. For normalization (that the right-hand side represents Q/R^{D-2} ar $r = R$) we choose

$$\frac{K}{4} = \frac{\pi^{(D-1)/2}}{\left(\frac{D-1}{2}\right)!}(D-1)$$

or

$$K = \frac{4\pi^{(D-1)/2}}{\left(\frac{D-1}{2}\right)!}(D-1). \quad (8)$$

For the scaler field equation we have upon varying Eq. (3) with respect to Φ

$$-\Box\Phi - A_2\Phi\left(\Phi^2 - \frac{A_1}{A_2}\right) = 0 \quad (9)$$

giving in the approximation $e^{\lambda} \simeq e^{\nu} = 1$

$$\frac{1}{r^{D-2}}\frac{d}{dr}(r^{D-2}\Phi_{,r}) - A_2\Phi\left(\Phi^2 - \frac{A_1}{A_2}\right) = 0. \tag{10}$$

When Eq. (10) is written in more detail we obtain

$$r^{(D-2)}\Phi_{,rr} + (D-2)r^{D-3}\Phi_{,r} - A_2\Phi\left(\Phi^2 - \frac{A_1}{A_2}\right)r^{D-2} = 0. \tag{11}$$

Eq. (11) can be rewritten as

$$r^2\Phi_{,rr} + (D-2)r\Phi_{,r} - A_2\Phi\left(\Phi^2 - \frac{A_1}{A_2}\right)r^2 = 0. \tag{12}$$

If we consider the cubic term as a perturbation, the equation (12) without the cubic term is

$$r^2\Phi_{,rr} + (D-2)r\Phi_{,r} + A_1\Phi r^2 = 0. \tag{13}$$

Eq. (13) always has the power series solution

$$\Phi = \sum_{i=0}^{\infty} a_i r^i$$

about $r = 0$. Eq. (12) with the cubic term can be solved in the perturbation theory in principle about the unperturbed solution. Thus, if the unperturbed solution converges for the interior of the charged sphere we studied, the perturbed solution will be convergent. If we substitute

$$\sum_{i=0}^{\infty} a_i r_i$$

into Eq. (13), we find

$$a_i = -\frac{a_{i-2}A_1}{i(i-1) + (D-2)r}, \tag{14}$$

which gives

$$\lim_{i\to\infty} \frac{a_i}{a_{i-2}} = 0.$$

Thus the power series for the unperturbed solution converges for all $r \leq R$ and thus the power series for the perturbed solution will always converge for all $r \leq R$ since it is constructed from the unperturbed solution in perturbation theory, provided the term $r^2A_2\Phi^3$ in Eq. (12) is small relative to the linear term $A_1\Phi r^2$.

To develop a power series solution of Eq. (12) we explore

$$\sum_{i=0}^{\infty} a_i r^i$$

in Eq. (12) and equate the coefficients of r^{α} up to $\alpha = 4$ equal to zero to obtain the first four terms of the series, this gives

$$\begin{aligned} a_1 &= 0, \\ a_2 &= \frac{a_0(A_2a_0^2 - A_1)}{2D-2}, \\ a_3 &= 0, \\ a_4 &= \frac{-A_1a_2 + 3a_0^2a_2A_2}{4D+4}. \end{aligned} \tag{15}$$

Suppose we choose $\Phi(R=0) = 0$, then $a_0 = 0$, $a_1 = a_2 = a_3 = a_4 \cdots = 0$ and the entire domain of $0 \leq r \leq R$ is in the false vacuum ($\Phi = 0$). Next suppose we choose $\Phi(r=0) = \sqrt{A_1/A_2}$, then $a_1 = 0$, $a_2 = 0$, $a_4 = 0$ and the entire domain of $0 \leq r \leq R$ is in the true vacuum ($\Phi = \sqrt{A_1/A_2}$). Thus to develop an inhomogeneous solution (Φ varying with r) we must have $\Phi(r=0) \neq 0, \sqrt{A_1/A_2}$. Let us call the central value of the field Φ_c, then from Eq. (15) we have

$$\begin{aligned} a_0 &= \Phi_c, \\ a_1 &= 0, \\ a_2 &= \frac{\Phi_c(A_2\Phi_c^2 - A_1)}{4D+4}, \\ a_3 &= 0, \\ a_4 &= \frac{3\Phi_c^2a_2A_2 - A_1a_2}{4D+4}. \end{aligned} \tag{16}$$

