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Quark matter in compact stars?

Arising from: F. Özel *Nature* **441,** 1115–1117 (2006)

In a theoretical interpretation of observational data from the neutron star EXO 0748–676, Özel concludes that quark matter probably does not exist in the centre of neutron stars[1]. However, this conclusion is based on a limited set of possible equations of state 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 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 $R \geq 13.8 \pm 1.8$ km. She correctly points out that these values exclude a soft equation of state, but then infers that there is no quark matter in this compact star. However, this conclusion is not justified because quark matter can be as stiff as nuclear matter, because effects from strong interactions (quantum chromodynamics, QCD) can harden the equations of state substantially. The corresponding hybrid or quark stars can indeed reach a mass of $2M_\odot$, as demonstrated in calculations using the MIT bag model[2], perturbative corrections to QCD[3], and the Nambu–Jona–Lasinio model[4]. The mass–radius relations for compact stars using various quark-matter and nuclear-matter equations of state, together with the lower limits derived by Özel, are shown in Fig. 1.

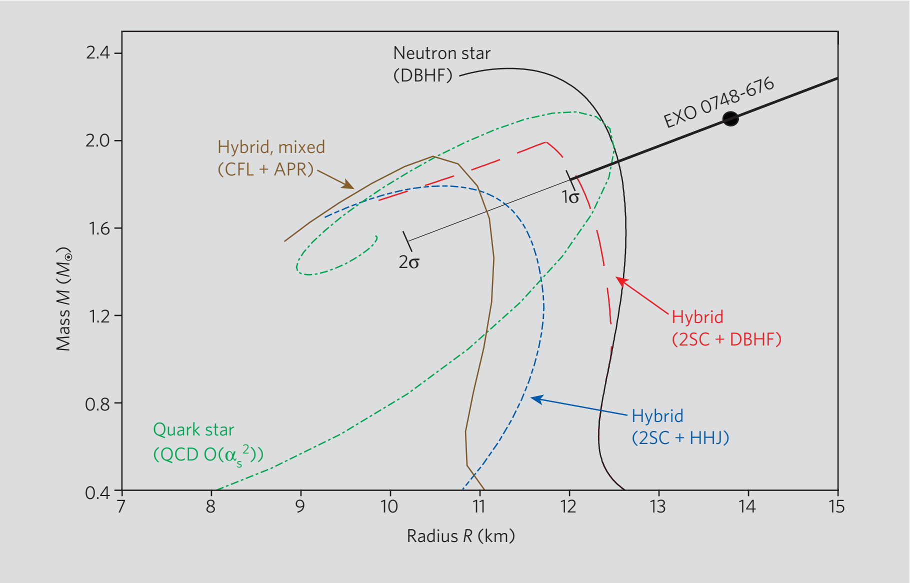

Figure 1 | Lower limit of mass, *M*, and radius, *R*, from Özel's analysis[1] of EXO 0748–676 (1σ and 2σ error bars are shown), and the calculated *M–R* curve for various quark- and nuclear-matter equations of state. These include pure nuclear matter described by the DBHF (relativistic Dirac–Brueckner–Hartree–Fock) equation of state[6] (black line); a hybrid star with a core of 2SC quark matter (a two-flavour colour-superconducting phase, in which only the up and down quarks form Cooper pairs) and a mantle of DBHF nuclear matter[8] (red line); a hybrid star with a core of 2SC quark matter and mantle of HHJ nuclear matter (APR with high-density causality corrections)[7] (blue line); a hybrid star whose core is a mixed phase of APR nuclear matter (based on the Argonne υ_{18} two-nucleon interaction with variational chain summation) and CFL quark matter (the 'colour–flavour-locked' colour-superconducting phase in which all three colours and flavours undergo Cooper pairing)[2] (brown line); and a pure quark-matter star using an equation of state with order α_s^2 QCD corrections[3] (green line). The presence of quark matter is therefore not excluded by the EXO 0748–676 results.

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. However, 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 elliptical flow in heavy-ion collisions, was unable to find any purely nuclear equation of state 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, because sufficiently low viscosity would lead to very fast spin-down by gravitational radiation from unstable *r*-modes. Preliminary calculations rule out a strange star made of 'colour–flavour-locked' (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, as there are superfluid and crystalline phases of quark matter[12,13].

Observations of quasi-periodic oscillations in soft gamma repeaters have 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 they put no limits on the presence of a quark-matter core inside them[14].

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 Özel's analysis, assuming that it is indeed correct, can be used to put constraints on the parameters of the quark-matter equations of state, but that neither Özel's analysis nor the other available observational data have yet ruled out the presence of deconfined quarks in compact stars.

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Özel replies

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In their comment[1] on my theoretical interpretation[2] of the observations of EXO 0748–676, Alford *et al.* suggest variants of quark-matter equations of state that produce stars consistent with my results. They do not challenge either the method that I propose or my conclusion that the data require a stiff equation of state[2].

Given the large uncertainties in the phenomenological description of quark matter used in predicting the properties of quark and hybrid stars, it is not surprising that models that meet the new constraints can be readily constructed. It is only through quantitative and uncoupled measurements of the masses and radii of neutron stars, such as the one that I propose[2], that the properties of matter at high densities will be constrained.

There are other methods related to the cooling of young neutron stars, pulsar glitches and quasiperiodic variability that offer the possibility of providing astrophysical constraints on the equation of state of the neutron-star matter. It is important to realize, however, that some of these methods rely on the two most uncertain properties of astrophysical objects, namely their distances and ages. Others lead to only qualitative inferences because of their strong dependence on models. In both cases, comparison of predictions with observations indicates that quark stars cannot be ruled out, but neither are they favoured[3–6].

Unlike these other methods, the one that I present results in a direct measurement of stellar masses and radii, with quantifiable uncertainties. In the case of EXO 0748–676, it leads to the firm conclusion that soft equations of state are ruled out, as Alford *et al.* concur.

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