Strange star equation of state fits the refined mass measurement of 12 pulsars and predicts their radii

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ABSTRACT
There are three categories of stars whose masses have been found accurately in recent times: (1) two for which Shapiro delay is used, which is possible due to GR light bending as the partner is heavy – PSR J1614−2230 and PSR J1903+0327, (2) six eclipsing stars for which numerical Roche lobe geometry is used and (3) three stars for which spectroscopic methods are used and in fact for these three the mass and radii both are estimated. Motivated by large colour (\(N_c\)) expansion using a modified Richardson potential, along with density-dependent quark masses thereby allowing chiral symmetry restoration, we get compact strange stars fitting all the observed masses.

Key words: stars: neutron – pulsars: general.

1 INTRODUCTION
High masses were found in different types of pulsar binaries, starting with some in globular clusters (Ransom et al. 2005; Freire et al. 2008a,b). In these cases, however, the masses rely on observations of periastron advance, which is assumed to be due to general relativistic effects only (rather than classical ones such as due to rotationally and tidally induced quadrupoles), and statistical arguments that the inclinations are unlikely to be very low. Thus, it was still possible to doubt that very massive neutron stars could exist. However, such doubts disappeared, with accurate mass determinations for PSR J1614+2230 (1.97 ± 0.04\(M_\odot\); Demorest et al. 2010) and PSR J1903+0327 (1.67 ± 0.02\(M_\odot\); Freire et al. 2011), both relying on measurements of Shapiro delay, which is not easily mimicked by other processes.

Also X-ray eclipses are now claimed to be a useful tool for determining masses of compact stars (Rawls et al. 2011). In previous studies, the X-ray eclipse duration had been approximated analytically by assuming that the companion star is spherical with an effective Roche lobe radius. Now, to include all these various mass limits that are calculated with a fair degree of accuracy, it is almost impossible to fit in any single neutron star model. The problem with the gravitationally bound nuclear matter is that as we go to the lower mass values, the gravitational bound becomes weaker and the compact star tends to become larger in size. Whereas the exotic strange matter stars are bound by strong interaction as well as with gravity, and hence for a small mass, the radius is also small. Emphasis must be placed on the fact that some of these masses are not large and only the strange star (SS) equation of state (EOS) can uniquely fit the masses of small and large compact objects.

The idea of SS is well studied by now and in the model of Dey et al. (1998) it was applied to 4U 1820−30 and Her X-1 claiming a more compact nature of stellar objects compared to neutron stars – and also SS based on the MIT Bag model. The analysis of spectroscopic data on multiple thermonuclear bursts from 4U 1820−30 in the globular cluster NGC 6624 yields well-constrained values for the apparent emitting area and the Eddington flux, both of which depend in a distinct way on the mass and radius of the compact star.

In the original model (Dey et al. 1998), the masses of the star 4U 1820−30 and Her X−1 were estimated theoretically including different and appropriate scales for quark confinement and asymptotic freedom. They are now fitted to more accurate observations in this paper. We find that the mass and radius of 4U 1820−30 and 4U 1608−52 which is found from new spectroscopic observations is fitted well with the new EOS. We also have fitted the large masses of PSR J1614−2230 and PSR J1903−0327 found from recent Shapiro delay observations and predict their radii. We have predicted the radii of the six eclipsing binary pulsars including

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Her X-1 using their masses fitted with current accurate determinations based on Roche lobe geometry (Rawls et al. 2011).

2 THE MODEL AND EOS

The strange matter EOS that we have chosen for this work is based on the fact that there are interacting quarks and the quark masses follow an asymptotic behaviour. It is an extension of the strange matter EOS developed by Dey et al. (1998), where there are interacting quarks, interaction taking place via the Richardson potential in a mean field Hartree–Fock prescription. The parameter set that we employ used the asymptotic parameter $\Lambda = 100$ MeV and confinement parameter $\Lambda' = 360$ MeV along with an $\alpha_0 = 0.43$. To obtain larger masses for the SS, we must have onset of chiral symmetry earlier with the free parameter $N = 2$ since the lighter quarks can carry more kinetic energy with the masses given as

$$M_i = m_i + M_q \text{sech} \left( \frac{n_B}{N n_0} \right), \quad i = u, d, s.$$  \hspace{1cm} (1)

The parameter $N$ dictates how fast the quark masses fall off with increasing density as is given in equation (1). The confinement in the medium is softened and the corresponding inverse Debye screening length to the lowest order is given by (Baluni, 1978)

$$(D^{-1})^2 \equiv \frac{2\alpha_0}{\pi} \sum_{i = u, d, s} k_i^2 \left[ \left( k_i^2 \right)^2 + m_i^2 \right], \hspace{1cm} (2)$$

where $k_i$, the Fermi momentum of the $i$th quark is obtained from the corresponding number density

$$k_i = (\rho_i \pi^2)^{1/3},$$  \hspace{1cm} (3)

and $\alpha_0$ is the perturbative quark gluon coupling.