For $r > R$ we choose the true vacuum so that it satisfies Eq. (12) for $r > R$, thus,

$$\Phi = \sqrt{\frac{A_1}{A_2}} \quad \text{for } r > R.$$

If we match

$$\Phi = \sqrt{\frac{A_1}{A_2}} \quad \text{at } r = R$$

to the approximate solution found in Eq. (16) for $r < R$, we can tune Φ_c so that the approximate solution given by

$$\Phi = \sum_{i=0}^{4} a_i r^i$$

with coefficients given by Eq. (16) matches smoothly to the exterior true vacuum solution at $r = R$ given by

$$\Phi = \sqrt{\frac{A_1}{A_2}};$$

this can be done to any order of r by calculating a_6, a_8, etc. and matching the interior solution to

$$\sqrt{\frac{A_1}{A_2}}$$

at $r = R$ by choosing Φ_c to have the appropriate values to accomplish this matching at $r = R$.

Thus,

$$\Phi = \sum_{i=0}^{4} a_i r^i \quad \text{for } r < R \tag{17}$$

with a_i given by Eq. (16), and

$$\Phi = \sqrt{\frac{A_1}{A_2}} \quad \text{for } r > R.$$

The above solution for Φ is continuous at $r = R$ but its derivative is not. To find a solution wherein the field Φ and its derivative are continuous at $r = R$ we take the approximate solution given by Eq. (17) with coefficients given by Eq. (16) and equate it to

$$\sqrt{\frac{A_1}{A_2}} \quad \text{at } r > R$$

and equate its derivative to 0 at $r = R$, since the derivative of $\sqrt{\frac{A_1}{A_2}}$ (exterior solution) is zero at $r = R$. This will place a restriction on Φ_c and R and determine the central value of Φ_c and R in terms of A_1 and A_2 since equating

$$\Phi = \sqrt{\frac{A_1}{A_2}} \quad \text{at } r = R, \quad \text{and } \frac{\mathrm{d}\Phi}{\mathrm{d}r} = 0 \quad \text{at } r = R$$

gives two equations for Φ_c and R in terms of $\sqrt{\frac{A_1}{A_2}}$ (from Eq. (16) and Eq. (17)).

When we do not insist that the derivative of Φ is zero at $r = R$, we have a less restrictive solution with arbitrary R.

We next solve for F_{10} for $r \le R$ and $r > R$. If we approximate $e^{\lambda} \simeq 1$, $e^{\nu} \simeq 1$ for $r \le R$, we have from Eq. 7

$$E(r) = \frac{K r \rho_0}{4(D-1)}. \tag{18}$$

For $r > R$ we have from Eq. (5)

$$\frac{\partial}{\partial r}\left(\frac{4}{K} r^{(D-2)} E\right) = 0 \tag{19}$$

or $\frac{4}{K} r^{(D-2)} E = Q\left(\frac{4}{K}\right)$ (Q = total electric charge of configuration).

Thus

$$E(r) = \frac{K r \rho_0}{4(D-1)} \quad \text{for } r \le R \quad (\text{using } e^{\nu} \cong e^{\lambda} \simeq 1),$$
$$E(r) = \frac{Q}{r^{D-2}} \quad \text{for } r > R; \tag{20}$$

for $r > R$ we have used the condition $\lambda + \nu = 0$, which follows from the $\binom{1}{1}$ and $\binom{0}{0}$ Einstein equations and the form of the electromagnetic energy momentum tensor for $r < R$, which is

$$(T_{\mu\nu})_{EM} = \frac{g_{\mu\nu}}{K} F_{\alpha\beta} F^{\alpha\beta} - \frac{4}{K} F_{\mu\alpha} F^{\alpha}_{\nu}. \tag{21}$$

With $r > R$, for the scalar field which is constant we have $T_1^1 = T_0^0$ and from Eq. (21) we have $T\binom{1}{1}_{EM} = T\binom{0}{0}_{EM}$ for $r > R$. These two contributions to T_1^1 and T_0^0 insure $\lambda + \nu = 0$ for $r > R$. Also equating the two values of $E(r)$ at $r = R$ from Eq. (20) we have

$$Q = \frac{K \rho_0}{4(D-1)} R^{(D-1)} \tag{22}$$

(in the approximation $e^{\nu} \cong e^{\lambda} \cong 1$ for $r < R$); this relation gives

$$Q = \frac{4}{3}\pi R^3 \rho_0 \quad \text{for } D = 4.$$

This is the mass-charge relation in the approximation $e^{\lambda} \simeq e^{\nu} \simeq 1$ for $r \le R$.

