QUARK STARS - CAN THEY EXIST?

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DECEMBER 9, 2011

Abstract:

The final stage in the life cycle of medium-high mass stars can be either degenerate neutron stars or black holes. However, quantum chromodynamics theory allows for the possibility of an intermediate state, known as a "quark star". Here I discuss the theory behind this type of matter, as well as possible quark star candidates and how gamma-ray bursts could be indicative of the existence of quark stars.

1. Introduction

The typical final stage in the lifetime of stars with masses between 4-8 $M_{\odot}$ is an extremely dense neutron star, which is formed when the star's central region gravitationally collapses to the point where the protons and electron combine to form neutrons. Assuming that the star's mass is not great enough to overcome the neutron degeneracy pressure and further collapse into a black hole, the star will remain stable. However, theoretical evidence suggests that the gravitational pressure inside the most massive neutrons stars will be strong enough to break down the neutrons into quarks, leaving a "soup" of free quarks. This matter would be sustained by the strong force, rather than by the typical degeneracy pressure.

While no definitive observational evidence of this type of star yet exists, a number of recent candidates have been found that point towards their existence. In this paper I intend to discuss the properties of quark interactions that would allow for this type of matter to exist, as well as some of the thermodynamic properties that an object of this nature would have need to have in order to exist in a stable form. I will also discuss some recent possible candidates for quark stars, as well as a possible connection to the study of gamma-ray bursts.

2. Theory

2.1. **Asymptotic Freedom of Quarks.** One feature of quantum chromodynamics (QCD), the study of the strong interaction, that allows for the existence of free quarks is that of asymptotic freedom. Essentially, this says that at large distances, quark interactions are large, whereas at short distances the interaction is weak [5]. This long distance behavior is what accounts for the usual quark confinement, and suggests that free quarks can only exist at short distances where their interactions are weak, such as where the density of a region exceeds that of the individual hadrons.

The central density of a neutron star can be up to 10^{16}-10^{17} g/cm^3, which greatly exceeds the density of a neutron (on the order of 10^{14} g/cm^3). Therefore, in these regions one can expect that the neutrons will overlap leaving a quark soup, rather than individual neutrons [6].

2.2. **MIT Bag Model.** Initial attempts at discussing the possibility of quark stars were based on the M.I.T. bag model of quark matter. This model is described by a finite object, quarks, contained by collective fields, the quark and gluon degrees of freedom (the strong force interaction). Figure 1 depicts a hadron following this model.

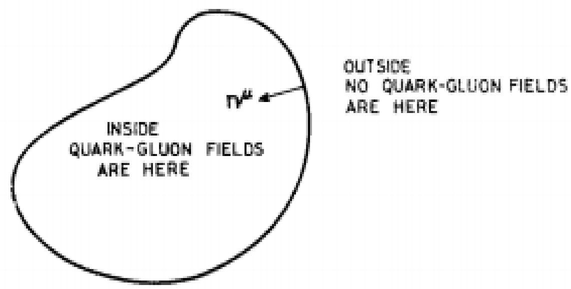

Figure 1: MIT bag model of a hadron [7].

The quarks within this bag are coupled via eight massless SU(3) vector gluons that describe their color as follows:

$$\mathcal{L}_{int} = i(g_c/2)\lambda^{\alpha}_{ab}\overline{\psi_{ai}}\gamma\mu\psi_{bi}A^{\alpha}_{\mu} \tag{1}$$

where ψ_{ai} is the quark field with color a and flavor i, A^{α}_{μ} represents the eight gluon fields, λ^{α}_{ab} are the SU(3) generators, and g_c is the color coupling constant [4].

Using this model, the energy density, ρ, of a quark phase consisting of N_i quarks, flavor i, in a volume V can be calculated by

$$\rho = B + \sum_i (\frac{3}{4\pi^2} + \frac{g_c^2}{8\pi^4})p_{fi}^4 \tag{2}$$

where B is a parameter associated with the bag model, $p_{fi} = (\pi^2 f_i N/V)^{\frac{1}{3}}$ is the bag energy, $f_i = N_i/N$ is the massless quarks' kinetic energy, and $\sum_i f_i = 3$ is the lowest order color interaction/exchange [4]. The values of f_i differ by both quark color and matter type ($f_u = 1$, $f_d = 2$, $f_{baryon} = 3/2$).

