Observability of neutron stars with quarks

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Recent Chandra observations have raised expectations that the objects RX J185635-3754 and 3C58 are either bare strange quark stars or stars with extended quark cores. However, these observations can also be interpreted in terms of normal neutron stars. Essential requirements for either explanation are that they simultaneously account for the observed (i) spectral features (i.e., thermal or nonthermal, possible lines), (ii) bounds on the inferred mass ($M$) and radius ($R$), and (iii) the cooling curves (effective temperatures $T$ and luminosities $L$ vs. age). Compact stars offer the promise of delineating QCD at finite baryon density [1] in a fashion complementary to relativistic heavy ion collider experiments, which largely address the finite temperature, but baryon poor regime.

Recently, multi-wavelength photon observations of the isolated neutron star RX J185635-3754 has attracted much attention since its distance from Earth and hence its radius was estimated. The basis of a radius estimation rests on relating the measured flux $f_\infty$ and effective temperature $T_\infty$ (hereon, the subscript $\infty$ refers to quantities measured far away from the source) from a thermal source of radius $R$, temperature $T$ and distance $D$ using

$$L_\infty = 4\pi R^2_\infty \sigma T^4_\infty = 4\pi D^2 f_\infty \quad \Rightarrow \quad R_\infty = D \sqrt{f_\infty/\left(\sigma T^4_\infty\right)},$$

(1)

where $L_\infty$ is the luminosity. The measured and in situ quantities are related by appropriate red-shift factors:

$$R_\infty = \frac{R}{\sqrt{1 - R_s/R}}, \quad R_s = \frac{2GM}{c^2} \quad \text{and} \quad T_\infty = T \sqrt{1 - R_s/R}.$$  

(2)

In practice, several additional considerations such as the gravitational bending of light, nonuniform surface temperatures, redistribution of flux through a neutron star atmosphere, and the effects of magnetic fields, etc., must be included before the radius (and, in some cases, the mass) of the neutron star can be estimated (see, e.g., Ref. [2]). Table 1 contains a summary of findings to date. The column labelled “THEN” refers to the findings of Ref. [2] and is based upon the reported parallax in Ref. [3], which, however, did not include corrections for geometrical distortions of the HST camera at the edges of the fields. Such corrections were incorporated in Refs. [4, 5] with the result that the parallax was reduced by roughly a factor of two. Hence, the distance $D$ has been revised to nearly twice the value quoted in Ref. [3] (see the column labelled “NOW”).
Table 1
RX J185635-3754 (ROSAT, EUVE, NTT, Keck, HST & Chandra)

|                  | THEN         | NOW*        |
|------------------|--------------|-------------|
| Parallax (mas)   | 16.5 ± 2.3   | 8.5 ± 0.9   |
| Distance D (pc)  | 60.6 ± 8.5   | 117 ± 12    |
| Surface $T_{\text{eff}}^\infty$ (eV): |             |             |
| X-ray (Blackbody)| 57           | 63          |
| X-ray + Opt. + Atm.| 45 ± 6       | 45 ± 6      |
| Age (yr)         | 0.9 $\times$ 10^6 | 5 $\times$ 10^5 |
| Proper Motion (mas/yr) | 332 ± 1     | 332 ± 1    |
| Transverse Velocity (km/s) | 100 ± 15     | 185 ± 26   |
| $R_{\infty} = R/\sqrt{1 - 2GM/c^2}$ (km) | 6 – 8 (BB) | 15 ± 3 |
| $z = (1 - 2GM/Rc^2)^{-1/2} - 1$ | 0.4 ± 0.1 | 0.35 ± 0.15 |
| Mass $M/M_\odot$ | 0.6 – 1.2   | 1.7 ± 0.4   |
| Radius $R$ (km)  | 4.5 – 8      | 11.4 ± 2    |
| Period $P$ (s)   | –            | $\sim$ 0.22 |

* Includes 4th observation and corrections for geometrical distortions of the HST camera at the edges of the fields.

Figure 1 shows mass-radius diagrams for uniform-temperature heavy element atmosphere models, taken from Ref. [2], for a revised distance of 117 pc. The left and right panels are for Fe and Si-ash compositions, respectively. Theoretical $M-R$ trajectories for representative equations of state EOSs labelled following Ref. [1] are shown by thick solid curves. The shaded region labelled “causality” is bounded by the compactness limit set by requiring EOSs to be causal. Thin lines are contours of fixed $R_{\infty}$. The crosses denote the $M$ and $R$ of models which best fit the optical and X-ray data, and the egg-shaped shaded regions surrounding them include the nominal errors indicated in the constraint relations in equations (4) through (7) of Ref. [3], as well as the nominal error in the distance.