We next evaluate the exterior metric. For the scalar field we have the energy momentum tensor from Eq. (3)

$$T_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\partial L_{\Phi}}{\partial g^{\mu\nu}} = \partial_{\mu}\Phi \partial_{\nu}\Phi - \frac{g_{\mu\nu}(\partial^{\alpha}\Phi \partial_{\alpha}\Phi)}{2} + g_{\mu\nu}\frac{A_2}{4}\left(\Phi^2 - \frac{A_1}{A_2}\right)^2, \tag{23}$$

for $r > R$ this gives

$$T_1^1 = T_0^0 = \frac{A_2}{4}\left(\Phi^2 - \frac{A_1}{A_2}\right)^2 = 0, \quad \text{since } \Phi = \sqrt{\frac{A_1}{A_2}} \quad \text{for } r > R. \tag{24}$$

For the electromagnetic field we have for $r > R$ from the second of Eq. (20) and Eq. (21)

$$T_1^1 = T_0^0 = \frac{2Q^2}{K r^{2D-4}}. \tag{25}$$

Combining Eq. (24) and Eq. (25) and inserting them in the $\binom{0}{0}$ in the Einstein equations for $r > R$ we have

$$\frac{\mathrm{d}}{\mathrm{d}r}(r^{D-3} e^{-\lambda}) = (D-3) r^{(D-4)} - \frac{8\pi G}{c^4}\left(\frac{2}{D-2}\right) r^{D-2}\left(\frac{2Q^2}{K r^{2D-4}}\right). \tag{26}$$

Integrating Eq. (26) gives for $r > R$,

$$e^{-\lambda} = 1 - \frac{2GM}{r^{D-3}c^2}F(D) + \frac{32\pi G Q^2}{c^4 K(D-2)(D-3)r^{(2D-6)}} = e^{\nu}. \qquad (27)$$

Here $F(D) = \dfrac{8\pi}{(D-2)A_{D-2}}$, $A_{D-2} = (D-1)\dfrac{\pi^{(D-1)/2}}{((D-1)/2)!}$.

We next find the interior metric. The total energy momentum tensor for $R \geq r$ is

$$T_0^0 = \varepsilon_0 + \frac{(\Phi_{,r})^2}{2} + \frac{A_2}{4}\left(\Phi(r)^2 - \frac{A_1}{A_2}\right)^2 + \frac{K\rho_0^2 r^2}{8(D-1)^2}, \qquad (28)$$

$$T_1^1 = -\frac{(\Phi_{,r})^2}{2} + \frac{A_2}{4}\left(\Phi(r)^2 - \frac{A_1}{A_2}\right)^2 + \frac{K\rho_0^2 r^2}{8(D-1)^2}. \qquad (29)$$

Eq. (28) and Eq. (29) follow from Eq. (4) for the matter and Eq. (21) for the electromagnetic field after inserting the first of Eq. (20) for $r \leq R$, (approximating $e^{\lambda} \cong e^{\nu} \cong 1$) and from Eq. (23), where we would insert the perturbed solution from Eq. (17) with coefficients calculated from Eq. (16) with the field at the center of Φ_c. For the $\binom{0}{0}$ Einstein equation we have for $r < R$

$$\frac{d}{dr}(r^{D-3}e^{-\lambda}) = (D-3)r^{(D-4)} - \frac{8\pi G}{c^4}\left(\frac{2}{D-2}\right)r^{(D-2)} \cdot \left[\epsilon_0 + \frac{(\Phi_{,r}r^2)^2}{2} + \frac{A_2}{4}\left(\Phi(r)^2 - \frac{A_1}{A_2}\right)^2 + \frac{K\rho_0^2 r^2}{8(D-1)^2}\right];$$

integration from 0 to R gives

$$(e^{-\lambda})_R = 1 - \frac{8\pi G}{c^4}\left(\frac{2}{D-2}\right)\frac{1}{R^{D-3}} \cdot \int_0^R r^{D-2}\left(\epsilon_0 + \frac{(\Phi_{,r})^2}{2} + \frac{A_2}{4}\left(\Phi(r)^2 - \frac{A_1}{A_2}\right)^2 + \frac{K\rho_0^2 r^2}{8(D-1)^2}\right)dr. \qquad (30)$$

When Eq. (30) is matched to Eq. (27) using Eq. (22) to eliminate ρ_0 and inserting Eq. (17) for $\Phi(r)$ into Eq. (30), an expression can be found for the mass of the configuration in terms of ϵ_0, Q, R and the parameters A_1 and A_2.