In order to determine the phase transition from neutron to quarks, it is necessary to look at the energies per baryon in the two phases. For the quark phase, the necessary equation of state is

$$P = -\frac{\delta E}{\delta V} = \frac{1}{3}(\rho - 4B) \tag{3}$$

where ρ is calculated from equation 2. The equations of state needed to determine the properties of the neutron phase vary within the literature, however early calculations by Baym and Chin [4], using four different equations of state (see paper for specifics) all came to the same conclusion. Figure 2 shows that regardless of the chosen equation of state for neutron matter, the density needed to transition to the quark phase as described by the bag model, ρ_T, is higher than the core density of the most massive neutron stars, ρ_c.

Eqs. of state	p_T (10^3 MeV fm^{-3})	n_T (bary. fm^{-3})	ρ_T (10^{15} gcm^{-3})	$M_{max}/M_{\odot}$	ρ_c (10^{15} gcm^{-3})
Meand field [15]	1.3	1.2 – 2.0	3.5 – 7.5	2.57	1.6
PS Solid [13]	1.9	1.7 – 2.6	5.4 – 11	2.28	1.1
Bag [18]	–	–	–	1.93	2.1
BJVN [12]	5.8	3.3 – 5.9	13 – 31	1.76	3.3
Reid [10]	7.5	3.7 – 7.1	14 – 40	1.66	4.1

Figure 2: Comparison of the transition density from the quark phase to the neutron phase of matter to the core density of neutron stars. Columns 4 and 6, which are of importance to this paper, show the transition density and core density respectively [4].

This seemed to indicate that quark matter could not exist stably within a neutron star. However, later studies incorporating QCD and the bag model seemed to suggest otherwise.

2.3. **Q.C.D [5].** A different model for determining the possibility of quark stars comes directly from Q.C.D. Given the energy density of quark matter

$$\epsilon = An^{4/3} \tag{4}$$

where n is baryon number density and A depends on the density and the number of quark flavors contributing (K in equation 5), one can determine the pressure and Gibb's energy per unit baryon number in a cold three-flavor quark gas (equations 7 and 8).

$$A = \frac{9}{4}(\frac{3\pi^2}{K})^{1/2}(1+\frac{8\alpha_c}{3\pi}) \tag{5}$$

$$\alpha_c = \frac{\pi}{22-\frac{4}{3}K}\frac{1}{ln\mu_F/\lambda_F} \tag{6}$$

$$P_{quark} = \frac{3\lambda_F^4}{4\pi^2}[1+\frac{4}{27lnx}(1-\frac{1}{lnx})]x^4 \tag{7}$$

$$\mu_{quark} = 3\lambda_F[1+\frac{4}{27lnx}(1-\frac{1}{4lnx})]x \tag{8}$$

Here μ_F is the Gibb's energy per quark, λ_F is a constant, and $x = k_F/\lambda_F$, with k_F as the quark Fermi momentum.

From an equation of state for quark matter, the densities and pressures necessary for stable quark stars can be determined. In order for a quark star to remain stable against gravitational collapse, its adiabatic index

$$\gamma = \frac{4}{3} + \frac{(2-lnx)}{3lnx[\frac{27}{4}ln^2x+lnx+1]} \tag{9}$$

must be greater than the critical adiabatic index for a cold star, $\gamma_c = 2.27$. As with the bag model, a quark star can only exist if the stars pressure exceeds the transition pressure for the transition between the neutron and quark states. The equation of state needed for the baryonic matter chosen in Chapline and Nauenberg [5] uses an energy density of

$$\epsilon = mn + an^{\nu} \tag{10}$$

where a and ν are constants and m is the nucleon mass. This gives a pressure of

$$P_{baryon} = (\nu - 1)an^{\nu} \tag{11}$$

and a Gibb's energy per baryon of

$$\mu_{baryon} = m + \nu a^{1/\nu}(\frac{P_b}{\nu - 1})^{(\nu-1)/\nu} \tag{12}$$

Whether or not a quark star can exist will depend greatly on the value of a, as seen in figure 3.

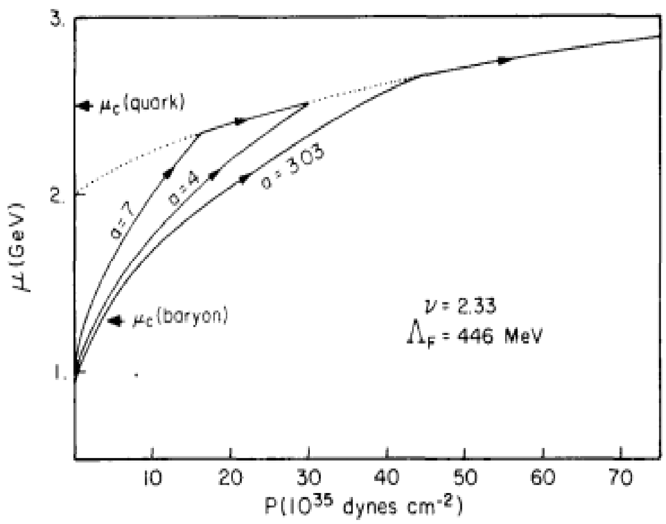

Figure 3 [5]: Curves of μ vs P, depending on a, with $\nu = 2.33$ and $\lambda_F = 446$ MeV. The critical pressure is $P_c = 3\text{x}10^{36}$ dyn/cm^3. The dotted line shows where the transition to the quark phase occurs.

