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# GAUGED Q MATTER IN THE ATMOSPHERE OF AN ERNST BLACK HOLE

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By considering an Ernst space time background describing a Black hole in an axial magnetic field, we discuss the radial and polar dependence of the field of a Q matter layer in such a background. Such a configuration may mimic the physical state surrounding a condensed neutron star that may represent a potential source of high energy gamma ray bursts.

## 1. *Introduction*

With the advent of spontaneously broken gauge theories, fundamental generic reasons for the gauge boson and fermion mass spectrum have emerged that follow from a vacuum expectation value and a symmetry group of the fundamental lagrangian[1,2]. Along with these great strides in understanding particle theory a whole host of both topological and non-topological solutions to the gauge Higgs system exist that may have profound significance in early universe cosmology[3]. Monopoles[4], cosmic strings[5], domain walls[6] and texture[7] all emerge when the true or false vacuum is realized along a line or surface. There is a wide popular belief that strings, domain walls and texture figure into the origin of large scale structure[8]. There is also another class of objects that are termed non-topological solitons[9] and are the results of a global symmetry that generates a conserved charge for a bound configuration of fields, this conserved charge is identical to that of a collection of free excitations in the theory, the mass of the bound configuration being less than that of free excitations of the theory. Q ball is the generic name invented by Coleman to describe this class of objects[10]. After the original idea suggested by Coleman (Ref. 10), L balls were "studied "which were configuration of Fermi fields and scalar fields inspired by the Gelmini Roncadelli model[11)] of neutrino mass generation which were stabilized by a conserved lepton number except for slow decay into fermions at the surface[12)]. If gauge symmetries are considered simultaneously with global symmetries, gauged Q balls result, these objects have been shown to be stable as long as the gauge charge is not to large[13)]. The stability criteria for gauged Q balls is similar to that of a large Z nucleus where the large electric charge (gauge charge) of a high Z nucleus to Coulomb instability. Thus within a general astrophysical picture both topological configurations of fields and non-topological configurations of fields (Q balls, L balls, neutrino balls, gauged Q balls) could exist in the cosmos and both their properties and signatures for identification are worthwhile considering.

In a previous note we have considered an $SO_2$ configuration of Q matter in the atmosphere of an Ernst Black Hole (Black hole immersed in an axial magnetic field)[14)]. The configuration of Q matter was both radially dependent as well as polar dependent because of the axial magnetic field. In this note, we choose to improve on this idea by considering a configuration of U(1) Q matter in the field of an Ernst Black Hole where the Q matter is gauged. We develop a formalism to calculate the Legendre components of both the U(1) field and the associated scalar potential. Our analysis applies when the gauged Q configuration does not appreciably alter the background Ernst space time. It is hoped that such a model might inspire the astrophysical community to look for gamma ray signatures that might result from the interplay between the gauged Q matter and the strong magnetic field of the Ernst space time.

## 2. *Gauged Q matter in an Ernst space time background*

We begin our analysis by writing down the metric for an Ernst space time as[15]

$$
\begin{aligned}
(\mathrm{d}s)^2 = {} & \left[1+\frac{B^2Gr^2\sin^2\theta}{c^4}\right]^2\left[\left(1-\frac{2GM}{rc^2}\right)(\mathrm{d}x_4)^2\right. \\
& \left. -\left(1-\frac{2GM}{rc^2}\right)^{-1}(\mathrm{d}r)^2-r^2\mathrm{d}\theta^2\right]-\frac{r^2\sin^2\theta(\mathrm{d}\varphi)^2}{\left(1+B^2Gr^2\sin^2\theta/c^4\right)^2}
\end{aligned}
\tag{2.1}
$$

with

$$\lambda = 1+\frac{B^2Gr^2\sin^2\theta}{c^4}$$

and

$$g_{44} = \lambda^2\left(1-\frac{2GM}{rc^2}\right)$$

$$g_{11} = -\frac{\lambda^2}{(1-2GM/(rc^2))}$$

$$g_{22} = -\lambda^2 r^2$$

$$g_{33} = -\lambda^{-2} r^2 \sin^2\theta$$

We next consider a layer of U(1) gauged Q matter far enough from an Ernst horizon so that the Q matter does not appreciably alter the background space time. For the lagrangian of the U(1) complex scalar field and U(1) gauge field we have

$$\mathcal{L} = \left( D_\mu \Phi (D^\mu \Phi)^* - \frac{A_2}{4}\left(\Phi\Phi^* - \frac{A_1}{A_2}\right)^2 - \frac{1}{16\pi} F_{\mu\nu}F^{\mu\nu} \right)\sqrt{-g} \tag{2.2}$$