The implications of the revised parallax and hence the distance are: (i) The inferred radius ($R = 11.4 \pm 2$ km) and mass ($M/M_\odot = 1.7 \pm 0.4$) are in the range of many EOSs both with and without exotic matter, including cases of stars with quarks in their core and bare strange quark matter stars, and (ii) Measurements have removed observational support for an “extremely soft” EOS. The atmospheric composition and the effects of magnetic fields, however, remain unresolved.

Recent Chandra observations of the pulsar J0205+6449 in the supernova remnant of 3C58 indicate that the thermal component must be very small, since the radiation is nearly completely fit by a power-law spectrum [6]. The temperature of a possible residual thermal component is thereby limited (see Table 2). Although this upper limit can be fit with standard neutrino cooling (e.g., $n + n \rightarrow n + p + e^- + \bar{\nu}_e$) plus pair-breaking and formation, the luminosity and ages of other neutron stars cannot be simultaneously fit using the same EOS [7, 8]. This has the interesting consequence that more exotic, rapid cooling processes may exist in the neutron star core.

Among such processes are Urca reactions involving deconfined quarks which may exist
in many possible forms. These include a mixed phase of hadrons and quarks, and color-flavor-locked (CFL) or 2-flavor superconducting (2SC) or crystalline phases surrounded by an hadronic phase with possible thin interfaces. It is also possible that Bose condensation may occur in the hadronic and/or CFL phases. The most exotic case would be a star made entirely of quark matter (the so-called strange quark star) with CFL and/or 2SC phases with no hadronic matter and therefore having so-called “bare” surfaces.

In Ref. [9], the prospects of detecting baryon and quark superfluidity from neutron stars during their long-term (up to $10^6$ years) cooling epoch was studied. Our assessment is that future photon observations of neutron star cooling (1) could constrain the smaller of the $n-$ or $\Lambda-$ pairing gaps and the star’s mass, but (2) deducing the sizes of quark gaps will be difficult, (3) large $q-$gaps would render quarks invisible, and (4) vanishing $q-$gaps would lead to cooling behaviors indistinguishable from those of ordinary nucleon or nucleon/hyperon stars.

In Ref. [10], neutrino emissivities from the decay and scattering of Goldstone bosons in the color-flavor-locked (CFL) phase of quarks at high baryon density were calculated. Both emissivities and specific heats are so small that, although the timescale for the cooling of the CFL core becomes exceedingly large, the CFL phase would remain invisible because the exterior layers of normal matter surrounding the quark core would continue to cool through significantly more rapid processes.

In Ref. [11], it was noted that thermal emission from the bare surface of a strange quark star can produce photon luminosities well above the Eddington limit for extended periods of time, from about a day to decades depending on the superconducting state of strange quark matter. But the spectrum of emitted photons would be significantly different from that of a normal cooling neutron star ($30 < E/\text{keV} < 500$ instead of $0.1 <
Table 2
Pulsar J0205+6449 in 3C58 (Chandra)

|                          |       |
|--------------------------|-------|
| Period (ms)              | 65    |
| Energy loss $\dot{E}$ (erg s$^{-1}$) | $2.6 \times 10^{37} I_{45}$ |
| Distance D (kpc)         | 3.2   |
| Column density $N_H$ (cm$^{-2}$) | $(3.75 \pm 0.11) \times 10^{21}$ |
| Power law index $\Gamma$ | 1.73 $\pm$ 0.07 |
| Age (yr)                 | 922 (SN association) |
|                          | 5481 (optical & radio) |
| Surface $T_{\infty eff}$ (eV) | $\leq 95^\dagger$ (BB) |

$^\dagger$ Data requires thermal component to be very small; $T_{\infty eff}$ is thus an upper limit.

$E/\text{keV} < 2.5)$. Due to its distinctive spectrum and time evolution, such an observation would constitute an almost unmistakable detection of a strange quark star and shed light on color superconductivity at “stellar” densities. These predicted characteristics are well within the capabilities of INTEGRAL [12] to be launched towards the end of 2002.

The influence of quarks on neutrino fluxes from proto-neutron stars were studied in Ref. [13]. Observable effects of quarks only become apparent for stars older than 10–20 s. Sufficiently massive stars containing negatively-charged, strongly interacting, particles (such as quarks, but also including hyperons and kaon condensates) may collapse to black holes during the first minute of evolution. Since the neutrino flux vanishes when a black hole forms, this would constitute an obvious signal that quarks (or other types of strange matter) have appeared. The collapse timescales for stars containing quarks are predicted to be intermediate between those containing hyperons and kaon condensates.

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