Neutron Stars and Pulsars: Challenges and Opportunities after 80 years
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Structure of Quark Stars

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Abstract. This paper gives an brief overview of the structure of hypothetical strange quarks stars (quark stars, for short), which are made of absolutely stable 3-flavor strange quark matter. Such objects can be either bare or enveloped in thin nuclear crusts, which consist of heavy ions immersed in an electron gas. In contrast to neutron stars, the structure of quark stars is determined by two (rather than one) parameters, the central star density and the density at the base of the crust. If bare, quark stars possess ultra-high electric fields on the order of 10^{18} to 10^{19} V/cm. These features render the properties of quark stars more multifaceted than those of neutron stars and may allow one to observationally distinguish quark stars from neutron stars.

Keywords. neutron stars, quark stars, pulsars, strange quark matter, equation of state

1. Introduction

The theoretical possibility that quark matter made of up, down and strange quarks (so-called strange quark matter; Farhi & Jaffe 1984) may be more stable than ordinary nuclear matter has been pointed out by Bodmer (1971), Terazawa (1979), and Witten (1984). This so-called strange matter hypothesis constitutes one of the most startling possibilities regarding the behavior of superdense matter, which, if true, would have implications of fundamental importance for cosmology, the early universe, its evolution to the present day, and astrophysical compact objects such as neutron stars and white dwarfs (see Alcock & Farhi 1986, Alcock & Olinto 1988, Aarhus 1991, Weber 1999, Madsen 1999, Glendenning 2000, Weber 2005, Page & Reddy 2006, Sagert *et al.* 2006, and references therein). The properties of quark stars are compared with those of neutron stars in Table 1 and Fig. 1. Even to the present day there is no sound scientific basis on which one can either confirm or reject the hypothesis so that it is a serious possibility of fundamental significance for various (astro) physical phenomena.

The multifaceted properties of these objects are reviewed in this paper. Particular emphasis is is put on stellar properties such as rapid rotation, ultra-high electric surface fields, and rotational vortex expulsion, which may allow one to observationally discriminate between quark stars and neutron stars and–ultimately–prove or disprove the strange quark matter hypothesis. Further information on the existence of quark stars may come

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Table 1. Theoretical properties of quark stars and neutron stars compared.

Quark Stars	**Neutron Stars**
Made entirely of deconfined up, down, strange quarks, and electrons	Nucleons, hyperons, boson condensates, deconfined quarks, electrons, and muons
Quarks ought to be color superconducting	Superfluid neutrons Superconducting protons
Energy per baryon $\lesssim$ 930 MeV	Energy per baryon $>$ 930 MeV
Self-bound ($M \propto R^3$)	Bound by gravity
Maximum mass $\sim 2\,M_\odot$	Same
No minimum mass	$\sim 0.1\,M_\odot$
Radii $R \lesssim 10 - 12$ km	$R \gtrsim 10 - 12$ km
Baryon number $B \lesssim 10^{57}$	$10^{56} \lesssim B \lesssim 10^{57}$
Electric surface fields $\sim 10^{18}$ to $\sim 10^{19}$ V/cm	Absent
Can be bare (pure quark stars) or enveloped in thin nuclear crusts (mass $10^{-5}\,M_\odot$)	Not possible Always possess nuclear crusts
Density of crust is less than neutron drip i.e., posses only outer crusts	Density of crust above neutron drip i.e., posses inner and outer crusts
Form two-parameter stellar sequences	Form one-parameter stellar sequences

from quark novae, hypothetical types of supernovae which could occur if neutron stars spontaneously collapse to quark stars (Ouyed *et al.* 2002).

2. Quark-Lepton Composition of Quark Stars

Quark star matter is composed of the three lightest quark flavor states (up, down, and strange quarks). Per hypothesis, the energy per baryon of such matter is lower than the energy per baryon of the most stable atomic nucleus, ^{56}Fe. Since stars in their lowest energy state are electrically charge neutral to very high precision, any net positive quark charge must be balanced by electrons. The concentration of electrons is largest at low densities due to the finite strange-quark mass, which leads to a deficit of net negative quark charge. If quark star matter forms a color superconductor (Rajagopal & Wilczek 2001, Alford 2001, Alford *et al.* 2008, and references therein) in the Color-Flavor-Locked (CFL) phase the interiors of quarks stars will be rigorously electrically neutral with no need for electrons, as shown by Rajagopal & Wilczek (2001). For sufficiently large strange quark masses, however, the low density regime of quark star matter is rather expected to form other condensation patterns (e.g. 2SC, CFL-K^0, CFL-K^+, CFL-$\pi^{0,-}$) in which electrons will be present (Rajagopal & Wilczek 2001, Alford 2001, Alford *et al.* 2008). The presence of electrons in quark star matter is crucial for the possible existence of a nuclear crust on quark stars. As shown by Alcock *et al.* (1986), Kettner *et al.* (1995), and Alcock & Olinto (1988), the electrons, because they are bound to strange matter by the Coulomb force rather than the strong force, extend several hundred fermi beyond the surface of the strange star. Associated with this electron displacement is a electric dipole layer which can support, out of contact with the surface of the strange star, a crust of nuclear material, which it polarizes (Alcock *et al.* 1986, Alcock & Olinto 1988). The