Assuming chiral symmetry is restored at high energy, the quark mass, $M_i$, of $i$th flavour, is taken to be density dependent so that it decreases with increasing density. $M_i$ is the quark mass when chiral symmetry is completely broken. $m_i$ are the current quark masses, $m_u = 4$ MeV, $m_d = 7$ MeV and $m_s = 150$ MeV and the chiral symmetry restoration is shown in Fig. 1 as a function of the baryonic density

$$n_B = n_u + n_d + n_s \frac{1}{3}.$$  \hspace{1cm} (4)

![Figure 1](https://example.com/figure1.png)

**Figure 1.** u-quark mass for densities $n = n_B/n_0$, where $n_B$ is the baryonic density and $n_0$ is the normal nuclear matter density. Notable is faster fall off u-quark mass with increasing $n$ for $N = 2$ compared to $N = 3$ (Dey et al. 1998).

Table 1. The parameters used for the EOS.

| Parameter | Symbol | Value |
|-----------|--------|-------|
| $\Lambda'$ | MeV    | 360   |
| $M_q$     | MeV    | 400   |
| $N$       |        | 2.0   |
| $\alpha_0$|        | 0.43  |
| $(E/A)_{\text{min}}$ | MeV | 728.12 |
| $R_{\odot}$ | kG | 2.0545 |
| $R$       | km     | 9.5   |

$n_0 = 0.17 \text{fm}^{-3}$. In the figure, we show two values of $N$, one corresponding to Dey et al. (1998) and the other, $N = 2.0$ taken in this paper. The argument for taking a lower value of $N$ is that the masses are decreasing faster as one goes inside the pulsar from the surface. That means there is a faster decrease in the scalar potential leading to sharper change in kinetic energy. The vector potential has not significantly changed from Bagchi et al. (2006), but both the asymptotic part and the Debye-screened part has relatively altered with sharper change in kinetic energy (Table 1).

The detection of massive ($\sim 2M_\odot$) pulsars has emphasized the need to study compact astrophysical objects since they place very strong constraints on the EOS of matter at extreme nuclear densities (e.g. Lattimer & Prakash 2004). Stars having hyperons or quark stars having boson condensates, with softer EOS can barely reach such limits. In this paper, we try to explain these heavy pulsars as SS with density-dependent quark mass. We will show that SS models fit the measured mass of pulsars ranging from $\sim 1$ to $\sim 2M_\odot$, because in these models the quark masses decrease fast with density as is shown in Fig. 1.

The work of Li, Dai & Wang (1995) on Her X−1 and that of Bombaci (1997) led us to our realistic SS model where the quark mass was taken to be density dependent and the interquark force had asymptotic freedom and confinement (with Debye screening) built into it through a Richardson-type potential. The spirit is that of large colour model of ’tHooft where quark degrees of freedom are effectively approximated.

3 THE STAR HER X−1

Is Her X−1 an SS? In 1995 Li, Dai and Wang first raised this question. They estimated its mass to be $0.98 \pm 0.12 M_\odot$. In a more recent paper in 2008, Abubekerov et al. (2008) reported the mass to be $0.85 \pm 0.15 M_\odot$. In another recent paper, Rawls et al. (2011) claim to have made more refined mass determinations of six eclipsing stars; the Her X−1 mass is not very well determined with a large range $1.07 \pm 0.36 M_\odot$.

In our prediction for the radius, we have chosen the mass estimate of Abubekerov et al. (2008) where they have deployed a physically justified technique of calculating the local absorption and taking into account external X-ray heating, and analysing the radial-velocity curve they obtained the mass for the X-ray pulsar to be $0.85 \pm 0.15 M_\odot$. The radius prediction for Her X−1 from our EOS is around $8.1 \pm 0.41$ km (Fig. 2). For the numerical X-ray eclipsing calculations, we expect that more precise determinations will be made soon.