As seen in figure 3, the lowest value of a transitions to the quark phase at a pressure that is greater than P_c, indicating that no stable quark star can be formed. However, both other values of a have a transition where $P_T \leq P_c$, and therefore allow for a range of stable stars. Unfortunately, these parameters all show a transition pressure above that of the core of neutron stars, which rules out the possibility of quark matter at their core. It does allow, however, for a quark star to be formed independently of a neutron star, as in if an object whose mass exceeds the maximum mass for a neutron star were to collapse and not form a black hole. The possibility of quark matter existing inside a neutron star exists when λ_F becomes small enough for μ_c of a quark star, equation 8, to be smaller than μ_c for a neutron star. For the parameters shown, this would occur for $\lambda_F <$ 0.226 GeV.

3. Possible Candidates

While theoretical evidence for the existence of quark stars has existed since at least the 1970s, observational evidence only appeared in recent years. I am going to discuss two possible candidates, which show evidence for a quark star in two different ways.

3.1. **RXJ1856.6-3754 [2].** RXJ1856.6-3754 is a soft X-ray source, discovered by Walter, Wolk & Neuhäuser (1996). At the time of its discovery, the object was considered to be an isolated neutron star. However, more recent observations of the object have not led to a definitive conclusion as to its nature. Through spectral analysis, Drake et. al. (2002) [2] was able to determine an angular radius for the object. The team used two sets of best-fit parameters[1] to fit the spectral data to a black-body model. Their fits resulted in an angular size (R_∞/D_{100}) of 4.12+/-0.68 km/100pc, where

$$R_\infty = R/\sqrt{1 - 2GM/Rc^2} \tag{13}$$

is the "radiation radius" corresponding to a true radius of R of a star of mass M.

Through current knowledge of neutron star equations of state, it has been determined that the typical neutron star $R_\infty \gtrsim 12$ km (e.g. Lattimer & Prakash 2000). This would indicate that RXJ1856.6-3754 is in fact too small to be considered a neutron star, and one strong possibility to explain its neutron-star like behavior is that it is actually made of quark matter.

3.2. **3C58 [1].** 3C58 is a young nebula, believed to be associated with the supernova of 1181 AD. Its age indicates that the nebula is powered by a young neutron star. Slane, Helfand, and Murray (2002) used *Chandra* observations to determine an upper limit to the surface temperature of the supposed neutron star, PSR J0205+6449. While the specifics as to how this limit was obtained are not important for the purpose of this paper, their results are very significant. The group found that for a radius of 12 km the upper limit on the black body temperature of PSR J0205+6449 is $1.13\text{x}10^6$ K. However, this result is not consistent with the standard neutron star cooling process.

The standard cooling process, known as the URCA process, is based upon neutrino emissions as follows [8]:

$$(n,p) + p + e^- -> (n,p) + n + \nu_e \tag{14}$$

$$(n,p) + n -> (n,p) + p + e^- + \overline{\nu_e} \tag{15}$$

The surface temperature of a neutron star cooling via this process can be seen in figure 4, represented by the solid line. As indicated by the solid arrow on figure 4, the upper limit on the surface temperature of PSR J0205+6449 is less than what the standard model would indicate by a factor of approximately 10^5 K, which is clearly a significant difference.

[1](1) T = 61.2 +/- 0.3 eV, NH = (1.10 +/- 0.02) x 10^{20} cm^{-2}, X-ray luminosity (2.96 +/- 0.03) x 10^{31} D_{100}^2 erg s^{-1}, where D_{100} is the distance in units of 100 pc; (2) T = 61.1+/-0.3 eV, NH = (0.81+/-0.02)x10^{20} cm^{-2}, X-ray luminosity (3.16 +/- 0.03) x 10^{31} D_{100}^2 erg s^{-1}

