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Possible evidence of surface vibration of strange stars from stellar observations.

Subharthi Ray ^{1,2,3} Jishnu Dey ^{1,4}, Mira Dey ^{1,5} & Siddhartha Bhowmick, ^{1,6}
[1] *Inter University Centre for Astronomy and Astrophysics, Post Bag 4, Pune 411007, India*
[2] *The Abdus Salam International Center for Theoretical Physics, 34100 Trieste, Italy*
[3] *Instituto di Fisica, Universidade Federal Fluminense, Niteroi 24210-340, RJ, Brasil*
[4] *UGC Research Professor, Dept. of Physics, Maulana Azad College, 8 Rafi Ahmed Kidwai Road, Kolkata 700 013, India*
[5] *Dept. of Physics, Presidency College, 86/1 College Street, Kolkata 700 073, India*
[6] *Department of Physics, Barasat Govt. College, Barasat, North 24 Paraganas, W. Bengal, India.*

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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. These stars under consideration, are the 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 $\sim$ in 0.7, 1.4, 2.1 and 2.8 keV 1E1207−5209 and 0.35, 0.7 and 1.4 keV RX J1856.5−3754 are due to harmonic surface vibrations in strange stars. We propose that these harmonic vibrations may also responsible for emission lines in the above mentioned compact stellar candidates.

Key words: dense matter – stars : realistic strange stars.

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 such 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 for most of the strange star EOSs have the feature of sharp surface. Besides the existing MIT Bag model EOSs for strange matter (Farhi & Jaffe, 1984; Haensel et al., 1986; Alcock et al., 1987, etc.), Dey et al. (1998)(henceforth, D98) gave an EOS for strange matter and used it to model strange stars having such property. Another strange star model having such phenomena is by Malheiro et al. (2003), where they have the feature of 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 called as SDDRB). In particular, the former star shows evidence of 4 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. 2003).

The presence of the vibrational frequencies we discuss, is related to surface compressional modes and it 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 the compact stars are still far from accuracy and depends on a lot of *assumptions*, like the surface temperature, luminosity, distance estimates, etc. With the size of the 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 and 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 the normal neutron stars. So, to bypass these kind of uncertainties and debates, an alternative signature is desperately sought in order to prove the existence of the strange stars. The estimates of the surface vibrations for the strange stars (for the D98 model, which is a realistic model of uds quark confinement and asymp-

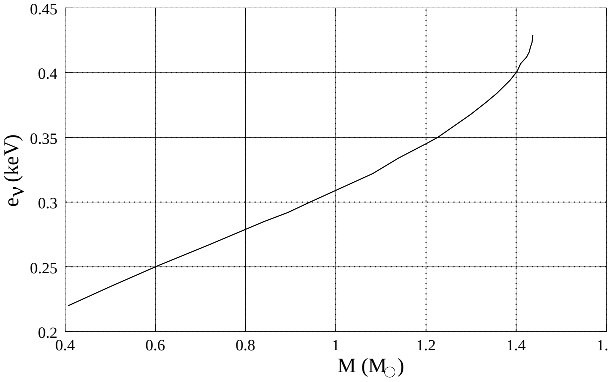

Figure 1. Fundamental vibrational energy (e$_\nu$) for skin vibrations of strange stars as function of the stellar mass.

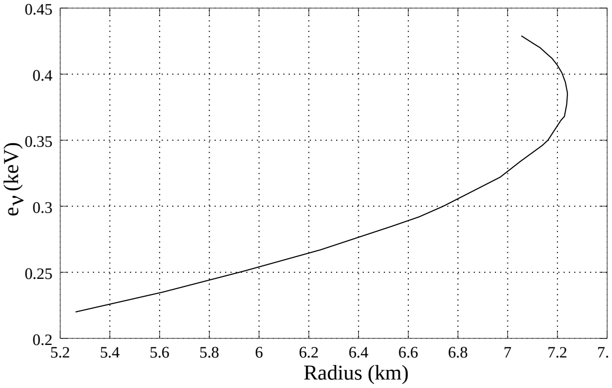

Figure 2. Fundamental vibrational energy (e$_\nu$) for skin vibrations of strange stars as function of the stellar dimensions.

totic 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 talk about 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 a chiral symmetry restoration as one moves from low to high density. When this is included along with a Debye screening for gluon propagation, a model may be described as a realistic one for exploring the possibility of a high density strange quark phase comprising of $u,\ d\ and\ s$ quarks. Considering the above mentioned properties, D98 developed their model for strange quark matter and strange star. The EOS1 of D98 has a minimum of energy per baryon (E/A) at a surface density of 4.586 times the normal nuclear matter density, where the pressure $p = 0$, and this surface can vibrate. The spectrum of the vibration frequency ν is controlled by dp/dr and is harmonic so frequencies $n\nu$ are expected to occur for $n = 1, 2, 3....$

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 the solutions of the Tolman - Oppenheimer - Volkof (TOV) equation for the star given in D98 and Li et al. (1999a & 1999b).

In D98 model, the energy per particle has a minimum at the surface. The nature of the curve near the minimum can be approximated by the potential of a harmonic oscillator. A Taylor expansion of the energy about $r = R$ gives

$$\frac{E(r)}{A} = \frac{E(R)}{A} + \frac{1}{2}k(r)\ (r-R)^2 \tag{1}$$

where R is the star radius,

$$k(r) = -4\pi\, r^2\, \frac{dp}{dr} \tag{2}$$

and

$$\frac{dp}{dr} = \frac{-G(p(r)+\epsilon(r))(m(r)+4\pi\ r^3 p(r))}{r^2\ (1-\frac{2Gm(r)}{r})} \tag{3}$$

is the TOV equation with conventional notation.

