The Effects of Charge On The Structure of Strange Stars

To cite this article: Manuel Malheiro et al 2011 J. Phys.: Conf. Ser. 312 042018

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The Effects of Charge On The Structure of Strange Stars

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Abstract. The effects of a charge distribution near the surface of a bare strange quark star is studied. The surface of these objects is characterized by the formation of an ultra-strong electric field, that maybe as high as $10^{18-19}$ V/cm. We model the charge distribution that originates such electric field as a narrow Gaussian distribution, centralized near the surface of the star. We will show that the charge may change the structure of the star substantially, possibly increasing its mass by 15%.

1. Introduction
Ultra-high electric fields are expected to exist on the surface of strange quark stars [1, 2]. This electric field is associated with an electric dipole that is formed on the surface of these objects. This dipole is established due to strange quark exhaustion (due to low chemical potential near the surface of the star), and the subsequent increase in the population of electrons (which are needed to maintain global charge neutrality). The electrons, that are not bound by the strong interaction, are screened to the outside of the star, establishing an electric dipole between the positively charged core and the negatively charged electron layer. An electric field that might be as high as $10^{18-19}$ V/cm [1, 2, 3, 4], will have an influence on the properties of the star. This have been studied in reference [5] where the effects of a net charge on the surface of a strange star was studied.

The influence of a non-zero charge on the structure of a relativistic compact star is three-fold: 1) it affects the metric, which means that the energy associated with the electric field causes
curvature of space-time; 2) it introduces an extra term on the relativistic hydrostatic equilibrium equation, to account for the Coulomb interaction. This extra term can either be negative or positive, accounting for Coulomb repulsion or attraction respectively; and 3) the energy-density associated with the electric field contributes to the gravitational mass of the star.

2. Structure Equations
The first two contributions of a non-zero charge distribution can be seen in the general relativistic hydrostatic equilibrium equation [5, 6, 7]

\[
\frac{dP}{dr} = -2G \left( m + 4\pi r^3 \left( P - \frac{Q^2}{4\pi r^4 c^2} \right) \right) \left( P + \epsilon \right)
\]

\[
+ \frac{Q}{4\pi r^4} \frac{dQ}{dr}.
\]

(1)

The first term in the right-hand-side (rhs) of equation (1) represents the gravitational pull. One can see that this term contain electrostatic corrections (\(\propto Q^2\)). The second term of the rhs of (1) is due to the Coulomb interaction among the charges. This term can be negative (if \(Q > 0\) and \(dQ/dr < 0\), or vice-versa), which denotes Coulomb attraction; or positive (if the product \(Q \times dQ/dr > 0\)), which denotes Coulomb repulsion.

The effects of charge on the gravitational mass of the star can be seen by analyzing the mass equation

\[
\frac{dm}{dr} = \frac{4\pi r^2}{c^2} \epsilon + \frac{Q}{c^2 r} \frac{dQ}{dr}.
\]

(2)

As shown in equation (2) the energy associated with the electric field will contribute to the gravitational mass of the object.

2.1. Charge Distribution
As shown in papers [1, 2], the positive charge is narrowly distributed over the the surface region of a strange star. In order to model this scenario we represent the charge distribution as Gaussian function centralized in a radius \(r_g\) near the surface of the star, and with width \(b\) [5]. Thus the charge distribution function can be written as

\[
\rho_{ch} = \sigma \left[ 8\pi \left( \sqrt{\pi} b^3/4 + r_g b^2 + \sqrt{\pi} r_g^2 b/2 \right) \right]^{-1} \times \exp(-((r - r_g)/b)^2),
\]

(3)

Where \(\sigma\) is a positive constant used to adjust the total amount of charge on the stellar surface. With charge distribution (3), the relativistic Gauss’s law can be written as

\[
\frac{dQ}{dr} = r^2 \sigma \exp(-((r - r_g)/b)^2) \exp(\Lambda/2)
\]

(4)

3. Results and Conclusions
Solving the structure equations for different values for the constant \(\sigma\), we find the stellar sequences shown in figure 1 [5]. The results presented here were obtained for a constant charge distribution width of \(10^{-3}\) km.

Figure 1 shows that for higher values of the constant \(\sigma\) the mass and radius of the star are increased. This can also be seen in table 1 [5], where the properties of the maximum mass stars of the sequences found in figure 1 are listed.

The increase in gravitational mass results from the increased amount of charge, which is associated with high values of the constant \(\sigma\). This is confirmed in figure 2 that shows the total
Figure 1. Mass-radius relationship of electrically charged strange stars [5]. Tick marks denote the maximum-mass star of each sequence, whose properties are given in Table 1.

Table 1. Properties of electrically charged maximum-mass strange quark stars [5]. The quantities $R$ and $M$ denote their radii and gravitational masses, respectively. The stars carry given electric charges, $Q$, which give rise to electric stellar surface fields $E$.

| $\sigma$ | $R$ (km) | $M$ ($M_\odot$) | $Q \times 10^{17}$ C | $E \times 10^{19}$ V/cm |
|----------|---------|-----------------|----------------------|------------------------|
| 0        | 10.99   | 2.02            | 0                    | 0                      |
| 500      | 11.1    | 2.07            | 989                  | 7.1                    |
| 750      | 11.2    | 2.15            | 1486                 | 10.5                   |
| 1000     | 11.4    | 2.25            | 1982                 | 13.5                   |

amount of charge for the stars of the sequences in figure 1 as a function of their gravitational mass.

The results presented here show that by taking into account the ultra-high electric fields found on the surface of strange stars, the mass of these objects may increase by up to 15%. The actual value by which the mass will increase depends on how strong is the electric field on the surface of these objects. This in turn depends on the bulk properties of strange matter, on whether or not strange quark matter is in a superconducting state, and on the surface tension of the interface between vacuum and strange quark matter. Nonetheless it is important to investigate how important the surface electric field is to the stellar properties. As shown in this paper and in references [5], the charge distribution on the surface of strange quark stars might increase the mass of these objects substantially, which might facilitate the interpretation of massive compact stars as strange quark stars.
Figure 2. Charge as a function of gravitational mass for charged stars shown in figure 1.

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