Our final task is to find e^{ν} for $r \leq R$. From the $\binom{1}{1}$ component of the Einstein equations we have for $r \leq R$

$$\frac{1}{2}\frac{(D-2)(D-3)}{r^2}(e^{-\lambda} - 1) + \frac{1}{2r}(D-2)e^{-\lambda}\nu' = -\frac{8\pi G}{c^4}\left(-\frac{(\Phi_{,r})^2}{2} + \frac{A_2}{4}\left(\Phi(r)^2 - \frac{A_1}{A_2}\right)^2 + \frac{K\rho_0^2 r^2}{8(D-1)^2}\right)$$

or

$$\nu' = \frac{(D-3)}{r}(e^{\lambda} - 1) - \frac{16\pi G}{c^4(D-2)}re^{\lambda}\left(-\frac{(\Phi_{,r})^2}{2} + \frac{A_2}{4}\left(\Phi(r)^2 - \frac{A_1}{A_2}\right)^2 + \frac{K\rho_0^2 r^2}{8(D-1)^2}\right).$$

Integrating gives

$$\nu = \int^r \frac{(D-3)}{r}(e^{\lambda} - 1)dr - \frac{16\pi G}{c^4(D-2)} \cdot \int^r re^{\lambda}\left(-\frac{(\Phi_{,r})^2}{2} + \frac{A_2}{4}\left(\Phi(r)^2 - \frac{A_1}{A_2}\right)^2 + \frac{K\rho_0^2 r^2}{8(D-1)^2}\right)dr + \overline{C}. \qquad (31)$$

In Eq. (31) we use e^{λ} calculated from Eq. (30) (in this case we integrate from 0 to r in Eq. (30) to obtain $e^{\lambda}(r)$). When Eq. (31) is matched to the natural log of Eq. (27) at $r = R$ we may obtain the integration constant $\overline{C}$ in Eq. (31).

Thus we have obtained the interior solution of a charged fluid sphere with vanishing normal pressure coupled to a symmetry breaking scalar field as expressed in Eq. (30) and Eq. (31) for the metric, Eq. (17) for the scalar field and first of Eq. (20) for $E(r)$. For the exterior solution we have the metric expressed in Eq. (27), the electric field expressed in the second of Eq. (20) and the scalar field is constant of value $\sqrt{\frac{A_1}{A_2}}$ for $r > R$. The mass of the charged sphere with vanishing normal pressure coupled to the scalar field is found my matching Eq. (30) to Eq. (27) at $r = R$.

CONCLUSION

The above analysis has provided us with a solution for the metric for a charged sphere in the presence of a symmetry breaking scalar field in an arbitrary number of dimensions. In the early universe it may very well be that the breaking of a G.U.T. symmetry by a scalar field may occur in a dimension of space time higher than four, in that case the collapse of a gravitationally bound object in a higher number of dimensions would release energy that might be related to γ ray burst phenomena. Galdi [13] has discussed the possible origin of γ ray bursts as emerging from objects with an internal non-linear electromagnetic field structure and Ressell and Turner [14] have surveyed the entire spectrum of extra-galatic radiation. It is not out of the question that certain features of the spectrum might reveal the presence of higher dimensional bound configurations of electromagnetic field and matter. Recently Sokolwski et al. [15] have discussed electromagnetic wave propagation in a multidimensional universe with the explicit formulas for the D dimensional frequency and the four dimensional frequency emerging as a consequence of studying the propagative equations. Perhaps with a combination of the above ideas we may entertain the idea of looking for γ ray bursts from higher dimensional electromagnetic configurations that collapse gravitationally and emit radiation that propagates from a domain of higher dimensionality to a domain of four space time dimensions.

ACKNOWLEDGMENT

I'd like to thank the Physics Departments at Williams College and Harvard University for the use of their facilities.

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Received April 5th, 1990
Accepted for publication March 13th, 1992

КОМПАКТНАЯ ОБЩАЯ РЕЛЯТИВИСТСКАЯ КОНФИГУРАЦИЯ ЗАРЯЖЕННОЙ МАТЕРИИ И СКАЛЯРНОГО ПОЛЯ В D РАЗМЕРНОМ ПРОСТРАНСТВЕ ВРЕМЕНИ

В работе изучена общая релятивистская проблема заряженной материи с нарушеной симетрией скалярного поля в D размерном пространстве времени. Создана внутренняя и внешняя метрики с применением некоторых приближений и условий, как нормальное давление зависящее от конфигурации заряда. Объединением внешних и внутренних уравнений получено выряжение для массовой и зарядовой конфигурации.