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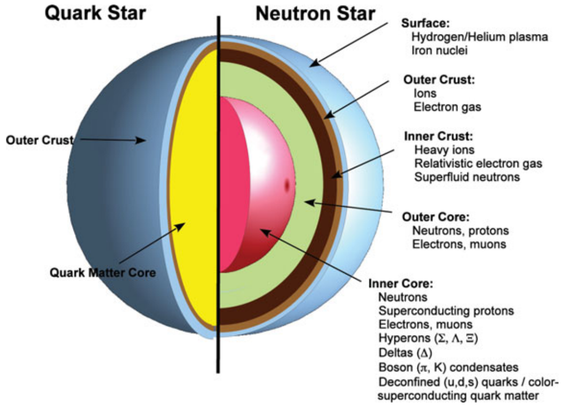

Figure 1. Schematic structures of quark stars and neutron stars.

maximum possible density at the base of the crust (inner crust density) is determined by neutron drip, which occurs at about 4.3×10^{11} g/cm^3.

3. Bare versus Dressed Quark Stars and Eddington Limit

A bare quark star differs qualitatively from a neutron star which has a density at the surface of about 0.1 to 1 g/cm^3. The thickness of the quark surface is just ~ 1 fm, the length scale of the strong interaction. The electrons at the surface of a quark star are held to quark matter electrostatically, and the thickness of the electron surface is several hundred fermis. Since neither component, electrons and quark matter, is held in place gravitationally, the Eddington limit to the luminosity that a static surface may emit does not apply, so that bare quark stars may have photon luminosities much greater than 10^{38} erg/s. It was shown by Usov (1998) that this value may be exceeded by many orders of magnitude by the luminosity of e^+e^- pairs produced by the Coulomb barrier at the surface of a hot strange star. For a surface temperature of $\sim 10^{11}$ K, the luminosity in the outflowing pair plasma was calculated to be as high as $\sim 3 \times 10^{51}$ erg/s. Such an effect may be a good observational signature of bare strange stars (Usov 2001a, Usov 2001b, Usov 1998, and Cheng & Harko 2003). If the strange star is enveloped in a nuclear crust, however, which is gravitationally bound to the strange star, the surface, made of ordinary atomic matter, would be subject to the Eddington limit. Hence the photon emissivity of such a "dressed" quark star would be the same as for an ordinary neutron star. If quark matter at the stellar surface is in the CFL phase the process of e^+e^- pair creation at the stellar quark matter surface may be turned off. This may be different for the early stages of a very hot CFL quark star (Vogt *et al.* 2004).

4. Mass-Radius Relationship of Quark Stars

The mass-radius relationship of bare quark stars is shown in Fig. 2. In contrast to neutron stars, the radii of self-bound quark stars decrease the lighter the stars, according to $M \propto R^3$. The existence of nuclear crusts on quark stars changes the situation drastically (Glendenning *et al.* 1995, Weber 1999, and Weber 2005). Since the crust is bound gravitationally, the mass-radius relationship of quark stars with crusts is then qualitatively similar to neutron stars.

In general, quark stars with or without nuclear crusts possess smaller radii than neutron stars. This feature implies that quark stars posses smaller mass shedding periods than

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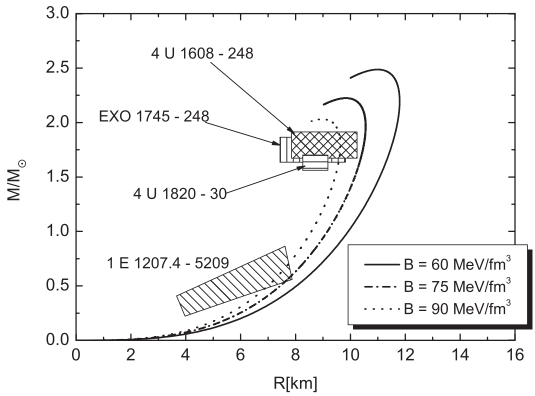

Figure 2. Mass-radius relationship of bare quark stars (from Orsaria *et al.* 2011).

neutron stars. Due to the smaller radii of quarks stars, the complete sequence of such objects–and not just those close to the mass peak, as it is the case for neutron stars–can sustain extremely rapid rotation (Glendenning *et al.* 1995, Weber 1999, and Weber 2005). In particular, a strange star with a typical pulsar mass of around $1.45\,M_\odot$ can rotate at Kepler (mass shedding) periods as small as $0.55 \lesssim P_{\rm K}/{\rm msec} \lesssim 0.8$ (Glendenning & Weber 1992, and Glendenning *et al.* 1995). This range is to be compared with $P_{\rm K} \sim 1$ msec obtained for neutron stars of the same mass (Weber 1999).