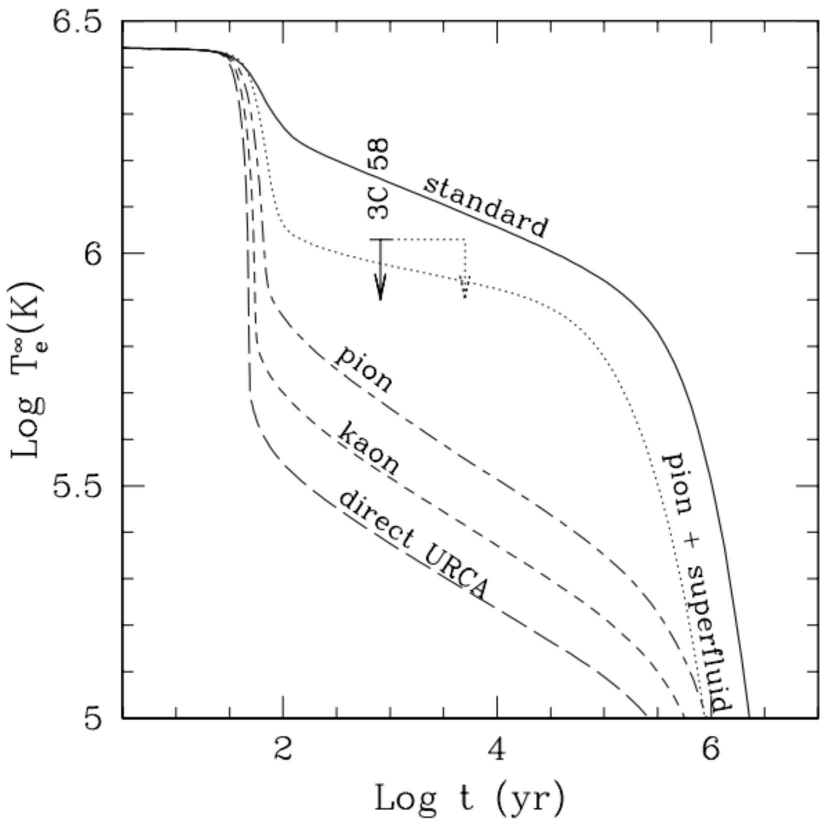

Figure 4 [1]: Surface temperature upper limit for 3C58. The solid line is for the standard cooling model. The dashed lines represent different models for neutron star cooling [10]. The solid arrow indicates the upper limit for PSR J0205+6449 based on the historical age, and the dashed arrow indicates the upper limit based on the characteristic age.

This discrepancy seems to indicate one of two things: either our knowledge of how neutron stars cool is incorrect, or PSR J0205+6449 actually cools via non-standard cooling mechanisms. These non-standard mechanisms, indicated by the dashed lines on figure 4, would speed up the process of neutrino emission due to non-neutron matter at the star's core. Quark matter is one possibility that would lead to a faster cooling rate and make these results possible.

4. Gamma Ray Bursts

Paczyński and Haensel (2005) [3] have suggested that these theoretical quark stars, specifically ones made mostly of strange quarks, could be responsible for long gamma-ray bursts (GRB) with a strong ultra-relativistic jet. GRBs are connected to supernovae type Ic (Sne Ic), which occur when massive stars, such as those that have the potential to collapse into quark stars, collapse and are stripped of their hydrogen and helium envelopes. The remaining core is typically a hot neutron star, however, as previously explained, it is possible for the core to become dense enough to form quark matter.

Should this happen, the quarks would be free to move inside of the star, but the strong interaction that keeps the core from further collapse would also confine the quarks to their "bag" [7] causing the star's surface to act as a sort of filtering membrane. While the quarks cannot escape, it would be possible for electrons, positrons, neutrinos, and other objects that are not subject to the strong interaction to cross the surface causing an outflow of energy that could be the start of an ultra-relativistic GRB.

Assuming that one of these ultra-relativistic GRBs is detected, it should involve a soft precursor followed by a regular GRB. The time delay for the regular GRB would depend on the details of the transition between a neutron star and a quark star. Paczyński and Haensel are of the opinion that the time delay as reported by Lazzati (2005) [9] is indicative, although not definitively, of the quark star model. Should future study give a more accurate picture of that time delay, these ultra-relativistic GRBs could be strong evidence for the existence of quark stars.

5. Conclusion

I have shown that the theory of quantum chromodynamics allows for the existence of matter made of free quarks. For certain conditions, specifically when the transition pressure between baryonic matter and quark matter is less than or equal to some critical pressure, it is theoretically possible for quark matter to exist both at the center of heavy neutron stars and even as stable standalone stars.

While there is still no definitive evidence for either type of star, two plausible neutron star candidates have appeared that seem to point towards their having quark matter at their cores. Lastly, there is a strong possibility that further evidence towards the existence of quark stars can be found through the study of ultra-relativistic GRBs.

6. References

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