Possible evidence of surface vibration of strange stars from stellar observations

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ABSTRACT
Emission lines in the eV and keV range by certain stellar candidates from their recent analysis invoke the question of their possible origin. The stars under consideration are 4U 0614+091 (0.65, 0.86 and 1.31 keV), 2S 0918−549 (0.8 keV with width 55 eV), 4U 1543−624 (0.7 keV), 4U 1850 −087 (0.7 keV) and 4U 1820−30 (0.6 and 0.9 keV) and also the 0.6-keV excess emission in RX J170930.2−263927. Recently, it has been suggested that the resonance absorption at ∼ 0.7, 1.4, 2.1 and 2.8 keV in 1E1207−5209 and 0.35, 0.7 and 1.4 keV in RX J1856.5−3754 are due to harmonic surface vibrations in strange stars. We propose that these harmonic vibrations may also be responsible for emission lines in the above mentioned compact stellar candidates.

Key words: dense matter – stars: interiors – stars: oscillations.

1 INTRODUCTION

Line emissions below and above the keV region have been observed in many compact star sources. It is intriguing to note that often their frequencies are multiples of each other, showing a harmonic origin. It is well known that such harmonic vibrations are seen in large nuclei and are called breathing-mode oscillations, whose origin is the compressional modes of surface vibrations. To see such behaviour in a compact star, it should have a sharp surface and the star should be self-bound with pressure $p = 0$ at the surface. For this criterion, it is required that the star be described by an equation of state (EOS) which has a minimum value of $E/A$ at a non-zero density, where $E$ is the binding energy and $A$ is the baryon number. All of the existing neutron-star EOSs have surface density zero, while most of the strange-star EOSs have the feature of a sharp surface. Besides the existing MIT Bag model EOSs for strange matter (Farhi & Jaffe 1984; Alcock, Farhi & Olinto 1986; Haensel, Zdunik & Schaeffer 1986, etc.), Dey et al. (1998, 1999) (henceforth, D98) gave an EOS for strange matter and used it to model strange stars having a minimum value of $E/A$ at a non-zero density. Another strange-star model having such a phenomenon is that by Malheiro, Fiolhais & Taurines (2003), where they have the feature of a sharp surface. We shall use the D98 model in our further discussions and shall consider only the EOS1 in D98 which is the same as the SS1 in Li et al. (1999a).

Recently, it has been shown that the resonance absorption in 1E 1207.4−5209 and RX J1856.5−3754 can be plausibly interpreted as being due to surface vibrations in strange stars (Sinha et al. 2003; henceforth SDDRB). In particular, the former star shows evidence of four harmonics (Bignami et al. 2003) and has been studied extensively by XMM–Newton, making it the most deeply scrutinized galactic target of the mission (De Luca et al. 2004a).

The presence of the vibrational frequencies we discuss is related to surface compressional modes and is only possible if (uds) quark matter is self-bound, as for example in D98. There cannot be harmonic compressional modes in neutron stars because of the lack of a minimum in the $E/A$ of its EOS which results in the absence of a sharp surface.

The direct estimate of the mass–radius relation of compact stars is still far from accurate and depends on a lot of assumptions, like the surface temperature, luminosity, distance estimates, etc. With the size of conventional neutron stars being slightly more than the more exotic strange stars, and they themselves being so far away, it is hardly possible to make any distinction between the two. Ambiguities arise in the estimates of these objects even with the most modern satellites and telescopes. A particular example is the recently debated object RX J1856.5−3754. Drake et al. (2002) claimed it to be a strange star, while at the same time Walter & Lattimer (2002) showed that if they assumed the surface temperature of 33 eV, instead of 61.2 eV as taken by Drake et al. (2002), then it gives a mass–radius relation perfectly consistent with normal neutron stars. So, to bypass these kinds of uncertainties and debates, an

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alternative signature is desperately sought in order to prove the existence of strange stars. Estimates of the surface vibrations for strange stars (for the D98 model, which is a realistic model of quark confinement and asymptotic freedom) has recently been studied by Sinha et al. (2003). Their predictions of the emissions from the bare strange stars, due to this effect, astonishingly match with the line emissions from certain candidates.

In the next section we discuss the radial breathing-mode oscillation problem. In Section 3 we discuss our results and remark on relevant observations. In the last section we conclude and summarize.

2 BREATHING OSCILLATIONS IN STRANGE STARS

The u and d quarks are believed to be light (4 and 7 MeV, respectively) and the strange quark s, moderately light (150 MeV) at very high density, whereas in hadrons they have a mass of roughly one-third of the hadron mass. One therefore thinks of chiral symmetry restoration as one moves from low to high density. When this is included along with a Debye screening for gluon propagation, a realistic model may be described for exploring the possibility of a high-density strange quark phase comprising u, d and s quarks. Considering the above-mentioned properties, D98 developed their model for strange quark matter and strange stars. The EOSI of D98 has a minimum energy per baryon (E/A) at a surface density of 4.586 times the normal nuclear matter density, where the pressure is $p = 0$, and this surface can vibrate. The spectrum of the vibration frequency $\nu$ is controlled by $dp/dr$ and is harmonic so frequencies $n\nu$ are expected to occur for $n = 1, 2, 3, \ldots$.