Another novelty of the strange quark matter hypothesis concerns the existence of a new class of white-dwarf-like objects, referred to as strange (quark matter) dwarfs (Glendenning *et al.* 1995). The mass-radius relationship of the latter may differs somewhat from the mass-radius relationship of ordinary white-dwarf, which may be testable in the future. Until recently, only rather vague tests of the theoretical mass-radius relation of white dwarfs were possible. This has changed dramatically because of the availability of new data emerging from the Hipparcos project (Provencal 1998). These data allow the first accurate measurements of white dwarf distances and, as a result, establishing the mass-radius relation of such objects empirically.

5. Pulsar Glitches

Of considerable relevance for the viability of the strange matter hypothesis is the question of whether strange stars can exhibit glitches in rotation frequency. From the study performed by Glendenning & Weber (1992) and Zdunik *et al.* (2001) it is known that the ratio of the crustal moment of inertia to the total moment of inertia varies between 10^{-3} and $\sim 10^{-5}$. If the angular momentum of the pulsar is conserved in a stellar quake one obtains for the change of the star's frequency $\Delta\Omega/\Omega \sim (10^{-5} - 10^{-3})f$, where $0 < f < 1$ (Glendenning & Weber 1992). The factor f represents the fraction of the crustal moment of inertia that is altered in the quake. Since the observed glitches have relative frequency changes $\Delta\Omega/\Omega = (10^{-9} - 10^{-6})$, a change in the crustal moment of inertia of $f \lesssim 0.1$ would cause a giant glitch (Glendenning & Weber 1992). Moreover it turns out that the observed range of the fractional change in the spin-down rate, $\dot\Omega$, is consistent with the crust having a small moment of inertia and the quake involving only a small fraction f of that. For this purpose we write $\Delta\dot\Omega/\dot\Omega > (10^{-1}$ to $10)f$ (Glendenning & Weber 1992). This relation yields a small f value, i.e., $f < (10^{-4}$ to $10^{-1})$, in

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agreement with $f \lesssim 0.1$ established just above. For these estimates, the measured values of $(\Delta\Omega/\Omega)/(\Delta\dot{\Omega}/\dot{\Omega}) \sim 10^{-6}$ to 10^{-4} for Crab and Vela, respectively, have been used.

6. Possible Connection to CCOs

One of the most amazing features of quark stars concerns the possible existence of ultra-high electric fields on their surfaces, which, for ordinary quark matter, is around 10^{18} V/cm. If strange matter forms a color superconductor, as expected for such matter, the strength of the electric field may increase to values that exceed 10^{19} V/cm. The energy density associated with such huge electric fields is on the same order of magnitude as the energy density of strange matter itself, which alters the masses and radii of strange quark stars at the 15% and 5% level, respectively (Negreiros *et al.* 2009). Such mass increases facilitate the interpretation of massive compact stars, with masses of around $2\,M_\odot$, as strange quark stars (see also Rodrigues *et al.* 2011).

The electrons at the surface of a quark star are not necessarily in a fixed position but may rotate with respect to the quark matter star (Negreiros *et al.* 2010). In this event magnetic fields can be generated which, for moderate effective rotational frequencies between the electron layer and the stellar body, agree with the magnetic fields inferred for several Compact Central Objects (CCOs). These objects could thus be interpreted as quark stars whose electron atmospheres rotate at frequencies that are moderately different (~ 10 Hz) from the rotational frequency of the quark star itself.

Last but not least, we mention that the electron surface layer may be strongly affected by the magnetic field of a quark star in such a way that the electron layer performs vortex hydrodynamical oscillations (Xu *et al.* 2012). The frequency spectrum of these oscillations has been derived in analytic form by Xu *et al.* (2012). If the thermal X-ray spectra of quark stars are modulated by vortex hydrodynamical oscillations, the thermal spectra of compact stars, foremost central compact objects (CCOs) and X-ray dim isolated neutron stars (XDINSs), could be used to verify the existence of these vibrational modes observationally. The central compact object 1E 1207.4-5209 appears particularly interesting in this context, since its absorption features at 0.7 keV and 1.4 keV can be comfortably explained in the framework of the hydro-cyclotron oscillation model (Xu *et al.* 2012).

A study which looks at the thermal evolution of CCOs is presently being carried out by Yang *et al.* (2012). Preliminary results indicate that the observed temperatures of CCOs can be well reproduced if one assumes that these objects are small quark matter objects with radii less than around 3 km.

7. Possible Connection to SGRs, AXPs, and XDINs

If quarks stars are made of color superconducting quark matter rather than normal non-superconducting quark matter. If rotating, superconducting quark stars ought to be threaded with rotational vortex lines, within which the star's interior magnetic field is at least partially confined. The vortices (and thus magnetic flux) would be expelled from the star during stellar spin-down, leading to magnetic reconnection at the surface of the star and the prolific production of thermal energy. Niebergal *et al.* (2010) have shown that this energy release can re-heat quark stars to exceptionally high temperatures, such as observed for Soft Gamma Repeaters (SGRs), Anomalous X-Ray pulsars (AXPs), and X-ray dim isolated neutron stars (XDINs). Moreover, numerical investigations of the temperature evolution, spin-down rate, and magnetic field behavior of such superconducting

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quark stars suggest that SGRs, AXPs, and XDINs may be linked ancestrally (Niebergal *et al.* 2010).

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