The frequency of the vibration is given by

$$\nu = \frac{c}{2\pi}\sqrt{\frac{k(R)}{m_{skin}}}, \tag{4}$$

where the mass of the skin (m_{skin}) is in energy units.

The m_{skin} is estimated to be very small (SDDRB). The very small depth of the surface d must be larger than the effective diameter of the ud quarks $D_{eff} : d \geqslant D_{eff}$.

For the extreme case when the equality sign holds, which means the layer is just one diameter thick, we can replace D_{eff} by d. This yields an estimate of the Maxwellian mean free path :

$$\lambda = \frac{1}{\sqrt{2}\ \pi\ \rho_{surf}\ d^2} = 4.28\,\text{mm}, \tag{5}$$

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

In terms of this d

$$m_{skin} = 4\pi R_{star}^2\ d\ \rho_{surf}\frac{M_u + M_d}{2}. \tag{6}$$

$M_u = 132$ and $M_d = 135\ MeV$ for SS1 at the star surface. Mark 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 ρ_0 or 46.85 $\times 10^{14}\ \text{gm/cm}^3$.

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 & 2) for the relevant value 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 black body spectrum ($kT = 3\ keV$) with a $\chi^2 = 1.65$ and shows a residual at 0.8 keV with width 55 eV. Including this line in the fit reduces the χ^2 to 1.14 Schulz (1999). We predict a mass of $1.4\ M_\odot$ and a radius of 7.22 km.

(iii) White et al. (1999) found a 0.7 keV line emission for 4U 1543−624.

(iv) Juett, Psaltis and Chakraborty (2001) suggest that the three stars above and 4U 1850−087 with a 0.7 keV line might have extra neon in the mass donors. However as these authors point out, a few type I X-ray bursts have been reported from three of these sources : two bursts from 4U 0614+091, one from 2S 0918−549 and three from 4U 1850−087. This may indicate that the donors in these systems are not C-O dwarfs (Juett et al., 2001). For 0.7 keV lines, we predict a mass of 1.23 $M_\odot$ and a radius of 7.16 km.

(v) 4U 1820−30, located in the Globular Cluster NGC 6625 is a binary star with period 685 sec. Schulz (1999) finds two peaking lines at 0.6 and 0.9 keV which enables us to suggest its mass as $0.94\ M_\odot$. Note that this star was predicted to be a strange star in Dey et al. (1998) from the mass-radius curve.

(vi) Finally the 0.6 keV excess emission in RX J170930.2−263927 is reported by Jonker et al. (2003). We predict the mass of this star to be $\sim\ 0.94\ M_\odot$.

Millisecond pulsars (MSPs) have long been considered one of the possible endpoints of low mass X-ray binary evolution. The star is thought to be spun up to a millisecond period by accretion from its low mass companion. In the last five years this theory has been confirmed with the identification of three accretion powered MSP-s the first one being SAX J1808.4−3658 which was hailed as the holy grail of X-ray pulsar astronomy by van der Klis (2000). It was suggested in Li et al. (1999a) that this may be a strange star.

The two other millisecond X-ray pulsars X1751−305 and XTE J0929−314 may also be strange stars. If so then all these three stars have a low magnetic field and low rate of accretion due to their age and they are not expected to feel strong excitations involving the entire accreting star surface like other younger strongly accreting stars. Hence the absence of line spectra and QPO-s from these stars is expected.

It may be recalled that electrons in strange stars are not bound by strong interaction and can stay outside the sharp star surface. A thin, negatively charged shell of about 100 fm may be formed outside the surface due to these electrons (Alcock et al., 1986; Alcock, 1991).

The stars SAX J1808.4−3658, X1751−305 and XTE J0929−314 all show highly coherent pulses whence their rotation frequencies are easily determined to be 401, 435 and 185 Hz respectively.

In trying to explain why coherent radiation are detected in the above MSPs, one may use the model of Titarchuk et al. (2002), for SAX J1808.4−3658. They suggested that the X-ray emission originates in the comptonization process in a relatively optically thin hot region. They estimated the electron density near the surface of the star to be about $3.3 \times 10^{19}/\mathrm{cm}^3$. The star radius with the maximum mass given by the TOV equation for eos1 can be seen to be 7.055 km (Dey et al., 1998; Li et al., 1999a & 1999b).[1] If we assume 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 get the number of electrons to be $N_e = 10^{24}$. There will a resultant positive charge Z, on the star. Assuming it is charge neutral $Z = N_e$ and to the outside electron this will appear to be concentrated at the centre producing a electrostatic potential $N_e e^2/R = 421.4\ MeV$. This has to be larger than the maximum kinetic energy of the electrons at the star surface

$$(\sqrt{(k_f(R)\hbar c)^2 + m_e^2\, c^4} - m_e\, c^2), \tag{7}$$

by a factor $f > 1$, in order that the electrons at the top of the Fermi surface do not escape. Using Titarchuk et al. (2002) we find $f = 13$. A guess value of $f = 10$ 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 seconds - the pairing can go on for hours (minutes) after a star has suffered prolonged accretion and all (some of) the pairs are broken. This can explain superbursts which are recurrent within 5 years as seen in 4U 1636−53. The alternate 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. 2004) 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 pulsars 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 QCD.

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[1] In strange stars the quark matter is bound tightly by strong interaction so that the star is very stable against possible fast rotation (Gondek-Rosińska et al., 2000; Bombaci et al., 2000) and vibration (Sharma et al., 2002; Sinha et al., 2002a). However the electrons are not affected by the strong interaction and with a electron Fermi momentum $\sim 30\ MeV$, many of them are energetic and move away from the surface.

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