Strange Quark Matter in Neutron Stars? – New Results from Chandra and XMM

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It has been predicted that quark and hybrid stars, containing strange quark matter in their core, have a significantly smaller radius than ordinary neutron stars. Preliminary X-ray observations of isolated neutron stars indicated a surprisingly small radius consistent with quark matter in the interior of the star. However, a new analysis of the data led to a radius corresponding to an ordinary neutron star. In the present talk we will discuss theoretical calculations of the mass-radius relation for quark and hybrid stars, taking into account medium effects in quark matter, and report on recent X-ray observations by Chandra and XMM and their latest interpretation.

I. INTRODUCTION

Neutron stars provide a unique possibility to study matter at “low” temperature and ultra-high density. The density in the interior of a neutron star could exceed a few times nuclear density, maybe up to about ten times at the center. Hence one might expect new forms of matter, such as hyperonic matter, pion or kaon condensates, or in particular deconfined quark matter.

The measurement of the mass $M$ and the radius $R$ of neutron stars puts stringent constraints on the equation of state (EOS) of the matter inside of the star. Since most, if not all, neutron stars have a mass of about $M = 1.4 M_\odot$,$^1$ it is especially important to determine the radius accurately. The observed radius $R_\infty$ is related to the actual radius $R$ by

$$R_\infty = R/\sqrt{1 - 2GM/Rc^2}. \quad (1)$$

A radius $R < 10$ km corresponding to $R_\infty < 13$ km ($M = 1.4 M_\odot$) cannot be explained with a conventional hadronic EOS. Hence it would be a strong indication for a phase transition to a new form of matter in the interior, since a phase transition leads to a softening of the EOS, allowing therefore for smaller radii.

Recently, Chandra and XMM have measured X-ray spectra of isolated neutron stars which had been discovered with ROSAT. These spectra give the surface temperature $T$ related to the observed temperature by $T_\infty = T/\sqrt{1 - 2GM/Rc^2}$. Assuming black-body radiation and measuring the distance $d$, the radius follows from

$$R_\infty = d\sqrt{f_\infty/\sigma T_\infty^4}, \quad (2)$$

where $f_\infty$ is the integrated flux (observed at a large distance from the star) corresponding to the temperature of the black-body.

In the case of the isolated neutron star RXJ1856, $R < 6$ km has been obtained in this way [2], suggesting that this isolated neutron star is either a strange quark star or a hybrid star, as we will discuss below. Other signatures for quark matter in neutron stars are e.g. the cooling rate [3] or the rotation frequency [4]. In this talk we will concentrate on the implications of radius measurements using X-ray spectra. We will show that the results from Chandra and XMM combined with optical data actually do not require RXJ1856 to be a quark matter star.

II. QUARK MATTER IN NEUTRON STARS (THEORY)

The idea of the presence of quark matter in compact stars was proposed a long time ago [5]. It turned out that a Fermi gas of up-, down-, and strange quarks is the energetically most favorable state of quark matter at high densities. Such a system could be realized in two possible ways:

1 At least, all binary neutron stars, for which the mass can be determined accurately, have masses close to $1.4 M_\odot$. There are indications for larger masses from X-ray observations, which, however, suffer from a large uncertainty or are model dependent [1].
1. Strange quark matter could be absolutely stable, i.e. more strongly bound than the ground state of normal nuclear matter, i.e. iron \[6\]. Then strange quark stars could exist as self-bound systems without any hadronic matter around it, although a thin hadronic crust is conceivable \[7\].

2. Quark matter is not absolutely stable but exists at high densities in the interior of a neutron star, where at a certain density the transition from hadronic to quark matter takes place. Such an object containing a quark matter core surrounded by a hadronic mantle is called a hybrid star \[8\].

Now we want to ask: What do quark star models predict for the radius of the star? Using the EOS of the model within the Tolman-Oppenheimer-Volkoff equation gives a characteristic mass-radius relation of the star model. Different quark matter EOS have been studied. First only the MIT bag model without \[9\] and with perturbative corrections \[10\] have been applied. Recently, a number of other models, such as the Effective Mass Bag Model \[11\], the NJL Model \[12\], the non-perturbative Dyson-Schwinger equation \[13\], a quasiparticle model using input from lattice QCD \[14\], the Hard-Dense-Loop approach \[15\], and color superconductivity \[16\], have been adopted.

