Quark matter in compact stars?

Alford, M.\textsuperscript{1}, Blaschke, D.\textsuperscript{2,3}, Drago, A.\textsuperscript{4,5}, Klähn, T.\textsuperscript{3,6}, Pagliara, G.,\textsuperscript{4,5} Schaffner-Bielich, J.\textsuperscript{7}

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1. Department of Physics, Washington University, St Louis, MO 63130, USA
2. Instytut Fizyki Teoretycznej, Uniwersytet Wrocławski, pl. M. Borna 9, 50-204 Wrocław, Poland
3. Institut für Physik, Universität Rostock, D-18051 Rostock, Germany
4. Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy
5. INFN, Sezione di Ferrara, I-44100 Ferrara, Italy
6. Gesellschaft für Schwerionenforschung mbH (GSI), Planckstr. 1, 64291 Darmstadt, Germany
7. Institut für Theoretische Physik, Goethe Universität, D-60438 Frankfurt am Main, Germany

In a theoretical interpretation of observational data from the neutron star EXO 0748-676, Özel concluded that quark matter probably does not exist in the center of neutron stars\textsuperscript{1}. However, this conclusion was based on a limited set of possible equations of state (EoS) for quark matter. Here we compare Özel’s observational limits with predictions based on a more comprehensive set of proposed quark matter equations of state from the existing literature, and conclude that the presence of quark matter in EXO 0748-676 is not ruled out.

Özel’s stated lower limits on the mass and radius are $M \geq 2.1 \pm 0.28\, M_{\odot}$ and $R \geq 13.8 \pm 1.8\, \text{km}$. She correctly points out that these values exclude a soft EoS. She then infers that there is no quark matter in this compact star. However, this conclusion does not follow because quark matter can be as stiff as nuclear matter, as effects from strong interactions (QCD) can harden the EoS substantially. The corresponding hybrid or quark stars can indeed reach a mass of $2M_{\odot}$ as demonstrated in calculations using the MIT bag model\textsuperscript{2}, perturbative corrections to QCD\textsuperscript{3}, and the Nambu–Jona-Lasinio model\textsuperscript{4}. The mass-radius relations for compact stars using various quark matter and nuclear matter EoS along with the lower limits derived by Özel are shown in Figure 1.

In addition to the mass and radius, there are potential constraints on (or signatures of) the presence of quark matter from observations of the cooling, spin-down, and
precession of neutron stars, and from transient phenomena such as glitches, magnetar flares, and superbursts.

Cooling observations of firmly-identified neutron stars are mostly consistent with a “minimal model” of nuclear matter cooling, but there is evidence of faster cooling in limits obtained from supernova remnants, and the presence of exotic forms of matter is not ruled out [5]. A detailed analysis of cooling data including information from elliptic flow in heavy ion collisions was unable to find any purely nuclear EoS that was compatible with all the data [6]. Models involving some quark matter in the cores of neutron stars were more successful [7, 8].

Measurements of the spin-down rate of neutron stars can be used to constrain the shear and bulk viscosity of the interior, since sufficiently low viscosity would lead to very fast spin-down via gravitational radiation from unstable r-modes. Preliminary calculations rule out a strange star made of CFL matter [9], but hybrid stars are not ruled out. More controversially, it has also been argued that the measured precession of some stars is inconsistent with the standard understanding of nuclear matter [10].

Glitches (temporary speeding-up in the rotation of a neutron star that is gradually spinning down) are only partially understood, but are believed to provide evidence for a substantial crust overlapping with a superfluid region inside the star [11]. This does not exclude the presence of a quark matter core, and may not even exclude strange stars, since there are superfluid and crystalline phases of quark matter [12, 13].

Observations of quasi-periodic oscillations in soft gamma repeaters have recently been used to obtain the frequencies of toroidal shear modes of their crusts. The results are not consistent with these objects being purely strange stars, but put no limits on the presence of a quark matter core inside them [14].

Finally, observations of superbursts in low-mass X-ray binaries yield ignition depths much smaller than those predicted for standard neutron stars, and are more compatible with these objects being hybrid stars with a relatively thin baryonic crust [15].

We conclude that if Özel’s analysis is correct, it can be used to put constraints on the parameters of the quark matter EoS, but neither Özel’s analysis nor the other available observational data has yet ruled out the presence of deconfined quarks in compact stars.

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Figure 1: The lower limit on $M$ and $R$ from Özel’s analysis of EXO 0748-676 [1] (we show one and two sigma error bars), and the calculated $M$-$R$ curve for various quark matter and nuclear matter equations of state. These include pure nuclear matter described by the DBHF (relativistic Dirac-Brueckner-Hartree-Fock) EoS [6]; a hybrid star with a core of 2SC quark matter (a two-flavor color-superconducting phase in which only the up and down quarks form Cooper pairs) and a mantle of DBHF nuclear matter [8]; a hybrid star with a core of 2SC quark matter and mantle of HHJ nuclear matter (APR with high-density causality corrections) [7]; a hybrid star whose core is a mixed phase of APR nuclear matter (based on the Argonne $v_{18}$ two-nucleon interaction with variational chain summation) and CFL quark matter (the “color-flavor-locked” color-superconducting phase in which all three colors and flavors undergo Cooper pairing) [2]; and a pure quark matter star using an equation of state with $O(\alpha_s^2)$ QCD corrections [3]. It is clear that the presence of quark matter is not excluded by the EXO 0748-676 results.