The four vector potential of the Ernst space time is $(A_\mu)$

$$A_1 = A_2 = A_3 = 0, \quad A_4 = -\frac{r^2 \sin^2\theta B}{2} \tag{2.3}$$

Here $B$ is in the $z$ direction.

For the U(l) field we have

$$D_\mu \Phi = (d_\mu + \mathrm{i} g A_\mu)\Phi$$

here

$$g = \frac{\bar{g}}{\hbar c}, \quad \bar{g} = \text{coupling constant}$$

The charged Q matter will generate a scalar potential

$$A_4 = \Psi(r,\theta)$$

plus a correction to A3. Thus

$$A_1 = 0$$

$$A_2 = 0$$

$$A_3 = -\frac{r^2\sin^2\theta B}{2} + \Psi(r,\theta) \tag{2.4}$$

$$A_4 = \chi(r,\theta)$$

For the U(1) field we write the U(1) symmetric solution as

$$\Phi = \Phi(r,\theta)\mathrm{e}^{-\mathrm{i}\omega t} \tag{2.5}$$

Varying Eq. (2.2) with respect to $A_\mu$ gives

$$\frac{\partial}{\partial x^\nu}\left(\frac{1}{4\pi}\sqrt{-g}F^{\mu\nu}\right)+\mathrm{i}g\Phi(\partial_\beta\Phi^*-\mathrm{i}gA_\beta\Phi^*)g^{\beta\mu}\sqrt{-g}$$

$$-\mathrm{i}g\Phi^*(\partial_\alpha\Phi-\mathrm{i}gA_\alpha\Phi)g^{\mu\alpha}\sqrt{-g}=0 \qquad (2.6)$$

Varying Eq. (2.2) with respect to 0 gives

$$\mathrm{i}gA_\alpha(\partial_\beta\Phi^*-\mathrm{i}gA_\beta\Phi^*)g^{\beta\alpha}\sqrt{-g}$$

$$-\frac{A_2}{2}\Phi^*\left(\Phi\Phi^*-\frac{A_1}{A_2}\right)\sqrt{-g} \qquad (2.7)$$

$$-\frac{\partial}{\partial x^\mu}(g^{\mu\beta}(\partial_\beta\Phi^*-\mathrm{i}gA_\beta\Phi^*)\sqrt{-g}=0$$

with a similar equation for $\Phi^*$. It turns out that Eq. (2.6) and Eq. (2.7) can be derived equivalently by substituting the U(1) symmetric solution along with Eq. (2.4) directly into the matter lagrangian (Eq. (2.2)) and varying with respect to the unknown components of the fields. For the U(l) solution of gauged Q matter with azimuthal symmetry we now consider $A_1=A_2=0$,

$$A_4=\Psi(r,\theta)=\sum_{l=0}^{\infty}\Psi_l(r)P_l(\cos\theta)$$

$$A_3=-\frac{r^2\sin^2\theta B}{2}+\sum_{l=0}^{\infty}\chi_l(r)P_l(\cos\theta) \qquad (2.8)$$

$$\Phi=\sum_{l=0}^{\infty}\Phi_l(r)P_l(\cos\theta)\mathrm{e}^{-\mathrm{i}\omega t}$$

Here $P_l(\cos\theta)$ = Legendre polynomial of order 1.