As an example, we want to discuss the Effective Mass Bag Model, in which medium effects in quark matter at zero temperature \(T = 0\) but finite baryon density, i.e. finite quark chemical potential \(\mu \neq 0\), have been taken into account. One of the most important medium effects considered in many fields of physics are effective masses generated by the interaction of the particles, e.g. within a mean-field approach or a quasiparticle Fermi gas. Here we consider effective quark masses following from the interaction of the quarks in quark matter by gluon exchange. The effective quark mass is defined here as the zero momentum limit of the quark dispersion relation. To lowest order perturbation theory, which should hold at ultra-high densities according to asymptotic freedom, the dispersion relation follows from the one-loop quark self-energy in the Hard-Dense-Loop limit \[11\] as

\[
m_q^* = \frac{m_q}{2} + \left( \frac{m_q^2}{4} + \frac{g^2 \mu^2}{6 \pi^2} \right)^{1/2},
\]

where the bare (current) up- and down-quark masses can be neglected, i.e. \(m_u = m_d \approx 0\), compared to typical values of the quark chemical potential \(\mu = 300 - 400\) MeV. The bare strange quark mass, on the other hand, which is of the order of \(m_s \approx 150\) MeV, has to be taken into account. In the Effective Mass Bag Model the strong coupling constant \(g\) is considered as a free quantity, which parametrizes the medium effect. We consider coupling constants from \(g = 0\), corresponding to no medium effect, up to \(g = 4\), giving the maximum medium effect in our model. Assuming that the most important effects of the interactions are included in the effective masses and the bag constant, we use these effective masses within the bag model.

In this model the density per flavor is given by \[11\]

\[
\rho_q(\mu) = \frac{1}{\pi^2} [\mu^2 - m_q^*(\mu)]^{3/2}.
\]
From the thermodynamic relations one finds the pressure and energy density

\[ \rho_q(\mu) = \frac{dp_q(\mu)}{d\mu}, \quad \epsilon_q(\mu) + p_q(\mu) = \mu \rho_q(\mu) \]  

(5)

The energy density and pressure of strange quark matter reads

\[ \epsilon_{SQM} = \epsilon_u + \epsilon_d + \epsilon_s + \epsilon_e + B, \]
\[ p_{SQM} = p_u + p_d + p_s + p_e - B, \]

where also the electron energy density \( \epsilon_e \) and pressure \( p_e \) have been considered.

We have restricted ourselves to bag constants between \( B^{1/4} = 165 \) and \( 200 \) MeV. For lower values the phase transition to quark matter takes place already at sub-nuclear density. In particular, absolutely stable strange quark matter is excluded in our model as it requires \( B^{1/4} < 155 \) MeV. For \( B^{1/4} > 200 \) MeV we find no quark matter in our star models. It should be noted that the effect of the effective quark mass cannot be reproduced by altering \( B, m_s \) or introducing \( \alpha_s \)-corrections.

Next we have solved the Tolman-Oppenheimer-Volkoff (TOV) equation numerically, where the EOS enters only through the pressure as a function of the energy density, \( p = p(\epsilon) \). In this way we obtained the mass-radius relation shown in Fig.1. Note the different qualitative behavior of strange quark stars and hybrid stars in this plot, where the latter behave similar as hadronic stars.

In the case of strange quark stars, which are located at radii \( R < 9 \) km, we observe that medium effects are negligible [11]. In the case of hybrid stars, on the other hand, medium effects play a crucial role. Small medium effects, corresponding to \( g < 2 \), imply a quark core in the center of the star whereas larger values allow at most a mixed phase in the center. This is caused by the fact that a large effective quark mass enhances the energy density of quark matter making its presence in the star less likely, as shown in Fig.2.

We have used the quark matter EOS for the quark core and for the quark component of the mixed phase, which builds a substantial part of the star, and a hadronic EOS for the hadronic component of the mixed phase and for the hadronic mantle. In order to test the sensitivity of our results to the hadronic EOS, we employed four different types of relativistic mean-field models including hyperons. It turns out that, independently of the hadronic model used, a neutron star with a quark matter core is typically 20 - 30% smaller than a pure hadronic star. A pure hadronic star has a radius larger than 13 km (for \( M = 1.4 \, M_{\odot} \)), while hybrid stars with a quark matter core have radii between 9 and 11 km.

The mass-radius relation of strange quark stars, using the MIT bag model without effective quark masses, and of hadronic stars, using different hadronic EOS, was also considered in Ref. [17]. It was also found that the strange

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FIG. 2. Schematic gross structure of a 1.4 \( M_{\odot} \) hybrid star (QP: quark phase, MP: mixed phase, HP: hadronic phase).