We recall the relevant formulae for breathing surface oscillations in SDDRB to calculate the mass, once the fundamental frequency of vibration is known. We get the corresponding radius of the star from

$$m_{\text{skin}} = 4\pi R^2 d \rho_{\text{surf}} \frac{M_u + M_d}{2}.$$  \hspace{1cm} (6)

where the surface density is $\rho_{\text{surf}} = 4.586 \rho_q$ for SS1 with $\rho_q = 0.51 \text{ fm}^{-3}$. The dimension of $\lambda$ is clearly macroscopic. It shows the onset of asymptotic freedom even at the surface of the strange star.

In terms of $d$

$$M_u = 132 \text{ MeV and } M_d = 135 \text{ MeV for SS1 at the star surface. Note that this shows chiral symmetry restoration is setting in already at the surface of the star, being much more prominent at the centre where the density is 15$\rho_q$ or 46.85 $\times$ $10^{14}$ gm cm$^{-3}$.

Due to strong interaction binding, the strange star surface is very firm and the portion that can oscillate symmetrically is thin, typically a one-quark layer as we have discussed above.

The star mass and radius are given in Figs 1 and 2 for the relevant values of the breathing resonance line.

3 DISCUSSION

Below we discuss the evidence for the line emissions from various stars.

(i) 4U 0614+091 is a moderately bright X-ray source. Three emission lines at around 0.65, 0.86 and 1.31 keV are proposed by Schulz (1999). This would correspond to a mass of about 1.1 $M_\odot$ with radius 7.02 km.

(ii) 2S 0918–549 is a source fitted to a power law plus blackbody spectrum ($kT = 3$ keV) with $\chi^2 = 1.65$ and shows a residual at

Figure 1. Fundamental vibrational energy ($e_v$) for skin vibrations of strange stars as a function of the stellar mass.

Figure 2. Fundamental vibrational energy ($e_v$) for skin vibrations of strange stars as a function of the stellar dimensions.

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
\textit{e} (keV) & \textit{\nu} (keV) \\
\hline
0.25 & 0.3 \\
0.35 & 0.4 \\
0.45 & 0.5 \\
\hline
\end{tabular}
\caption{Fundamental vibrational energy ($e_v$) for skin vibrations of strange stars.}
\end{table}
be 7.055 km (Dey et al. 1998; Li et al. 1999a, 1999b). If we assume maximum mass given by the TOV equation for EOS1 can be seen to the star surface and take the value from Titarchuk et al. (2002) we the electron density to be uniform over a depth of 100 fm on top of the star surface and take the value from Titarchuk et al. (2002) we the electron density to be uniform over a depth of 100 fm on top of the star surface.  

\[ \sqrt{\left(k_f/R\right)hc^2 + m_e^2c^4 - m_e^2c^2}, \]  

\[ \text{by a factor } f > 1, \text{ in order that the electrons at the top of the Fermi surface do not escape. Using Titarchuk et al. (2002) we find } f = 13. \text{ A guess value of } f = 10 \text{ was used in SDDRB. So the electron number expected by us is justified by the work of Titarchuk et al. (2002), giving more credibility to our calculations.} \]

4 CONCLUSIONS AND SUMMARY

In conclusion we point out that there are bits and pieces of evidence in support of the existence of strange stars. For example, the short-range pairing of ud quarks by a few MeV can provide for events parallel to fusion bursts which release about 5 MeV per event. Whereas the latter last typically for only 10 s, the pairing can go on for hours (minutes) after a star has suffered prolonged accretion and all or some of the pairs are broken. This can explain superbursts which are recurrent within 5 yr as seen in 4U 1636–53. The alternative scenario involving carbon burning may work for 4U 1820–30 but cannot be uniformly applied to all superbursters and long bursters (Sinha et al. 2002b). The absorption spectra of 1E 1207.4–5209 (De Luca et al. 2004a) is another case in evidence which may turn out to be a strange star showing resonance absorption (Sinha et al. 2003).

In summary, we point out that lines observed in many stars at more or less around 1 keV may be due to harmonic surface oscillations, if they are strange stars. We also reaffirm that the millisecond X-ray pulsar SAX J1808.4–3658 may be a strange star.

Confirmation of the existence of strange stars would lead to a rich interplay between X-ray astrophysics and quantum chromodynamics (QCD).

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