The field tensor values corresponding to Eq. (2.8) are

$$F_{14}=-\sum_{0}^{\infty}\Psi_l'(r)P_l(\cos\theta)$$

$$F_{24}=-\sum_{0}^{\infty}\Psi_l(r)P_l'(\cos\theta)$$

$$F_{23} = r^2 \sin^2\theta \cos\theta B - \sum_0^\infty \chi_l(r) P_l'(\cos\theta)$$

$$F_{13} = r^2 \sin^2\theta \beta - \sum_0^\infty \chi_l'(r) P_l(\cos\theta)$$

$$F^{14} = -\lambda^{-4} F_{14} \tag{2.9}$$

$$F^{24} = -\frac{\lambda^{-4}}{r^2\big(1-2GM/(rc^2)\big)} F_{24}$$

$$F^{23} = \frac{1}{r^4 \sin^2\theta} F_{23}$$

$$F^{13} = \frac{1}{r^2 \sin^2\theta}\left(1 - \frac{2GM}{rc^2}\right) F_{13}$$

Substituting Eq. (2.8) and Eq. (2.9) into Eq. (2.2) we have after much algebra and integration over the $\theta$, $\varphi$ coordinates

$$\mathcal{L} = \sum_l \sum_{l'} a_{ll'} \frac{\omega^2 r^2}{c^2} \Phi_l \Phi_{l'} \frac{1}{\big(1-2GM/(rc^2)\big)} - \frac{2g\omega r^2}{c} \frac{\sum_l \sum_{l'} \sum_{l''} \Phi_l \Phi_{l'} \chi_{l''} b_{ll'l''}}{\big(1-2GM/(rc^2)\big)}$$

$$+ g^2 r^2 \frac{\sum_l \sum_{l'} \sum_{l''} \sum_{l'''} \Phi_l \Phi_{l'} \chi_{l''} \chi_{l'''}}{\big(1-2GM/(rc^2)\big)} c_{ll'l''l'''} - \left(1 - \frac{2GM}{rc^2}\right) r^2 \sum_l \sum_{l'} \Phi_l' \Phi_{l'}' a_{ll'}$$

$$- \sum_l \sum_{l'} \Phi_l \Phi_{l'} d_{ll'} - g^2 r^2 \sum_l \sum_{l'} \Phi_l \Phi_{l'} S_{ll'} + g^2 r^2 \sum_l \sum_{l'} \sum_{l''} \Phi_l \Phi_{l'} \chi_{l''} r_{ll'l''}$$

$$-g^2 \sum_l \sum_{l'} \sum_{l''} \sum_{l'''} \Phi_l \Phi_{l'} \chi_{l''} \chi_{l'''} \times t_{ll'l''l'''} - \frac{A_2}{4} r^2 \sum_l \sum_{l'} \sum_{l''} \sum_{l'''} \Phi_l \Phi_{l'} \Phi_{l''} \Phi_{l'''} (h_{l'l''l'''})$$

$$+ \frac{r^2 A_1}{2} \sum_l \sum_{l'} \Phi_l \Phi_{l'} k_{ll'} + F r^2 \tag{2.10}$$

$$+ \sum_l \sum_{l'} \Psi_l' \Psi_{l'}' r^2 \alpha_{ll'} + \sum_l \sum_{l'} \frac{\beta_{ll'} \Psi_l \Psi_{l'}}{\big(1-2GM/(rc^2)\big)}$$

+ (terms containing only $\chi_l$ and terms independent of the fields $\Phi_l$, $\Psi_l$ and $\chi_l$). Also

$$\Phi_l' = \frac{\mathrm{d}\Phi_l}{\mathrm{d}r}, \quad \chi_l' = \frac{\mathrm{d}\chi_l}{\mathrm{d}r}, \quad \Psi_l' = \frac{\mathrm{d}\Psi_l}{\mathrm{d}r}, \quad P_l'(\cos\theta) = \frac{\mathrm{d}}{\mathrm{d}\theta} P_l(\cos\theta)$$

here

$$a_{ll'} = \int_0^\pi 2\pi P_l P_{l'} \sin\theta \mathrm{d}\theta, \quad b_{ll'l''} = \int_0^\pi 2\pi P_l P_{l'} P_{l''} \sin\theta \mathrm{d}\theta$$

$$c_{ll'l''l'''} = \int_0^\pi 2\pi P_l P_{l'} P_{l''} P_{l'''} \sin\theta \mathrm{d}\theta, \quad d_{ll'} = \int_0^\pi 2\pi P_l' P_{l'}' \sin\theta \mathrm{d}\theta$$