4 MASS MEASUREMENT OF 4U 1820−30, 4U 1608−52 AND EXO 1745−248

Simultaneously measuring the mass and radius of a distant compact star requires measurement of combination of several spectroscopic phenomena observed from the stellar surface. If the red-shifted absorption line is absent from the spectroscopic feature, then it is extremely essential to know the distance of the source/object. In a recent work, Güver et al. (2010a) used time resolved X-ray
spectroscopy of the thermonuclear burst of 4U 1820−30, and side by side they measured the distance of the globular cluster NGC 6624, which hosts the same. They report well-constrained values of the apparent emitting area and the Eddington flux, both of which depend in a distinct way on the mass and radius of the compact star. They find the mass to be 0.4 km. From our EOS, we have a radius estimate of about 9.65 km assuming $M(4U 1820 − 30) = 1.58 \pm 0.06 M_\odot$ and the radius to be $R = 9.1 \pm 0.4$ km. From our EOS, we have a radius estimate of about 9.65 km assuming $M(4U 1820 − 30) = 1.58 M_\odot$, which is very close to their estimated value (Fig. 3). That said, they also mention that the relatively large uncertainty in the source distance estimate was taken care of using the Bayesian analysis of the probability density of a few set of values for the mass and radius pair for different distance values and optimizing them for those set of values which fit well with the spectroscopic data, using a maximum likelihood method.

In another work, Güver et al. (2010b) measured the mass and radius of the lower mass X-ray binary (LMXB) 4U 1608−52. For this, they used red clump giants as the standard candles to measure the distance of the LMXB and found the best-fitting distance estimate to be 5.8 kpc. Then, they combined this distance estimate together with the time-resolved spectroscopy of the type I X-ray bursts to measure the mass and radius of the compact star in the X-ray binary, by carrying out the similar likelihood analysis of the probability density functions of the mass and the radius, and found the optimized values to be $M(4U 1608 − 52) = 1.74 \pm 0.14 M_\odot$, $R = 9.3 \pm 1.0$ km. Again, comparing this with our estimated value of the radius for 1.74 $M_\odot$ star to be at 9.8 km (Fig. 3), we observe that it falls well within the 1σ contour of their observed value.

Özel, Güver & Psaltis (2009) used time resolved spectroscopic data from EXO 1745−248 during thermonuclear bursts to measure the Eddington flux and apparent surface area of the compact star. EXO 1745−248 is located in the metal-rich globular cluster Terzan 5, in the galaxy. A refined measurement of the distance of Terzan 5 using Hubble Space Telescope Near Infra-red Camera and Multi Object Spectrometer data revealed that this globular cluster is situated at a distance of 6.3 kpc, with an uncertainty of 10 per cent. The EXO 1745−248 was observed with the RXTE for 148 ks, where there were evidence of the photospheric radius expansion. Combining the distance estimate to the Terzan 5 and the photospheric radius expansion, they found a refined mass and radius estimate of 1.7 $M_\odot$ and 9 km, respectively.

5 MASS MEASUREMENT WITH SHAPIRO DELAY

Shapiro delay is a general relativistic increase in light travel time through the curved space–time near a massive body. For highly inclined (nearly edge on) binary millisecond radio (msr) pulsar system, this effect allows us to infer the masses of both the neutron star and its binary companion to high precision.

Demorest et al. (2010) used the measured arrival times of the pulses to determine key physical parameters of the compact star and its binary system by fitting them to a comprehensive timing model that accounts for every rotation of the star over the time spanned by the fit. The model predicts at what times pulses should arrive at Earth, taking into account pulsar rotation and spindown, sky position, binary orbital parameters, time-variable interstellar dispersion and general-relativistic effects such as the Shapiro delay. They compared the observed arrival times with the model predictions and obtained the best-fitting parameters by $\chi^2$ minimization.

Two such determinations have already been made, the most accurate one to date being PSR J1903+0327 with the mass of 1.667 ± 0.021 $M_\odot$ (Freire et al. 2011) and a more heavy msr PSR J1614+2230 with the mass of 1.97 ± 0.04 $M_\odot$ (Demorest et al. 2010). The radii of these stars still remain ambiguous and are dependent on the choice of the model/EOS to describe them.