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quark stars are typically smaller than hadronic stars, although some overlap between the radii of those stars is possible depending on the mass of the star and the choice of the strange quark matter parameters, in particular if a soft hadronic EOS is used. However, in recent investigations of perturbative [18] and Hard-Dense-Loop corrections [15] to the Bag Model, it has been shown that the presence of ultraviolet divergences leads to a strong dependence of the mass-radius relations of strange quark and hybrid stars on the renormalization scale, which had to be introduced to remove the divergences. For example, in Ref. [18] the choice of the renormalization constant of $2\mu$ gives a maximum radius of about 6 km with a maximum mass of about $1\, M_\odot$, while the choice $3\mu$ yields a maximum radius of more than 12 km and a maximum mass of about $2\, M_\odot$.

Using the NJL model for the quark matter EOS, neither a strange quark star nor a hybrid star with a quark matter core exists. Only a mixed phase in center is possible for certain parameter choices [12], similar as in the Effective Mass Bag Model in the case of large values of the strong coupling constant.

Finally, recent studies of neutron stars, based on a hadronic model with strongly interacting (attractive) hyperons [19] and with a kaon condensate [20] showed a radius possibly as small as about 8 km for a $1.4\, M_\odot$ star which is comparable to hybrid and even to strange quark stars.

From the various results discussed above, we conclude that there is a large theoretical uncertainty for extracting useful constraints on the EOS from the mass-radius relation. Hence it would be desirable to have a reliable EOS for quark as well as hadronic matter within a single approach. In principle such a possibility could be provided by lattice QCD simulations, which, however, so far are not possible at finite density and zero temperature, although some progress has been made recently [21].

![Image of RXJ1856](image)

**FIG. 3.** Counts and spectra of RXJ1856 measured by Chandra and compared to a solar-mixture model (left) and a black-body (right). Figure taken from Ref. [22].

### III. CHANDRA AND XMM OBSERVATIONS

Neutron stars are X-rays sources. The X-rays are emitted either from the hot surface ($T \sim 10^6$ K) or are due to a nonthermal radiation from the co-rotating magnetosphere in the case of a pulsar. These radiation modes are distinguishable by their spectra, namely a black-body or a power law spectrum, respectively. So far seven isolated
neutron stars with a thermal X-ray spectrum have been discovered with ROSAT. RXJ1856 is the brightest of these objects. It shows no indications of pulsation [22]. It is important that RXJ1856 has also been detected by the Hubble space telescope at a magnitude of $V \simeq 26$ mag [23]. From optical measurements of the parallax the distance has been determined as $d = 117 \pm 12$ pc [24].

Chandra and XMM have measured high-resolution X-ray spectra of RXJ1856. These spectra agree perfectly with black-body spectra and show no indication of lines which are predicted by existing photospheric models [25]. In Fig.3 the measured counts and the spectra, corrected for the acceptance of the detectors, are shown. In the left panels these quantities are compared to a solar-mixture model containing 0.2% of heavy elements given by the solid line. The right panels, on the other hand, show the comparison with a black-body spectrum. Whereas the latter agrees perfectly with the data, the solar-mixture model is clearly ruled out. Also a broad-band spectral feature, e.g. caused by a fast rotation are unlikely. However, a strong magnetic field may lead to a splitting and smearing of the lines by field variations across the surface, which could result in a featureless spectrum similar to a black-body.

Assuming black-body radiation in the X-ray regime, a temperature of $kT_{\infty}^X = 63 \pm 0.5$ eV is inferred from these measurements. Together with the known distance an amazingly small radius of

$$R_{\infty}^X = 4.3 \pm 0.2\text{ km } (d/120\text{ pc})$$

is found. From this radius it was concluded that RXJ1856 has to be a strange quark star without a hadronic crust explaining also the absence of lines [2,26].

![Graph showing X-ray and optical fluxes](image)

**FIG. 4.** Possible explanations of X-ray and optical fluxes, assuming a two-temperature spectrum (left) and a uniform temperature distribution together with a grey-body X-ray spectrum (right). The black crosses are the data, the solid and dotted lines the extrapolated spectra for the two different models. Figure taken from Ref.[22].