$$S_{ll'} = \int_0^\pi \frac{2\pi\lambda^4 B^2 P_l P_{l'} \sin^4\theta}{4\sin\theta} \mathrm{d}\theta, \quad r_{ll'l''} = 2\pi \int_0^\pi \frac{\lambda^4}{\sin\theta} \sin^2\theta B P_l P_{l'} P_{l''} \mathrm{d}\theta$$

$$t_{ll'l''l'''} = 2\pi \int_0^\pi \frac{\lambda^4}{\sin\theta} P_l P_{l'} P_{l''} P_{l'''} \mathrm{d}\theta, \quad h_{ll'l''l'''} = 2\pi \int_0^\pi \lambda^2 \sin\theta P_l P_{l'} P_{l''} P_{l'''} \mathrm{d}\theta,$$

$$k_{ll'} = 2\pi \int_0^\pi \lambda^2 \sin\theta P_l P_{l'} \mathrm{d}\theta, \quad F = 2\pi \int_0^\pi \frac{A_1^2}{4A_2} \lambda^2 \sin\theta \mathrm{d}\theta \tag{2.11}$$

$$\alpha_{ll'} = \frac{1}{4} \int_0^\pi \frac{P_l P_{l'} \sin\theta \mathrm{d}\theta}{\lambda^2}, \quad \beta_{ll'} = \frac{1}{4} \int_0^\pi \frac{P_l' P_{l'}' \sin\theta \mathrm{d}\theta}{\lambda^2}$$

If we calculate out the additional terms containing $A_3$, we find that some of the terms containing $\chi_l$, $\chi_l'$ are singular since they contain a term

$$\int_0^\pi \frac{1}{\sin\theta} \mathrm{d}\theta$$

We assume that the Q matter or the horizon of the black hole develops a mechanism to eliminate the polar singularities by inducing a current to counterbalance the effect of the singularity induced by the space time metric. In this note we will not include the effect of $\chi_l$ and only include the effect due to the original

$$A_3 = -\frac{r^2 \sin^2\theta B}{2}$$

of the Ernst space time. We thus have a lagrangian in terms of $\Phi_l$ and $\Psi_l$ (the scalar field and the scalar potential). The lagrangian in Eq. (2.10) thus becomes up to an additive constant independent of the fields,

$$\mathcal{L}(r) = \sum_l \sum_{l'} \frac{a_{ll'} \omega^2 r^2 \Phi_l \Phi_{l'}}{c^2\big(1 - 2GM/(rc^2)\big)}$$

$$
\begin{aligned}
&-\frac{2g\omega r^2}{c}\sum_l\sum_{l'}\sum_{l''}\frac{\Phi_l\Phi_{l'}\Psi_{l''}b_{ll'l''}}{\big(1-2GM/(rc^2)\big)} \\
&+g^2r^2\sum_l\sum_{l'}\sum_{l''}\sum_{l'''}\Phi_l\Phi_{l'}\Psi_{l''}\Psi_{l'''}\frac{c_{ll'l''l'''}}{\big(1-2GM/(rc^2)\big)} \\
&-\left(1-\frac{2GM}{rc^2}\right)r^2\sum_l\sum_{l'}\Phi_l'\Phi_{l'}'a_{ll'}-\sum_l\sum_{l'}\Phi_l\Phi_{l'}d_{ll'} \\
&-g^2r^4\sum_l\sum_{l'}\Phi_l'\Phi_{l'}'S_{ll'}-\frac{A_2}{4}\sum_l\sum_{l'}\sum_{l''}\sum_{l'''}\Phi_l\Phi_{l'}\Phi_{l''}\Phi_{l'''}h_{ll'l''l'''}r^2 \\
&+\frac{r^2A_1}{2}\sum_l\sum_{l'}\Phi_l\Phi_{l'}k_{ll'}+\sum_l\sum_{l'}\Psi_l'\Psi_{l'}'k_{ll'}r^2\alpha_{ll'} \\
&+\sum_l\sum_{l'}\frac{\beta_{ll'}\Psi_l\Psi_{l'}}{\big(1-2GM/(rc^2)\big)}
\end{aligned}
\tag{2.12}
$$