The origin of the heavy PSR J1614+2230 has been of considerable interest. Tauris, Langer & Kramer (2011) have looked at this star whose mass also was determined very accurately using Shapiro delay method and concluded that this star must have originated with mass of either 1.95 or 1.7 ± 0.15 $M_\odot$, which according to them significantly exceeds birth-masses of previously discovered pulsar systems and they suggested that it was born massive from a progenitor star more massive than 20 $M_\odot$.

To account for the high mass of PSR J1614+2230, Demorest et al. (2010) points out that such high mass can be supported by quark matter EOS only if the quarks are interacting. In our refined strange matter and SS model, where we have interacting quarks, we can see that if the compact star in PSR J1614+2230 is an exotic strange matter star, then it should have a predicted radius of ~9.5 km (Fig. 4).

There has also been excitement about the nature and evolution of the unique binary pulsar PSR J1903+0327, which has a mass of 1.667 ± 0.021 $M_\odot$ (0.99 per cent confidence limit). Freire et al. (2011) have suggested that it is a black widow which accreted up its
nearest partner fully or partially so that it disappeared from a tertiary system after it was formed from a supernova. They have further suggested that its rather large eccentricity is relatively constant.

6 COMPARING WITH SIX ECLIPSING BINARY PULSARS

Rawls et al. (2011) have refined mass determination for six eclipsing X-ray pulsar binaries which fit into our present investigation of SS candidates. Of these the Her X-1 has a mass with big errors: 1.07 ± 0.36 M⊙ but was the first star suggested to be strange on the basis of its radius estimate.

Rawls et al. (2011) now use a numerical code based on Roche geometry with various optimisers to analyse the published data for these systems, which we supplement with new spectroscopic and photometric data for 4U 1538–52. This allows them to model the eclipse duration more accurately and thus calculate an improved value for the neutron star mass. The derived neutron star mass also depends on the assumed Roche lobe filling factor β of the companion star, where β = 1 indicates a completely filled Roche lobe. In previous work, a range of β between 0.9 and 1.0 was usually adopted. Now optical ellipsoidal light-curve data is used to constrain β. Rawls et al. (2011) find neutron star masses of 1.77 ± 0.08 M⊙ for Vela X–1, 0.87 ± 0.07 M⊙ for 4U 1538–52 (eccentric orbit), 1.00 ± 0.10 M⊙ for 4U 1538–52 (circular orbit), 1.04 ± 0.09 M⊙ for SMC X–1, 1.29 ± 0.05 M⊙ for LMC X–4, 1.49 ± 0.08 M⊙ for Cen X–3 and 1.07 ± 0.36 M⊙ for Her X–1 (Fig. 5).

The earlier methods relied on analytic approximations for the Roche lobe geometry, whereas ELC code of Jerry Orosz does not rely on such approximations but rather solves the Roche lobe geometry numerically. In figs 2–4 of Rawls et al. (2011), they explore the parameter space and show that the analytic approximations can be off by as much as 10 to 20 percent in some cases. Figs 5 and 6 of Rawls et al. (2011) again show how much the shape of the Roche lobe filling donor star can differ based on whether you use analytic approximations (red lines) or their numerical code (solid black lines).

The important things from their paper are the results presented in table 4 and visually summarized in fig. 10. The solid lines in fig. 10 are their ‘improved’ mass estimates and the dotted lines are what you would get by older/analytic methods. As we can see, in most cases the error bars for their new/numerical method are indeed smaller than those derived via analytic method. But other than 4U 1528–52, the changes in compact star masses (derived by the two methods) are quite small. For 4U 1528–52, it appears that their numerical method gives two (almost significantly) different results whether one assumes the orbit to be eccentric (then one gets a lower NS mass) or circular (then one gets a bit higher NS mass). Current data cannot distinguish between eccentric or circular orbits for this one.

7 RAMIFICATIONS FROM PSR J1614–2230, VELA X-1 FOR HEAVY COMPACT STARS WITH HEAVIER PARTNERS

Mass determinations of Vela X-1 (Rawls et al. 2011) suggest that this compact star has a high observed mass. The companion star to Vela X-1 is a B0.5 Ib supergiant (HD 77581) with a mass of about 23 M⊙, which implies that the present mass of the neutron star is very close to its birth-mass as suggested by Tauris et al. (2011). Even a hypothetical strong wind accretion at the Eddington limit would not have resulted in accretion of more than about 10⁻² M⊙ given the short lifetime of its massive companion. We therefore conclude that not only was the compact star in PSR J1614–2230 born massive 1.97 ± 0.04 M⊙, but also the compact star Vela X-1 was born with a mass 1.77 ± 0.08 M⊙. In these cases, it is possible that the pulsars did not have time to go over to the paired phase. Even if they did, we checked that the masses would not change very much but the radius will decrease – in other words the stars will be more compact. In what follows, we are trying to show that all the 11 compact stars above, some with high masses and some lower, can be explained with a single SS EOS.