However, this interpretation does not explain the optical data (see Fig.4). Extrapolating the X-ray spectrum to the optical regime, one observes that the optical flux exceeds the extrapolated one by a factor of about 7. A possible explanation would be that there are two different sources of the optical and the X-ray emission: the X-ray spectrum is produced by a hot spot on the surface, while the optical data come from the entire surface. Then using the constraint that the soft component should not distort the X-ray spectrum of the hard component, a surface temperature of $T_{\infty}^{soft} < 33.6$ eV follows, which results in a radius of $R_{\infty}^{soft} > 16.3$ km ($d/120$ pc) [22,25]. This solution is shown in the left panel of Fig.4, where the optical black-body spectrum is constructed in way that the extrapolation to the X-ray regime falls below the measured data. The difference between the X-ray data and the extrapolation of these data to the optical regime (dotted grey curve) arises by taking interstellar absorption into account.

However, the two-temperature explanation is questionable since an upper limit of 1.5% for periodic variations in the X-ray data has been found by XMM. This puts a severe constraint on the relative alignment of the rotational axis and the line of sight. Hence, a more reasonable explanation may be based on the assumption of a uniform surface temperature distribution together with a suppressed X-ray emission in the X-ray band [22]. As discussed above, a
suppression of the X-ray flux by a factor 0.15 is needed for explaining the optical data. However, the shape of the observed black-body spectrum should not be changed. Such a spectrum corresponds to a “grey-body” spectrum. Fitting the optical spectrum, assumed to be a black-body spectrum, to the X-ray spectrum taking into account the observed black-body spectrum should not be changed. Such a spectrum corresponds to a “grey-body” spectrum. 

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The electron plasma frequency in a condensed matter surface is estimated to be $h\omega_{pl} \simeq 0.66 B_{12}^{3/5} \text{keV}$ ($B = B_{12} \times 10^{12} \text{G}$), which is much larger than the typical photon energy $kT \sim E_{\gamma}$. Hence, photons cannot be excited easily within the metallic surface [30], resulting in a high reflectivity of the surface. Then the spectrum can be described by a black-body spectrum times an energy dependent absorption factor, $J(E_{\gamma}) = \alpha_x(E_{\gamma}) J_{BB}(E_{\gamma})$. The best fit, corresponding to a surface temperature $kT_{\infty} = 54 \text{eV}$, yields an even better fit than a pure black-body. This leads to an observed radius of $R_{\infty} \geq 13.3 \text{km}$ [22]. (The equal sign holds if there is no suppression of the emission in the optical regime.) For a $1.4M_{\odot}$ star an actual radius of $\tilde{R} > 10.3 \text{km}$ follows which is consistent with the assumption of a normal neutron star. Similar models and conclusions have been discussed by Walter in [31] and by Zane, Turolla and Drake in [32].

We conclude that there is no need for exotic matter in the interior of neutron stars for explaining the observations so far. Either a two-temperature model, a strong magnetic field, or a grey-body X-ray emission are capable of explaining the observed data in accordance with a conventional hadronic EOS. In addition, the various theoretical predictions of the mass-radius relation suffer from a large uncertainty, which does not allow one to distinguish between quark matter and hadronic matter if the radius is not clearly below 8 km. Hence a better understanding of the EOS would be desirable. Also, it appears to be equally important to understand the surface properties of neutron stars better.

After presenting this talk, new evidence appeared that smearing of the spectrum by a strong magnetic field is the most likely explanation. First, a strong overall suppression of the blackbody spectrum by a factor of 7 appears to be difficult to explain. New investigations show only a suppression by a factor 2 to 3 [32]. Second, an iron condensate surface, as discussed by Lai [29], is not supported by other investigations [33]. At least, models describing an iron condensate surface are still quite crude [32]. A hydrogen condensate, however, requires a probably unrealistically high magnetic field ($B > 5 \times 10^{13} \text{G}$). A strong magnetic field (up to $10^{13} \text{G}$, on the other hand, as it might exist at RXJ1856 leads to a splitting of the atomic levels in the X-ray regime into numerous Landau levels. A field variation between the pole and the equator of the star by a factor of two, as expected in the case of a dipole field, results in a smearing of the dense lines such that the lines cannot be resolved anymore. In this way a X-ray spectrum arises in accordance with the one measured by Chandra and XMM. A strong magnetic field has also been discussed recently as the most likely interpretation of the observed spectra of the isolated neutron stars RXJ1308 [34] and RXJ0720 [35]. Combining such a X-ray spectrum with the optical spectrum, one finds a black-body radius $R_{\infty} > 17 \text{km}$, indicating a stiff equation of state, which would exclude a strange quark matter star or even hybrid star. This is a rather conservative lower limit for the radius since a black-body emitter is the most efficient radiator.

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