To find the equations to determine $\Phi_l$, $\Psi_l$ we vary Eq. (2.12). If we just have a single Legendre polynomial of order I, Eq. (2.12) becomes

$$
\begin{aligned}
\mathcal{L}=&\frac{a_{ll}\omega^2r^2\Phi_l^2}{c^2\big(1-2GM/(rc^2)\big)}-\frac{2g\omega r^2}{c}\frac{\Phi_l^2\Psi_lb_{lll}}{\big(1-2GM/(rc^2)\big)} \\
&+g^2r^2\frac{\Phi_l^2\Psi_l^2}{\big(1-2GM/(rc^2)\big)}c_{llll}-\left(1-\frac{2GM}{rc^2}\right)r^2(\Phi_l')^2a_{ll} \\
&-(\Phi_l)^2d_{ll}-g^2r^4S_{ll}(\Phi_l)^2-\frac{A_2}{4}(\Phi_l)^4h_{llll}(r^2) \\
&+\frac{r^2A_1}{2}\Phi_l^2k_{ll}+(\Psi_l')^2r^2\alpha_{ll}+\frac{(\Psi_l')^2\beta_{ll}}{\big(1-2GM/(rc^2)\big)}
\end{aligned}
\tag{2.13}
$$

Varying Eq. (2.13) with respect to $\Phi_l$ gives

$$-\frac{\mathrm{d}}{\mathrm{d}r}\left(-\left(1-\frac{2GM}{rc^2}\right)r^2\Phi_l' 2a_{ll}\right)+2a_{ll}\frac{\omega^2}{c^2}\frac{r^2\Phi_l}{\big(1-2GM/(rc^2)\big)}$$

$$+\frac{2g^2r^2\Phi_l\Psi_l^2c_{llll}}{\big(1-2GM/(rc^2)\big)}-\frac{4g\omega r^2\Phi_l\Psi_l b_{lll}}{c\big(1-2GM/(rc^2)\big)}-2\Phi_l d_{ll} \tag{2.14}$$

$$-2g^2r^4S_{ll}\Phi_l-A_2\Phi_l^3h_{llll}r^2+r^2A_1\Phi_l k_{ll}=0\,.$$

Varying with respect to $\Psi_l$, we have

$$-\frac{\mathrm{d}}{\mathrm{d}r}(2\Psi_l' r^2a_{ll})+\frac{2g^2r^2\Psi_l\Phi_l^2c_{llll}}{c\big(1-2GM/(rc^2)\big)}$$

$$-\frac{2g\omega r^2\Phi_l^2b_{lll}}{c\big(1-2GM/(rc^2)\big)}+\frac{2\Psi_l\beta_{ll}}{\big(1-2GM/(rc^2)\big)} \tag{2.15}$$

For the boundary conditions in the above system we must know the scalar field and scalar potential on both boundaries of a layer of inner radius $R_1$ and outer radius $R_2$. We write

$$\Psi=\sum_0^\infty c_{1l}P_l \quad \text{for} \quad r=R_1$$

$$\Psi=\sum_0^\infty c_{2l}P_l \quad \text{for} \quad r=R_2 \tag{2.16}$$

$$c_{1l},\ c_{2l}=\text{constants.}$$

For the scalar field we have

$$\Phi=\sum_0^\infty P_lD_{1l}\mathrm{e}^{-\mathrm{i}\omega t} \quad \text{for} \quad r=R_1$$

$$\Phi=\sum_0^\infty P_lD_{2l}\mathrm{e}^{-\mathrm{i}\omega t} \quad \text{for} \quad r=R_2 \tag{2.17}$$

$D_{11}$, $D_{21}$are constants.

To solve the problem for the gauged Q matter layer, we must solve the complicated series of equations found by varying Eq. (2.12) with respect to $\Phi_l$, $\Psi_l$ and then use the boundary conditions in Eq. (2.16) and Eq. (2.17) to find the arbitrary constants for each $l$ in the solution for $\Phi_l$, $\Psi_l$. To calculate the conserved Q charge[16] we have under the U(l) symmetry

$$\delta\Phi_l = \mathrm{i}\alpha\Phi, \quad \delta\Phi^* = \mathrm{i}\alpha\Phi^*.$$