8 THE COMPACT STAR XTE J1739–285 AND SAX J1808.4–3658

Zhang et al. (2007) considered the star XTE J1739–285 which is very interesting since its spinning period may be as high as 1122 Hz. The uncertainty in the determination of the spin remains a problem since it is observed in only one burst but not in the whole set of bursts (Kaaret et al. 2007). In Zhang et al. (2007), the authors suggested that if the higher twin quasi-periodic oscillations (QPOs) are detected in XTE J1739–285, a strong constraint on mass and radius can be placed using the upper kHz quasi-periodic
oscillation frequency and the star frequency one gets $M = 1.51 M_\odot$ and radius $< 10.9 \text{ km}$ and this excludes most EOS of normal neutron matter. They observed that this is fitted well with EOS SS1 given in Dey et al. (1998). The present SS EOS used here is a refined and modified form of the SS EOS (SS1) of Dey et al. (1998).

The SAX J1808.4–3658 has a mass of $0.9 \pm 0.3 M_\odot$ from optical measurements (Elebert et al. 2009) but according to our QPO study (Gangopadhyay et al. 2012) for this star the central value of the mass is preferred.

Furthermore, the precise orbital measurements have prompted Di Salvo et al. (2008) and Burderi et al. (2009) to suggest that the orbit enhancement and the estimated accretion from the luminosity of the X-ray bursts over 10 years suggest that there is unconventional mass-loss from the binary system. Electrons form a layer outside the X-ray bursts over 10 years suggest that there is unconventional mass-loss from the binary system. Electrons form a layer outside SS since they are held by electromagnetism, as opposed to quarks held by strong interaction. These electrons will interact with the u-quarks of the incoming accreting particles (normal matter). Hence, in terms of the conversion of the normal matter from the brown dwarf at the surface of the SS the reaction is simply

$$u + e^- = s + v,$$

since the gain in energy in our EOS at the surface of the SS is 200 MeV whereas the mass excess of $s$ over $u$ is only 150 MeV. This strongly supports the conclusions of Li et al. (1999) suggesting that SAX J1808.4–3658 is an SS.

Further confirmation in future burst detections is awaited hopefully with detection of higher twin QPOs. In a recent paper, we have shown that for many stars with measured higher twin QPOs including SAX J1808.4–3658, one can indeed predict the mass and radius for fast rotating stars using Kerr geometry results (Gangopadhyay et al. 2012).

### 9 DISCUSSION

The predicted radii of all the 12 pulsars from our equation of state are enlisted in Table 2. Four stars Her X-1, 4U 1820–30, SAX J1808.4 and more recently the fast spinning XTE J1739–285 were suggested to be SS. We add the stars whose masses are recently determined accurately; two from Shapiro delay, six from Roche lobe geometry for eclipsing stars which includes Her X-1 and three from spectroscopic studies including 4U 1820–30. Fitting these stars with an $M-R$ curve of SS effectively restricts the radii of these stars within sharp limits since the nature of the curve is restricted to smaller radii as compared to neutron stars. As is well known, the reason is that neutron stars have to be bound by gravitation so that to have a small radius it has to have a large mass. SS on the other hand are bound by strong interaction as well as gravitation so that small-mass stars have necessarily small radii and for the large-mass stars also the radius is not too large – as can indeed be seen from our Figs 2, 3 and 4. The discovery of a 2 $M_\odot$ binary millisecond pulsar raises the interesting possibility that PSR J1614–2230 was born from the collapse of a very massive 29 $M_\odot$ as discussed by Tauris et al. (2011). This would support the idea of it being an SS since this might lead to the strange matter phase. There is problem regarding the origin of the other Shapiro delay star PSR J1903+0327, and Freire et al. (2011) comment that stellar evolution studies may provide new insights on how millisecond pulsars form. In a recent paper, Logoteta et al. (2012) find that it is difficult to obtain masses larger than 1.62 $M_\odot$ even with hyperon or hybrid stars.

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