Varying Eq. (2.2) and using the field equations we have

$$\begin{aligned}\mathcal{L} &= \frac{\partial\mathcal{L}}{\partial\Phi}\delta\Phi + \frac{\partial\mathcal{L}}{\partial\Phi^*}\delta\Phi^* + \frac{\partial\mathcal{L}}{\partial\Phi_{,\mu}}\delta\Phi_{,\mu} + \frac{\partial\mathcal{L}}{\partial\Phi^*_{,\mu}}\delta\Phi^*_{,\mu} \\ &= \frac{\partial}{\partial\chi^\mu}\left(\frac{\partial\mathcal{L}}{\partial\Phi_{,\mu}}\delta\Phi_{,\mu}\right) + \frac{\partial}{\partial\chi^\mu}\left(\frac{\partial\mathcal{L}}{\partial\Phi^*_{,\mu}}\delta\Phi^*_{,\mu}\right)\end{aligned} \tag{2.18}$$

upon integrating over $r$, $\theta$, $\varphi$ we have for the conserved Q charge

$$Q = \int_0^{2\pi}\int_0^{\pi}\int_{R_1}^{R_2}\left(\frac{\partial\mathcal{L}}{\partial\Phi_{,4}}\delta\Phi + \frac{\partial\mathcal{L}}{\partial\Phi^*_{,4}}\delta\Phi^*\right)\mathrm{d}r\mathrm{d}\theta\mathrm{d}\varphi$$

By using Eq. (2.1) and Eq. (2.2) along with $\delta\Phi = \mathrm{i}\alpha\Phi$, $\delta\Phi^* = -\mathrm{i}\alpha\Phi^*$ we have finaly

$$\begin{aligned}Q = 2\pi\int_{R_1}^{R_2}\int_0^{\pi} -\frac{2\omega}{c\big(1-2GM/(rc^2)\big)}\sum_l\sum_{l'}\Phi_l\Phi_{l'}P_lP_{l'}r^2\sin\theta\mathrm{d}\theta\mathrm{d}r \\ +2\pi\int_{R_1}^{R_2}\int_0^{\pi} 2g\sum_l\sum_{l'}\sum_{l''}\frac{\Phi_l\Phi_l'\Psi_{l''}P_lP_{l'}P_{l''}}{\big(1-2GM/(rc^2)\big)}r^2\sin\theta\mathrm{d}\theta\mathrm{d}r\end{aligned} \tag{2.19}$$

Eq. (2.19) allows us to calculate the angular frequency in terms of the conserved Q charge.

## 3. *Conclusion*

Our analysis above has suggested a general method to treat gauged Q matter in the atmosphere of an Ernst space time when the Q matter does not appreciably alter the background space time. Generalization of this technique to the atmosphere of a Kerr black hole[17] should also have deep astrophysical significance. We have also chosen a very simple potential and a more complete analysis should involve a more realistic potential. Since primordial magnetic fields are a likely possibility in the early universe and present cosmological studies indicate black holes are also likely possibility, the fusion of these ideas along with a surrounding shell of Q matter makes for a plausible as well as interesting astrophysical study. If such a gauged Q matter configuration decays we would expect a polar dependence of the radiation emitted, we also point out that any gamma ray bursts from such a configuration would have signatures that are both polar dependent and sensitive to the gauge charge of a Q matter layer[18]. Lastly, since neutrinos are a likely possibility for dark matter in galaxies, a black hole might trap a neutrino layer in an axial symmetric magnetic field with a conserved Q number represented by the lepton number as mentioned in the introduction (Ref. 12). These L balls have been previously studied as emerging from the Gelmini-Roncadelli model of neutrino mass generation and a L layer neutrinos around an Ernst black hole would be a very attractive astrophysical possibility.

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# BAŽDARNA Q MATERIJA U ATMOSFERI ERNSTOVE CRNE RUPE

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Promatrajući prostorno vremensku pozadinu Ernsta koja opisuje crnu rupu u aksijalnom magnetskom polju, diskutiramo radijalnu i polarnu ovisnost polja Q-materije u takvoj pozadini. Takva konfiguracija može imitirati fizikalno stanje koje okružuje krutu neutronsku zvijezdu. i može predstavljati potencijalni izvor bljeskova visokoenergetskog gama zračenja.